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Role of Echocardiography in the Evaluation of Left Ventricular Assist Devices: the Importance of Emerging Technologies

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Abstract The role of left ventricular assist devices (LVAD) in patients with end-stage heart failure is well known, both as a temporary treatment before transplantation and as destination therapy, in a scenario of a relative shortage of donors to satisfy the increasing requests for transplantation. The increased population of LVAD patients needs careful imaging assessment before, during, and after LVAD implantation; echocardiography is the best tool for their evaluation and is considered the diagnostic technique of choice for the assessment before, during, and after device implantation. Although the conventional echocardiographic assessment is quite effective in evaluating the main critical issues, the role of new technologies like three-dimensional echocardiography and myocardial deformation measurements is still not properly clarified. In this review, we aim to provide an overview of the main elements that should be considered in the assessment of these patients, underlining the role that could be played by new techniques to improve the diagnostic and prognostic effectiveness of echocardiography in this setting.

Keywords Left ventricular assist device · Echocardiography · Strain · 3D echocardiography · Heart failure

This article is part of the Topical Collection on *Echocardiography*

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Introduction

The role of left ventricular assist devices (LVAD) in patients with end-stage heart failure (HF) is established. Significant changes have occurred in pump design, patient selection, and diagnostic imaging strategies since the REMATCH trial era (late 1990s; Fig. 1) [1]. LVAD therapy is now considered a mainstay treatment option for end-stage heart disease and can be used for several indications, including bridge to transplant, bridge to candidacy, destination therapy, and bridge to recovery. Echocardiography currently plays a pivotal role in the assessment, management, and optimization of LVAD therapy, with emerging newer techniques poised to improve accuracy and quantification.

Currently, the global prevalence of HF is estimated at approximately 25 million people, and it is expected to increase [2]. From 2006 to 2014, more than 15,000 patients in the USA received a ventricular assist device implant, with 1- and 2-year survival of 80 and 70 %, respectively [3]. This select population of patients is resource-intense and requires structured care to achieve an optimal outcome. Echocardiography has been advocated by the International Society for Heart and Lung Transplantation's current guidelines for mechanical circulatory support (2013) [4]. The first fundamental goals of the echocardiographic evaluation of patients with end-stage HF are the identification of the subgroup that could benefit from device implantation, followed by stratification of the risk profile of individual patients. Moreover, echocardiography plays a key role in the perioperative evaluation of the clinical conditions and in the early detection of complications that could severely threaten the life of a patient. Finally, serial echocardiographic assessments are required during follow-up to detect device malfunction or to adjust LVAD working parameters. However, conventional parameters for the evaluation of right ventricular (RV) and left ventricular (LV) size, volumes, and

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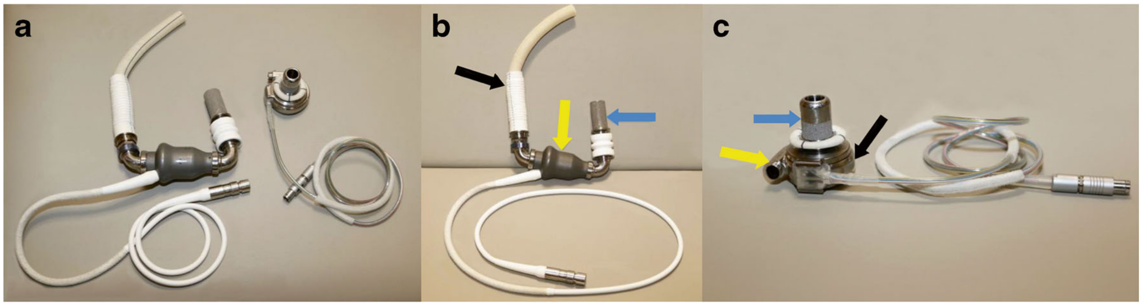


Fig. 1 **a** The Thoratec Corp. HeartMate II (*left*) and HeartWare HVAD System (*right*) ventricular assist devices are shown. The inlet cannula (*blue arrows*), impeller housing (*yellow arrows*), and outflow graft (*black arrow*) are the main components of a left ventricular assist device (**b** and **c**)

function cannot always be used successfully in the LVAD population, so new measurements and algorithms are needed to improve the effectiveness of the echocardiographic assessment. Nevertheless, newer technologies, including three-dimensional (3D) echocardiography and strain and strain rate measurements, are still widely underutilized in this setting.

