The ABCs of left ventricular assist device echocardiography: a systematic approach

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Echocardiography is an important imaging modality used to determine the indication of left ventricular assist device (LVAD) implantation for patients with advanced heart failure (HF) and for serial follow-up to make management decisions in patient care post-implant. Continuous axial-flow LVAD therapy provides effective haemodynamic support for the failing left ventricle, improving both the clinical functional status and quality of life. Echocardiographers must develop a systematic approach to echocardiographic assessment of LVAD implantation and post-LVAD implant cardiac morphology and physiology. This approach must include the evaluation of left and right heart chamber morphology and physiology and the anatomy and physiology of the inflow and outflow cannulas and the rotor pump, and the determination of the degree of tricuspid regurgitation and the presence of interatrial shunts and aortic regurgitation. Collaboration among the echocardiography and HF/transplant teams is essential to obtain this comprehensive evaluation. We outline a systematic approach to evaluating patients with HF who have failed conventional therapy and require LVAD therapy as a bridge to cardiac transplantation or destination therapy.

Keywords
HeartMate II • Left ventricular assist device • Echocardiography pre- and post-implant • Bridge to transplantation • Destination therapy

Introduction
Heart failure (HF) is a major cause of death, morbidity, and health care expenditures in the USA, despite routine clinical use of scientifically proved therapies that reduce mortality and improve quality of life.1 In patients unresponsive to aggressive HF therapy, a left ventricular assist device (LVAD) is an option to provide mechanical circulatory support as a bridge to cardiac transplantation or destination therapy. LVAD therapy is effective in supporting cardiovascular circulation for weeks to years.2-5 The continuous axial-flow LVAD is designed to minimize the operative risk, improve durability, and lower the risk of device-related adverse events.6-8 Continuous axial-flow LVAD provides effective haemodynamic support for greater duration with both an improved clinical functional status and quality of life.9,10

Increased use of LVAD therapy for patients with HF has resulted in a knowledge gap for practising physicians treating such patients, and created a growing need for evaluation of how these devices impact cardiac morphology, physiology, and function. Echocardiography is the most important imaging modality for LVAD assessment pre- and post-implantation and for long-term follow-up.

It facilitates serial, non-invasive evaluations before and after implantation to document cardiac morphology and physiology, guide management decisions, and identify mechanical dysfunction. This review will identify a comprehensive approach for sonographers and echocardiographers in their evaluation of patients for the appropriateness and timing of LVAD implantation and post-LVAD implant evaluation using echocardiography.

New technology for cardiac anatomy
The HeartMate II®, developed by Thoratec Corp. (Pleasanton, CA, USA), is a continuous axial-flow pump that consists of a propeller in a pump. The main advantage of this LVAD is that it can be easily adjusted to run at low-flow/high-pressure and high-flow/low-pressure settings by changing the pitch on the propeller. The parts of the HeartMate II are positioned in succession—spinney rotor pump, inflow cannula, outflow cannula, and a single drive line that exits percutaneously towards the electronic controller—to act as the left ventricle (LV).7,8

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The inflow cannula is inserted into the apex of the LV; the outflow cannula is anastomosed to the right anterior aspect of the ascending aorta. The LVAD pump is placed within the peritoneal cavity. The percutaneous lead carries the electrical cable to an electronic controller and battery pack that are worn on a belt and shoulder holster. The spinning of the rotor draws blood from the inflow cannula through cardiac diastole and systole into the ascending aorta (Figure 1).

Echocardiography caveats in patients with left ventricular assist devices

Tips and tricks

Echocardiographic assessment of patients undergoing LVAD implantation must include morphological and physiological parameters that delineate the benefits and risks of proceeding. This review will focus on specific imaging concerns pertaining to patients undergoing LVAD implantation. The four types of echocardiographic LVAD evaluations are:

(i) pre-operative transthoracic echocardiography (TTE);
(ii) perioperative transoesophageal echocardiography (TEE);
(iii) post-operative echocardiography TEE/TTE;
(iv) serial TTE, post-operatively.

Examining the heart structure and function pre-LVAD implantation has two main purposes: (i) to determine the suitability of LVAD treatment for a patient with HF, and (ii) to identify cardiac abnormalities that could predict post-surgical complications. Specifically, the pre-operative echocardiographic examination should include the assessment of the structure and function of the left heart chambers, right ventricular (RV) function and degree of tricuspid regurgitation (TR), and presence of intracardiac clots, interatrial shunts, and degree of aortic regurgitation (AR).