LVAD Components and Function

The main elements of an LVAD include an inflow cannula, an outflow cannula, a propulsion pump, and an external controller. Inflow and outflow cannulas link the pump, the true core of the LVAD, to the left ventricle and ascending aorta, respectively, whereas the controller allows the clinician to change the machine settings. The main goal of LVAD is to support LV systolic function by mechanically unloading the LV through the inflow cannula, usually placed in the LV apex, and to provide blood to the systemic circulation through the outflow cannula. According to the pumping mechanisms, LVAD can be classified as "pulsatile" and "continuous flow." Pulsatile LVADs, the first generation of VADs available, were characterized by a pumping mechanism that simulated the pulsatile action of the heart; these models of LVADs have unidirectional valves in the inflow and outflow cannulas that regulate the blood direction but increase the risk of thrombus formation. On the other hand, continuous LVADs provide a continuous blood flow that could be axial or centrifugal, according to the mechanical structure of the pump. Continuous LVADs do not require unidirectional valves, are smaller, and guarantee higher flows at lower pressures compared with pulsatile ones.

Echocardiographic Assessment of Left Ventricular Structure and Function

Preoperative Assessment

LV structure and function play a pivotal role in the assessment of HF, and preoperative echocardiographic assessment is fundamental to the evaluation of a patient's eligibility for LVAD therapy. Several clinical and echocardiographic variables previously have been identified to stratify the risk profile for morbidity and mortality of patients with end-stage HF [5], and a reduced LV ejection fraction (EF), an altered LV geometry, and a restrictive LV filling pattern seem to be the most reliable to help identify patients at high risk [6–8]. However, two-dimensional (2D) echocardiographic assessment of LV volumes and ejection fraction can be affected by both geometric assumptions and the use of foreshortened apical views; these limitations could be overcome by 3D echocardiography. Most vendors now have the capability to provide comprehensive quantitative and reproducible assessment of LV volumes and function without geometric assumptions, with adequate spatial and temporal resolution [9] (Fig. 2). A recent meta-analysis definitively showed the lesser variability and better accuracy of 3D echocardiographic evaluation of LV volumes and EF compared with 2D echocardiography [10]. Moreover, the application of myocardial deformation measurements, such as speckle-tracking echocardiography (STE) strain and strain rate, could provide a further risk stratification in patients with HF (Fig. 3). STE provides frame-by-frame tracking of natural acoustic markers, is angle-independent, and is not influenced by translational movement due to respiration and tethering from the adjacent myocardium. 2D [11–13] and 3D [14, 15] STE strains have been shown to predict hospitalization for HF and an increased mortality risk and should be considered robust prognostic elements.

Once the eligibility for LVAD therapy is established, preoperative assessment should focus on the evaluation of specific elements that could modify the surgical procedure or complicate the clinical course, including the presence of ventricular clots and intracardiac shunts. A detailed assessment for ventricular clots, particularly at the LV apex, is highly recommended in patients with HF because depressed LV systolic function is an important determinant of thrombus formation and the presence of a thrombus increases the risk of inflow cannula obstruction. 2D transthoracic echocardiography (TTE) is usually sensitive enough for the detection of LV apical thrombosis. However, when LV endocardial definition is poor, the use of intravenous contrast agents [16, 17] or transesophageal echocardiography (TEE) is recommended to

Fig. 2 Pre-implantation left ventricular assist device evaluation using 3D transthoracic echocardiography to assess left ventricular end-diastolic volume (*EDV*), end-systolic volume (*ESV*), and ejection fraction (*EF*). EDV = 301 ml, ESV = 229 ml, left ventricular EF = 24 %

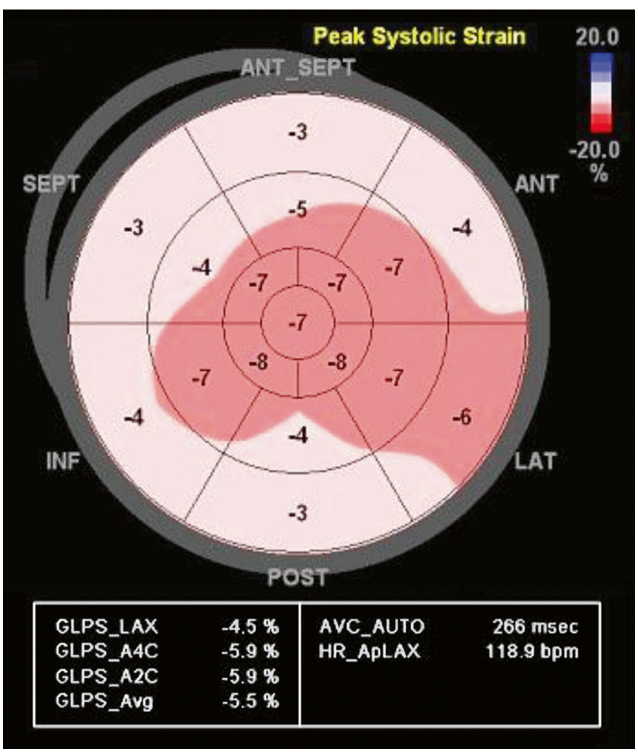


Fig. 3 Transthoracic strain echocardiography displaying a diffuse abnormal strain pattern in a 65-year-old man with ischemic cardiomyopathy. Global longitudinal peak systolic strain measure −5.5 %

improve the accuracy of the evaluation. In this regard, TEE can be used to define the location and extent of intracardiac shunting, the presence of which will alter the surgical approach. Indeed, the use of agitated saline along with the Valsalva maneuver facilitates recognition of interatrial septal shunting. Moreover, the evaluation for intracardiac shunts should be repeated after LVAD placement because the decompression of the left chambers can unmask a patent foramen ovale [18]. It is imperative that intracardiac shunting be defined and corrected at the time of LVAD surgery since LV unloading drastically reduces LV and left atrial pressure throughout both systole and diastole, a scenario that will result in right-to-left shunting, systemic oxygen desaturation, and possible paradoxical embolization [4, 19]. The detection of ventricular thrombi and intracardiac shunts might be enhanced with 3D echocardiographic assessment, as full-volume data can define the anatomy of abnormalities without the assumptions made using 2D echocardiography [20–25]. 3D evaluation is superior to 2D echocardiography for differentiation of thrombus from myocardium and assessment of thrombus mobility, structure, and dimensions. Furthermore, it is considered the technique of choice to study patent foramen ovale anatomy and to guide its closure.

Thus, we advocate the use of 3D echocardiography for a more reliable quantification of LV volumes and function and the detection of ventricular thrombi and intracardiac shunts; in addition, we suggest including 2D or 3D STE LV strain and strain rate in the risk stratification algorithms to improve the prognostic power of conventional parameters (Table 1).

Perioperative Assessment

Intra-operative TEE evaluation is advocated during implantation of LVADs and should focus on four main concerns: (1) de-airing of the heart chambers, (2) assessment of a proper LV unloading, (3) evaluation of pericardial effusion, and (4) detection of intracardiac shunts unmasked by the decompression of the left chambers (previously discussed).