Function of left heart chambers

During pre-operative echocardiographic examination, identify LV chamber dimensions, diastolic and systolic functions, left atrial (LA) volume and pressure, mitral annulus dimension, tethering of mitral valve leaflets secondary to geometrical changes of the LV and papillary muscles, and degree of mitral regurgitation.11–14 The persona of restrictive diastolic physiology is reflected by increased LV and LA pressures and, when severe, supports the indication for LVAD implantation (Supplementary data online, Video S).

Right ventricular function and degree of tricuspid regurgitation

The RV is a complex structure and not completely visualized in any single echocardiographic imaging window. Several methods are commonly applied to evaluate RV functions pre-LVAD implantation. First, imagers obtain semi-quantitative assessment of the RV dimensions/function using four-chamber and inflow views via TTE. Additionally, the mid-oesophageal four-chamber and transgastric short- and long-axis views via TEE can be used. This semi-quantitative assessment is based on the usual appreciation of longitudinal and radial motions.15 Semiquantitation has limitations.

Additionally, the RV systolic function can be measured by several alternative approaches. These include global fractional area change (FAC), tricuspid annular plane systolic excursion (TAPSE), tissue Doppler-derived lateral annular systolic velocity (S’), isovolumic acceleration, RV outflow tract (RVOT) fractional shortening using M-mode echocardiography, and longitudinal strain and strain rate.16,17 Commonly, FAC is used as a quantitative measure and represents a surrogate of the RV ejection fraction. The calculation of RV FAC (Figure 2) is:

\[
\text{RV FAC} = \frac{\text{RV diastolic area} - \text{RV systolic area}}{\text{RV diastolic area}}.
\]

The RV diastolic and systolic areas are traced in the apical four-chamber view.18 RV FAC ≥ 40% is considered normal. A typical LVAD candidate has an RV FAC between 20 and 30%. Patients with an RV FAC < 20% are at risk for RV failure with the initiation of LVAD therapy.

A more quantitative evaluation of RV myocardial performance is the Tei index. The Tei index is reproducible, independent of ventricular geometry, and not significantly impacted by heart rate or blood pressure.16 Ventricular loading conditions do not appear to affect the index to a meaningful clinical extent.16 The Tei index obtained by echocardiographic assessment is concordant with invasive measures of systolic and diastolic function.19 The calculation for the Tei index using the tricuspid valve (TV) annular...
velocity (Figure 3) (where \( a \) is the TV opening to closure time and \( b \) is the ejection time) is:

\[
\text{Tei index} = \frac{a - b}{b}.
\]

A result \( \leq 0.4 \) is normal. Limitations of the Tei index include pseudonormalization and the fact that it cannot be measured in patients with first-degree atrioventricular block.

TAPSE is a methodology to measure the distance of systolic excursion of the RV annular segment along its longitudinal plane from a standard apical four-chamber view. As with other regional methodologies, it assumes that the displacement of the basal and adjacent segments in the apical four-chamber view is representative of the function of the entire RV, an assumption that is not valid in many disease states. A TAPSE cut-off value of \(<17 \text{ mm} \) yields high specificity to distinguish abnormal from normal systolic function (Figure 4).\(^{20}\)

The RV \( S' \) (systolic excursion velocity) is another measure of RV systolic function that is easy to measure, reliable, and reproducible. To perform this measurement, an apical four-chamber window is used with a tissue Doppler mode region of interest highlighting...
the free wall. $S' < 10$ cm/s is indicative of RV systolic dysfunction. It is important to maintain the RV basal segment and keep the annulus aligned with the Doppler cursor to preclude measurement errors (Figure 5).

Myocardial acceleration during isovolumic contraction is available as a method to measure RV systolic function, but there are limited normative data. Additional methods include RVOT fractional shortening using M-mode echocardiography and longitudinal strain and strain rate, but these techniques are evolving at this time.

Functional TR is a common finding in patients with HF. Significant post-operative TR contributes to RV dysfunction and is a contributor to the development of a low output state. LVAD implantation has competing beneficial and adverse effects on the severity of TR (Supplementary data online, Video S2).

Factors increasing TR are the following:

(i) Leftward shift of the interventricular septum (IVS);
(ii) Decreased RV function post-LVAD implant; and
(iii) LVAD function increasing RV preload to an already dysfunctional RV.