De-airing of the heart chambers is fundamental to avoiding right coronary artery ischemia and the consequent high risk of RV failure [19, 26] and stroke from air embolism. 2D TEE performed after LVAD implantation and before LVAD activation is required to exclude air in the left ventricle and ascending aorta before the cross-clamp of cardiopulmonary bypass is released. Common sites for air trapping should be inspected and resolved, including anastomotic sites, inflow and outflow cannulas, and the anterior interventricular septum [27]. Again, the use of 3D TEE may improve the detection of bubbles by allowing better anatomic visualization of adjacent cardiac structures in the same volume data set image.

The evaluation of proper LV decompression after LVAD activation requires the assessment of central hemodynamics. The most direct measure is obtained by direct catheterization; however, several echocardiographic parameters for the indirect quantification of LV hemodynamics have been shown to have excellent correlation with invasive findings [28•, 29–31]. Estep et al. [28•] compared various measurements obtained by 2D TTE with cardiac catheterization findings and created a comprehensive, easy-to-use diagnostic algorithm to distinguish normal from elevated LV filling pressures with high accuracy. Doppler parameters considered by the authors were mitral ratio of the early to late ventricular filling velocities (*E*/*A*), right atrial pressure (RAP), systolic pulmonary artery pressure (sPAP), left atrial volume index (LAVi), and ratio of mitral inflow early diastolic filling peak velocity to early diastolic mitral annular velocity (*E*/*e*′). Mitral *E*/*A* ratio was considered the main point to predict elevated left-sided filling pressures. Patients with *E*/*A* ≤1 and with any one other parameter between RAP ≤10 mmHg or sPAP ≤40 mmHg and/or LAVi ≤33 ml/m^2 and/or *E*/*e*′ ≤14 were shown to have pulmonary capillary wedge pressure (PCWP) ≤15 mmHg; patients with *E*/*A* >2 and one between RAP >10 mmHg or sPAP >40 mmHg and/or LAVi >33 ml/m^2 and/or *E*/*e*′ >14 were shown to have PCWP >15 mmHg; finally, to predict elevated PCWP for patients with *E*/*A* ratios >1 to ≤2, two concordant findings from the three parameters examined were requested. Further, qualitative estimation of good LV unloading could be obtained by comparing the size of the left heart chambers and the position of the interventricular septum (IVS) after LVAD

Table 1 Echocardiographic assessment of main issues concerning the left ventricle before, during, and after left ventricular assist device (LVAD) implantation

Structure	LVAD implantation phases	Main issues	Techniques and parameters
LV	Preoperative	HF patient risk stratification for LVAD eligibility	2D TTE and 3D TTE evaluation of LV volumes, LVEF, mitral inflow velocities, and LV strain and strain rate
		Intraventricular clots	2D TTE and TEE and 3D TTE and TEE assessment of LV apex (with contrast, if necessary)
		Intracardiac shunts	2D TEE Doppler and 3D TTE and TEE Doppler assessment of interatrial and interventricular septa
	Perioperative	De-airing of heart chambers	2D TEE and 3D TTE and TEE assessment of LV, ascending and descending aorta, anastomotic sites, and both inflow and outflow cannulas for the detection of air bubbles
		LV unloading	2D TEE and 3D TTE and TEE assessment of mitral inflow velocities, right atrial pressure, sPAP, left atrial volume, LV volumes and size, and IVS position
		Pericardial effusion	2D TTE and TEE and 3D TTE and TEE assessment of pericardium
		Intracardiac shunts	2D TEE and 3D TTE and TEE assessment of intracardiac shunts unmasked by decompression of left heart chambers
	Follow-up	LV unloading	2D TTE and 3D TTE assessment of mitral inflow velocities, right atrial pressure, sPAP, left atrial volume, LV volumes and size, and IVS position
		Native LV function	2D TTE and 3D TTE aortic valve opening, LV strain, and strain rate

2D two-dimensional, *3D* three-dimensional, *HF* heart failure, *IVS* interventricular septum, *LV* left ventricle, *LVAD* left ventricular assist device, *LVEF* left ventricular ejection fraction, *TEE* transesophageal echocardiography, *TTE*, transthoracic echocardiography, *sPAP* systolic pulmonary arterial pressure activation with images obtained prior to implantation. Reductions of 20 to 30 % in LV end-diastolic diameter and 40 to 50 % in LV volumes are expected when an LVAD is properly unloading the LV [32, 33]. The IVS is expected to be neutral or to have a slight leftward shift during peak systole because of the reduction of relative LV/RV pressure through the cardiac cycle [34]. The presence of a dilated LV and rightward shift of the septum should raise the consideration of inadequate LVAD speed, device malfunction, or cannula obstruction (Fig. 4), whereas a small LV and leftward septal shift may indicate an excessive unloading due to high pump speed and could result in RV dysfunction, worsening of tricuspid regurgitation, and onset of RV failure. 3D TEE could improve the evaluation of both RV and LV volumes and the assessment of IVS position during the cardiac cycle, allowing a better evaluation of hemodynamics.

The clinical recognition of pericardial effusion is enhanced with either TTE or TEE imaging. Cardiac tamponade can occur with even small collections of pericardial blood or fibrinous material in the postoperative state. Since right and left heart pressures may not have the usual interdependence during LVAD support, the Doppler diagnosis of increased pericardial pressures can be challenging [35]. 3D echocardiography provides incremental value to 2D for the evaluation of pericardial effusion, allowing a more comprehensive assessment of its size and extent and providing better characterization of its nature [36] and, therefore, should be considered the technique of choice in this setting (Table 1).

Follow-up

After LVAD implantation, patients typically undergo serial clinical evaluation with echocardiography-guided optimization of LVAD pump speeds. In addition, TEE or TTE is among the mainstay diagnostic tools for the assessment of LVAD complications such as thrombosis, hemolysis, and valvular or RV dysfunction. The ease and reproducibility of 3D TTE to evaluate cardiac structure and function should allow this technique to replace traditional 2D techniques for the accurate quantification of volumes, masses, and shunts. LVAD implantation is expected to improve patient hemodynamics [37, 38] and in a minority of patients can induce LV reverse remodeling [39]. When the typical successful pattern of smaller LV cavity, neutrally positioned IVS, grade 1 or less mitral regurgitation, and rare or only partial opening of the aortic valve is not demonstrated, potential pump adjustments or further diagnostic studies should be performed (example: echocardiography-guided ramp study). Indeed, persistent rightward deviation of the septum in the presence of elevated left atrial pressure is associated with poor mid-term outcomes [30, 40]. We advocate serial echocardiographic evaluations of these patients to improve early detection of complications. The proper LV unloading can be obtained through echocardiographic measurements during adjustments of rotor speed; the speed should be increased if the LV is dilated or reduced if the LV is underfilled. Several algorithms have been proposed [41] for LVAD optimization but, thus far, standardized protocols are lacking.

Another important role of follow-up assessments is the quantification of native LV function. Since LV function is preload- and afterload-dependent, both dramatically altered by LVAD therapy, true EF cannot be calculated with loading the LV. Therefore, the most used method to assess native function is reducing pump speed to reduce LVAD support [42–44]. In this context, strain could be used as a measure of LV function. Strain has been shown to be more sensitive and accurate in the detection of myocardial contractility compared to other parameters in several clinical settings [45]. Although limited experience is available using STE strain with LVAD therapy [46], we believe that in the coming years, myocardial deformation (strain, strain rate, etc.) measurements will have great importance in the evaluation of native cardiac mechanics (Table 1).