The factor blunting TR is as follows:

(i) TR may be blunted or absent when the right atrial (RA) pressure is very high.

The following is a beneficial effect whereby TR is reduced:

(i) Unloading of the LV decreases TR and pulmonary artery pressure.

The competing beneficial and aggravating effects of LVAD implant have variable effects on different patients. The leftward IVS shift is more pronounced in LVAD patients who are hypovolaemic, have reduced RV function, or significant TR pre-LVAD implant. Additionally, patients with elevated LVAD flow will demonstrate an IVS shift culminating in a spiral ‘suction event’. This finding mandates decreasing the pump speed with a resultant reduction of TR and improved RV function (Figure 6). An additional clinical caveat is recognition that the absence of TR does not imply that the TV orifice is free from abnormality. Significant TV annular dilation represents a risk factor for post-LVAD implant TR. All these variables reinforce the importance of a meticulous examination of RV size and function and TV pre-LVAD implantation. The mechanism of TR is extremely important to define. TR determined to be moderate or greater may require surgical correction at the time of LVAD implantation.

**Intracardiac clots**

The risk of thrombosis formation is 9 to 16% in patients receiving an LVAD. Left heart chamber thrombosis increases the risk of embolic events during cannulation. The axial LVAD impeller is a substrate for thrombosis formation, which may precipitate catastrophic pump malfunction in addition to common clinical complications such as stroke, myocardial infarction and mesenteric, renal, and peripheral ischaemia. An apical thrombus is often located in small pockets next to the inflow cannula orifice and IVS inferior wall. Pre-operative and post-operative interrogations of the LV and the LA for the presence of thrombosis are essential. Intra-venous contrast injection increases the sensitivity and specificity of detecting an LV apical and LA appendage thrombus (Figure 7). The stitched-closed aortic valve creates a substrate for stasis of blood flow, and becomes a potential site for clot formation (Supplementary data online, Video S3).

**Interatrial shunts**

Identification of a patent foramen ovale (PFO) is clinically important (pre- and post-cardiopulmonary bypass) prior to LVAD implantation. The prevalence of a PFO in the USA population is 25%. The LVAD has important cardiopulmonary physiological effects: unloading of the LV results in a decrease in LA pressure, and RA pressure is maintained or increased through increased venous return resulting from an increased systemic flow. Those haemodynamic results may elicit two detrimental consequences post-LVAD implant: paradoxical embolization and hypoxaemia. Paradoxical embolism can result in immediate thrombosis with immediate or delayed LVAD malfunction. The development of severe hypoxaemia may occur acutely upon activation of the LVAD or several months post-LVAD implantation (Supplementary data online, Video S4).

A meticulous search for a PFO must be performed during the pre-LVAD implant echocardiogram. The identification of a PFO may be difficult in intubated or uncooperative patients and patients in respiratory distress. Agitated saline and colour-flow Doppler TEE are highly sensitive and specific methods for identifying a PFO. The variable physiological status of the patient pre-LVAD implant can make the identification of a PFO elusive. The LA pressure may be greater than in the RA. This situation may result in a left-to-right shunt; however, a bubble study may not demonstrate the shunt even with an appropriate Valsalva manoeuvre. In the case of biventricular failure, the elevated biatrial pressure may reduce/eliminate any gradient and that may interfere with PFO detection by colour-flow Doppler and agitated saline. The imaging team must be aware of these variable physiological states (Figure 8).
Aortic regurgitation

Recognition of pre- and post-operative AR is critical to the management of patients with an LVAD (Supplementary data online, Video S5). Managing AR at the time of an LVAD implantation is challenging. The approach is variable depending on the severity of the AR and the experience of the institution. Options include:

Figure 6 The ‘spiral suction’ event leading to significant tricuspid regurgitation (TR) and right ventricular (RV) failure. Patients with an elevated left ventricular (LV) assist device flow will demonstrate an interventricular septum shift and decreased LV volume, which culminates in a spiral ‘suction event’ (A). This ‘suction event’ leads to increased TR (green arrow) and depressed RV function (B). These findings mandate decreasing the pump speed with a resultant reduction of TR and improved RV function. RA, right atrium; TV, tricuspid valve.