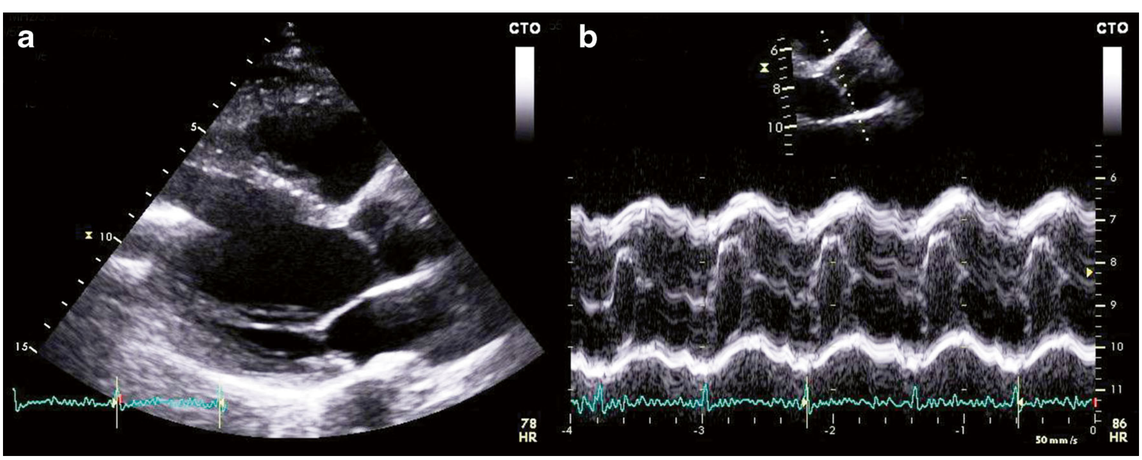


Fig. 4 Parasternal long-axis and aortic valve M-mode of a 63-year-old male left ventricular assist device (LVAD) patient. Panel **a** demonstrates slight rightward septal shift. Panel **b** shows aortic valve opening with every systolic beat. Images demonstrate improper LVAD unloading or decompression of the left ventricle

Echocardiographic Assessment of RV Function: a Pivotal Element for Patient Outcomes

Preoperative Assessment

The assessment of RV function plays a pivotal role in the comprehensive evaluation of patients selected for LVAD therapy. Indeed, RV dysfunction is a powerful prognostic tool in the risk assessment of patients with advanced heart failure, and it is able to predict reduced exercise capacity and shorter survival [47]. Although conventional echocardiographic parameters such as RV fractional area change [48], tricuspid annular plane systolic excursion [49], and tricuspid annular longitudinal velocity (*S′*) have shown a good prognostic effectiveness in the detection of RV dysfunction in this population, the application of STE strain to RV assessment has strongly improved patient risk stratification. It has emerged as the most accurate and sensitive tool for evaluation of RV function [50, 51], with an incremental prognostic value to LV EF [52]. In addition, STE strain has shown a great correlation with invasive hemodynamics, allowing a noninvasive evaluation of hemodynamic parameters such as RV stroke work index [53]. The importance of strain as a diagnostic tool for the quantification of RV function is perhaps superior than in the LV setting, because the complex RV chamber shape and geometry, with the inflow and outflow portions in different planes, preclude the assessment of a reliable RV EF by 2D echocardiography. These limitations can be overcome by 3D echocardiography because it provides a more accurate evaluation of RV volumes with higher feasibility and accuracy than 2D [54]. 3D echocardiography has shown excellent correlations with cardiac magnetic resonance imaging in the quantification of RV volumes and EF [54], and the volumetric semiautomated border detection approach is the recommended method for the assessment of RV EF. Therefore, in patients with HF, 3D TTE should be considered the technique of choice for the assessment of RV volumes and function.

RV dysfunction is a powerful determinant of poor outcomes after LVAD implantation [55, 56]. Indeed, RV failure (RVF) is one of the most life-threatening complications after implantation, and a high RVF risk profile is a key element affecting the surgical management of patients. The pathophysiology of RVF is not completely understood. It is probably based on the presence of concomitant RV myocardial dysfunction, increased RV preload due to augmented cardiac output, disturbance of the interventricular pressure gradients, and uncoupling of interventricular dependence. In general, the evaluation of RV failure risk post-LVAD implantation is dependent on hemodynamic assessment, which could be obtained invasively by catheterization or indirectly by echocardiography, and the quantification of RV function. Pulmonary hypertension [57] and high pulmonary vascular resistance [58] are highly associated with RV failure and reduced survival. Doppler TTE can provide reliable estimation of most hemodynamic parameters, allowing noninvasive and easily repeatable assessment. Conventional parameters—e.g., tricuspid annular plane systolic excursion (TAPSE), tricuspid annular longitudinal velocity by tissue Doppler imaging (TDI *S′*), right-sided index of myocardial performance (RIMP), and fractional area change (FAC)—have good prognostic value [55, 59] in the risk stratification for RVF; however, there is no concordance in the literature about their accuracy and sensitivity [60••, 61]. On the other hand, RV strain and strain rate obtained by 2D STE provide reliable and accurate prognostic information, with absolute strain and strain rate being reduced in patients who are at risk of developing RVF [60••, 62–65]. Patients with low risk show higher strain at baseline and an improvement in its value at follow-up [66, 67]. Grant et al. [60••] were the first authors who evaluated RV strain by STE in this context. They demonstrated that a peak strain cutoff value of −9.6 % predicted RVF with 76 % specificity and 68 % sensitivity, and it provided incremental predictive value when added in models including the Michigan score (which uses the need for preoperative treatment with vasopressors and evidence of an AST ≥80 IU/liter and bilirubin ≥2.0 mg/dL to predict RVF) [64]. Therefore, we advocate that 2D strain and strain rate should be considered the most reliable and accurate parameters for RVF risk stratification and should be routinely used. While the role of 3D echocardiography for the assessment of RVF has not been completely determined, Kiernan et al. [68] reported that RV volumes assessed by 3D echocardiography were predictive of RVF in LVAD recipients independent of hemodynamics (Table 2).

Perioperative Assessment

The main elements that should be evaluated by TEE in the perioperative RV assessment are RV size and function changes associated with LVAD activation. LVAD implantation can have a beneficial or a detrimental effect on the RV. Ideally, LV mechanical decompression results in reduction of pulmonary pressure and RV afterload, which should improve RV function. Conversely, improved left-sided output as seen with an LVAD increases venous return to the RV, which may not be tolerated in a patient with a compromised RV. Moreover, excessive LV unloading leads to leftward IVS shift, which alters RV geometry, impairing contractility and worsening tricuspid regurgitation. This scenario, also known as "suction cascade," has the paradoxical effects of reducing LVAD flow, increasing right atrial pressure leading to venous congestion, and worsening systemic perfusion. 2D and 3D TEE are the most useful techniques for the evaluation of RV structure, function, and hemodynamics among patients supported with LVAD therapy. The evidence of small LV volumes, dilated RV, and leftward IVS shift should suggest a reduction in LVAD pump speeds,

Table 2 Echocardiographic assessment of main issues concerning right ventricle before, during, and after left ventricular assist device implantation

Structure	LVAD implantation phases	Main issues	Techniques and parameters
RV	Preoperative	HF patient risk stratification for LVAD eligibility	2D TTE assessment of RV volumes, function (FAC, TAPSE, and TDI *S*′), and hemodynamics (sPAP, right atrial pressure); 3D TTE quantification of RV volumes and EF; 2D TTE evaluation of RV strain and strain rate
		Post-LVAD implant RV failure risk stratification	2D TTE assessment of RV volumes, function (FAC, TAPSE, and TDI *S*′), and hemodynamics (sPAP, right atrial pressure); 3D TTE quantification of RV volumes and EF; 2D TTE evaluation of RV strain and strain rate
	Perioperative	RV size and function after LVAD activation	2D TEE assessment of RV volumes, IVS position, and hemodynamics (sPAP, right atrial pressure); 3D TTE quantification of RV volumes, IVS position, and EF; 2D TTE evaluation of RV strain and strain rate
	Follow-up	RV size and function after LVAD activation	2D TTE assessment of RV volumes, IVS position, and hemodynamics (sPAP, right atrial pressure); 3D TTE quantification of RV volumes, IVS position, and EF; 2D TTE evaluation of RV strain and strain rate