Figure 7 Identification of an inflow cannula clot. The apical four-chamber view on a transoesophageal echocardiogram demonstrates a clot (green arrow) on the inflow cannula (white arrow) (A). The inflow cannula (A) was explanted and the pannus and the clot were found (B). A clot inside the inflow cannula (C). The surgeon extracting the clot from the inflow cannula (D). LV, left ventricle.
valve replacement with a bioprosthesis, aortic valve patching with
polytetrafluoroethylene, or primary closure. A simple coaptation
stitch placed at the central portion of the main aortic cusps can
be performed through a small lateral aortotomy incision. Correc-
tion of the AR is important because the regurgitation volume
increases as the LVAD preload increases and causes secondary
up-regulation of the pump flow volume, resulting in increased
blood flow into the ascending aorta. The pump spirals to high
levels with the systemic flow decreasing. Thus, a ‘futile cycle’

Figure 8 Pre- and post-interatrial shunting. Pre-left ventricular assist device (LVAD) implantation, transoesophageal echocardiography (TEE)
revealing no right-to-left shunt (A). Post-LVAD implantation, TEE demonstrating a right-to-left shunt (B). The patient, a 60-year-old man, under-
went ablation for atrial fibrillation prior to an LVAD implant for treatment of heart failure. Ablation did not lead to recovery from heart failure.
After the LVAD implant, the patient experienced oxygen desaturation as evidenced by the right-to-left atrium low-flow shunting (B). He then
underwent surgery to close the atrial defect and regain normal oxygen saturation.

Table 1 Preoperative echocardiographic evaluation of the potential LVAD patient: ASSESS

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<td>LV and RV chamber dimensions</td>
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<td>LV and RV systolic function</td>
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<td>Diastolic function</td>
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AR, aortic regurgitation; AV, aortic valve; LA, left atrial; LV, left ventricular; LVAD, left ventricular assist device; MR, mitral regurgitation; PASP, pulmonary artery systolic pressure; RV, right ventricular; TR, tricuspid regurgitation; TV, tricuspid valve.

Figure 9 Inflow cannula alignment. Apical four-chamber trans-
oesophageal echocardiography demonstrating the correct align-
ment of the inflow cannula (white arrow) in relationship to the
mitral valve. A perpendicular line (green) drawn from the
inflow cannula should bisect the mitral valve leaflets. LA, left atrium; LV, left ventricle; RV, right ventricle.
occurs, resulting in a high pump flow, low stroke volume, and elevated LA and LV pressures (Table 1).

Post-surgical evaluation

Post-surgical evaluation has two purposes: (i) to evaluate the surgical results of the LVAD implant, and (ii) to assess and troubleshoot postoperative haemodynamics. Specifically, the echocardiography team must evaluate the de-airing, structure and function of left and right heart chambers, degree of TR, presence of interatrial shunts, and inflow and outflow cannula placement.

The TEE operator must detect air bubbles in the immediate post-LVAD implant period before the device is activated. The air bubbles are observed as white refractors (Supplementary data online, Video S6). Inspection should include the ascending and descending aorta using the mid-oesophageal aortic valve long-axis, mid-oesophageal ascending aorta long-axis, and descending aorta short- and long-axis views. The cannulas, as well as anastomotic sites, and the LV apex should be inspected (Figures 9 and 10; Supplementary data online, Video S7). This is extremely important because air is lighter than blood and will migrate towards the anterior chest of the supine patient with preferential embolization to the right coronary artery.36 This can result in RV ischaemia/infarction, which can have a deleterious impact on LVAD functions because of the decreased preload to the LV.

**Function of left heart chambers**

LVAD activation should result in unloading of the LV and the LA with a reduction in each chamber’s size.37 Slightly leftward interventricular and interatrial septal positions indicate adequate LV and LA decompression (Figure 11). Lack of decompression post-LVAD implant with a rightward shift of the septum should raise the possibilities of suboptimal LVAD support, abnormal device function, or cannula obstruction. Alternatively, an extreme leftward shift rouses the suspicion of excessive unloading due to high pump speed, significant TR, or RV dysfunction. Evidence of spontaneous echocardiographic contrast in the LV or LA is a sign of an LVAD malfunction (Supplementary data online, Video S8).

**Right ventricular function and degree of tricuspid regurgitation**

The RV function and the degree of TR must be carefully evaluated. The post-bypass examination should follow the same protocol as the pre-LVAD examination. The examination must identify whether RV assist device support will be necessary.

**Interatrial shunts**

The haemodynamic changes associated with LVAD implants may surface a detectable PFO in 20% of patients with no evidence of a PFO on pre-implant echocardiographic examination.38 The
decrease in the LA pressure associated with unloading the LV and the maintained increased RA pressure can create a gradient that produces a shunt. The search for a PFO should occur while recovering from cardiopulmonary bypass because early detection leads to re-institution of cardiopulmonary bypass and PFO closure. The post-implant TEE must include agitated saline administration. Although rare in our experience, it is important to identify any shunting across the IVS. Recently, we identified an apical ventricular septal defect in a follow-up LVAD evaluation (Figure 12; Supplementary data online, Video S9).

Inflow cannula

Inflow cannula orientation within the LV apex should be aligned with the mitral valve opening (Figure 9). Doppler assessment should be performed in the mid-oesophageal four-chamber view to evaluate deviation towards the IVS, and a two-chamber view to evaluate antero posterior direction (Figure 13). A properly aligned inflow cannula should have laminar flow from the ventricle to the device (Figure 14). Turbulence and elevated Doppler velocity suggest obstruction of the inflow cannula (thrombus/intermittent obstruction by LV wall; Figure 15). Pulsed-wave Doppler should reveal low velocity, laminar flow without regurgitation. Elevated velocities via continuous-wave Doppler should raise a suspicion of cannula obstruction, and regurgitation flow suggests an LVAD pump malfunction. The normal filling velocity is between 1 and 2 m/s depending on the preload and the intrinsic LV function. Acoustic shadowing on TTE may limit Doppler interrogation of the inflow cannula and require TEE to obtain valid, reliable velocities.

Outflow cannula

The outflow cannula is best visualized in the high, long-axis view of the ascending aorta at the level of the right pulmonary artery. The ascending aorta should be interrogated for the presence of plaque, calcification, and dilation. The outflow cannula will be localized most commonly at the right anterolateral aspect of the ascending aorta concordant with an end-to-side anastomosis. Computed tomography imaging is frequently used to assess for kinking of the outflow cannula (Figure 16).

Figure 11 Left ventricular assist device (LVAD) activation should result in the unloading of the left ventricle (LV) and the left atrium (LA) with a reduction in the chamber size. Panels A and B demonstrate a dilated LV and LA. LVAD activation results in slightly leftward interventricular and interatrial septal positions and indicate adequate LV and LA decompression (C and D).
Colour-flow and pulsed- and continuous-wave Doppler are used to evaluate flow patterns of the outflow cannula. The pulsed-wave sample volume should be 1 cm proximal to the aortic anastomosis. Peak velocity usually ranges from 1 to 2 m/s with unidirectional and slightly pulsatile flow (Figure 17).\textsuperscript{37,40} Flow patterns of the outflow cannula are affected by the insertion angle of the cannula into the native aorta.\textsuperscript{41} Acoustic shadowing may limit Doppler interrogation of the outflow cannula, resulting in a need for TEE evaluation.

**Post-operative troubleshooting**

Post-operative haemodynamic instability should prompt a differential thought process:\textsuperscript{28}

- hypovolaemia;
- acute RV dysfunction;
- cardiac tamponade;
- pulmonary embolism; and
- LVAD malfunction, most commonly secondary to an impella thrombosis.

Echocardiography allows for an immediate assessment and detection of the underlying aetiology of haemodynamic instability. Hypovolaemia should be considered when the RV and LV cavities are small. Acute RV dysfunction will manifest as a dilated, hypococontractile RV with significant functional TR, small LV, and intermittent inflow cannula obstruction by the collapsed LV (Figure 18). Cardiac tamponade is an elusive diagnosis post-LVAD. The typical approach for assessing interventricular independence is not possible. The operator must diligently search for subtle blood collections compressing a particular chamber as RA and LA tamponade can occur with small collections of blood. The RV tamponade may be the consequence of a loculated substernal thrombus (Figure 19).\textsuperscript{28} LVAD dysfunction/thrombosis should be suspected when there is a combination of a rightward deviation of the IVS (reduced unloading of the LV), functional mitral regurgitation with annular dilation, aortic valve opening each cardiac cycle, spontaneous contrast in the LA and/or LV, and regurgitant flow through both cannulas. An impaired LVAD output allows the diastolic aortic pressure to exceed the LV diastolic pressure, resulting in a reverse flow from

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**Figure 12** Identification of a ventricular septal defect. Parasternal long-axis view of the inflow cannula (A) and the colour-flow jet from the right to left ventricle through the ventricular septum defect (B).

**Figure 13** Alignment of the inflow cannula. Misalignment of the inflow cannula (yellow arrow) towards the interventricular septum (red arrow). A perpendicular line (blue) drawn from the cannula should bisect the mitral valve (MV). The angle between the blue and green lines reflects the degree of misalignment. LA, left atrium; LV, left ventricle.
the ascending aorta through the outflow and inflow cannulas. The ventricular septal motion is complex in LVAD patients and depends on the electrical conduction system, LV and RV loading conditions, and the ‘unloading’ capacity of the LVAD. The typical features of the ventricular septum when there is interventricular interdependence (tamponade/constriction) are not present post-LVAD implantation. Neutral or slight leftward shift of the interventricular and interatrial septum is indicative of adequate LV and LA compression. A rightward shift of the septum should raise the suspicion of inadequate LV decompression and considerations include a device malfunction or inlet obstruction. Alternatively, a leftward shift may indicate excessive decompression due to high pump revolutions per minute, significant TR, or RV systolic dysfunction. Understanding the ventricular septal motion is crucial to LVAD assessment (Table 2).

Function of left heart chambers

The LV cavity at end-systole and end-diastole should remain stable with a decreased dimension secondary to LV unloading.37

Follow-up transthoracic echocardiography

The two main purposes for follow-up TTE are: (i) comprehensive routine evaluation of optimal LVAD function, and (ii) assessment of potential aetiologies of recurrent HF. The critical variables to carefully evaluate include the structure and function of left heart chambers and IVS position, RV function and TR, evaluation of inflow and outflow cannula position and flow, degree of AR, status of aortic valve opening, and LVAD setting in relationship to haemodynamic findings.

Figure 14 The inflow cannula Doppler profile. Doppler profile demonstrating a normal laminar flow in the inflow cannula. The normal velocity range is 1 to 2 m/s. There is flow towards the cannula during systole as the cannula comes out of the left ventricular apex. The flow is pulsatile as the heart is still contracting. No minimal velocity. The maximum velocity should be <2 m/s, otherwise suspect a problem.

Figure 15 The inflow cannula Doppler profile demonstrating an obstruction to the flow. Doppler profile demonstrating a turbulent flow in the inflow cannula (A). The turbulent flow raises the concern of an obstruction. The clot (green arrow) on the inflow cannula (white arrow) was identified as causing the velocity to be 4 m/s (B). LV, left ventricle.
Increased dimensions should alert the clinician to a possible malfunction. Alternatively, a leftward shift of the IVS, marked decrease in LV dimension, and enlarged RV should alert the clinician to excessive decompression due to a high pump speed or suggest a deterioration in RV functions and increased TR. The LV ejection fraction is not a valid measure of LV function because the LVAD...
promotes non-physiological LV unloading. To assess the LV function, there must be temporary LVAD interruption. Under these circumstances, the LV ejection fraction, LV end-diastolic diameter, and ejection period divided by the ejection time can be measured in an attempt to assess intrinsic LV function. Assessment must be individualized to the patient’s haemodynamic status.

**Right ventricular function and degree of tricuspid regurgitation**

RV dysfunction can present months or years post-LVAD implant. Routine evaluation should include apical four-chamber, parasternal short-axis at the level of aortic root and apex, parasternal RV inflow, and subcostal four-chamber views. Semi-quantitative assessment should be based on the visual appreciation of longitudinal and radial RV motions. Quantitative approaches using global RV FAC, TAPSE, $S'$, and the Tei index are advised. Mechanical parameters will be part of future assessment. The estimation of TR is visually estimated by colour-flow Doppler using the TR jet area and RA areas on the same image, with the TR area/RA area (ratio) being quantitative. Also, the peak systolic TR velocity in end expiration is integrated into the estimation of the RV function. The RA pressure is estimated by the inferior vena cava diameter and its response to respiration (Figure 20). RV systolic pressure = $4 \times (\text{TR velocity})^2 + \text{RA pressure}$

**Aortic regurgitation**

During normal LVAD function, the aortic valve is closed. The retrograde aorta-to-LV gradient is high. This gradient makes the aortic valve susceptible to deterioration over time. The AR can create ‘futile cycles’ and ineffective LVAD function, as discussed previously. The estimation of the AR severity is essential. The most commonly used methods are by colour-flow Doppler and the vena contracta, measuring the width of the regurgitate jet at its origin relative to the dimension of the LV outflow tract in the parasternal long-axis view. To be quantitative, it is recommended to use the proximal isovelocity surface area method when feasible.

**Inflow and outflow cannula location and flow**

The inflow cannula should be aligned with the mitral valve opening and should not have any contact with the LV walls. Colour-flow Doppler should demonstrate laminar, unidirectional flow from the LV to the inflow cannula. Misalignment can lead to an obstruction of the inlet flow at rest and with activities. The misalignment can lead to clinical symptoms. Post-LVAD placement, a patient experienced syncope every time he coughed. Imaging with TEE revealed an obstruction to the flow at the level of the inlet cannula; the cannula was misaligned and coughing caused the obstruction to the inlet flow, causing ‘sucking down’ on the LVAD from 9400 to 8000 rpm concomitant with the patient experiencing syncope lasting 8 to 10 s (Supplementary data online, Video S10). Turbulent flow suggests an obstruction at the cannula and the
regurgitant flow suggests a pump malfunction. Pulsed-wave Doppler assessment should reveal a laminar, low velocity flow no more than 2 m/s with no regurgitation. TTE interrogation can be technically challenging. Optimal views are a high left parasternal long-axis view, demonstrating an end-to-side anastomosis of the outflow cannula to the mid-ascending aorta, and right parasternal view with the patient lying on the right side, showing the long-axis view of the outflow cannula traversing from the pump towards the ascending aorta. Colour-flow and pulsed- and continuous-wave Doppler are used to evaluate flow patterns; the peak velocities in the outflow graft range from 1 to 2 m/s.27 The angle of insertion of the LVAD outflow cannula into the native aortic can influence flow patterns and velocities (Table 3).41

Extracorporeal membrane oxygenation and left ventricular assist devices

Extracorporeal membrane oxygenation (ECMO) is temporary support of the heart and lung functions by partial cardiopulmonary bypass in critically ill patients. It has a potential role as a bridge to cardiac transplantation, to recover from early graft failure post-cardiac transplantation, and as a bridge to a bridge (ECMO to LVAD) in cardiac transplantation. ECMO may provide short-term haemodynamic and oxygenation support to patients with severe haemodynamic instability, permitting recovery from multi-organ injury. It allows time to complete a transplant evaluation before long-term circulatory support with an implantable LVAD.46 The role of ECMO must be individualized on a case-by-case basis in this subset of patients.

Assessment of recurrent heart failure associated with left ventricular assist device dysfunction

LVAD malfunction can be broadly characterized into three main groups: (i) low pump flow with increased power, (ii) low pump flow with normal power, and (iii) high pump flow with low cardiac output.
Low pump flow with increased power
The differential for low pump flow with increased power includes pump failure and an increased afterload.

Pump failure can be attributed to thrombosis and mechanical malfunction. Echocardiographic findings include a rightward deviation of the IVS, functional mitral regurgitation, aortic valve opening each cycle, spontaneous echocardiographic contrast in the LV and/or LA, and regurgitant flow through both cannuulas. Controller device interrogation will identify the LVAD settings. The differential is crucial as an LVAD thrombosis or malfunction may require urgent surgery for pump replacement.

When there is diminished or loss of Doppler signal in the outflow cannula, the differential thought process should include an outflow cannula obstruction and increased afterload.

Low pump flow with normal power
The combination of a low pump flow with normal power is the result of a reduced LVAD preload, which is encountered with RV failure, significant TR, or hypovolemia. Additionally, one should consider an inflow cannula obstruction.

High pump flow with low cardiac output
Calculated total cardiac output less than an LVAD output should raise the suspicion of ‘futile cycles’. This could represent underlying significant AR.

Summary
Echocardiography is essential to evaluate the need for an LVAD implantation in patients with advanced HF and to assess the LVAD performance post-implant. Standard echocardiographic imaging allows for optimal LVAD programming immediately post-implantation and during routine follow-up, and rapid and accurate identification of mechanical or systemic malfunctions. All echocardiography laboratories evaluating patients with an LVAD must understand the ABCs of LVAD echocardiographic assessment.

Communication between the clinician providing patient care and the echocardiology team is crucial in directing the focus of the echocardiographic evaluation.

Supplementary data
Supplementary data are available at European Heart Journal - Cardiovascular Imaging online.

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