2D two-dimensional, *3D* three-dimensional, *EF* ejection fraction, *FAC* fractional area change, *HF* heart failure, *IVS* interventricular septum, *LVAD* left ventricular assist device, *RV* right ventricle, *TAPSE* tricuspid annular plane systolic excursion, *TDI S*′ tricuspid annular longitudinal velocity by tissue Doppler imaging, *TEE* transesophageal echocardiography, *TTE* transthoracic echocardiography, *sPAP* systolic pulmonary arterial pressure

with frequent re-assessment and alteration of pump speed as needed (Table 2).

Follow-up

Echocardiographic RV assessment during follow-up should be focused on the quantification of RV systolic function and hemodynamics, which can be obtained using the same parameters and techniques previously mentioned. RV remodeling may occur over an extended period of time, despite the profound and usually early reduction of pulmonary pressures and pulmonary vascular resistance [58]. Finally, the post-LVAD assessment of RV mechanics with 2D STE is feasible [65] and adds incremental information to that obtained from preoperative imaging (Table 2).

Echocardiographic Assessment of Cardiac Valve Function

Preoperative assessment of valve heart disease, either with TTE or TEE, is important for surgical preparation as specific valve lesions may require corrective intervention at the time of LVAD implantation. With the exception of mitral regurgitation, valve lesions may require modification of the surgical procedure. Precise identification and quantification of significant valve dysfunction are critical, as concurrent valve replacements increase the mortality rates among patients undergoing LVAD therapy [69]. In particular, tricuspid regurgitation may require a surgical ring or Devega stitch, while aortic regurgitation often requires valve replacement with a biologic valve (Table 3).

Aortic Valve

Normal continuous-flow LVAD function is usually associated with the intermittent opening of the aortic valve, depending on the balance between native LV systolic function, LVAD pump speed, and preload and afterload pressures (Fig. 5). A permanent valve closure suggests excessive LV unloading (Fig. 6), whereas too-frequent opening indicates (1) an LVAD speed set below optimal unloading, (2) LVAD malfunction, or (3) an improvement of native LV function. Doppler echocardiographic assessment of aortic valve alterations is by TTE. Usually, 2D TTE is sensitive enough to detect aortic regurgitation (AR) or stenosis; however, TEE provides a better assessment of valvular anatomy and function. Further evaluation could be obtained with 3D echocardiography, which has recently allowed greater appreciation of specific leaflet abnormalities [70, 71]. It should be performed during the perioperative assessment, when transvalvular gradients are closer to those to be observed during follow-up after LVAD insertion [72]; indeed, AR could be underestimated in the TTE preoperative study because of the increased LV end-diastolic pressure and low aortic diastolic pressure.

Surgical correction of aortic stenosis with LVAD implantation is usually not indicated as most LVAD flow bypasses the aortic valve, delivering blood from the LV to the ascending

Table 3 Echocardiographic assessment of main issues concerning cardiac valves and left ventricular assist device components

Structure	Main issues	Techniques and parameters
Cardiac valves	Aortic regurgitation Mitral regurgitation Mitral stenosis Tricuspid regurgitation	2D TTE and TEE and 3D TTE and TEE echo-Doppler evaluation of anatomy and severity of valve dysfunction
LVAD components	Inflow cannula Outflow cannula	2D TEE and 3D TTE and TEE evaluation of LV apex and ascending aorta and detection of cannula position; 2D TEE and 3D TTE and TEE Doppler assessment of flow pattern and velocities

2D two-dimensional, *3D* three-dimensional, *LV* left ventricle, *LVAD* left ventricular assist device, *TEE* trans-esophageal echocardiography, *TTE* transthoracic echocardiography

aorta. However, permanent aortic valve closure in a heavily calcified valve may predispose to thrombus formation. Conversely, even among patients with a normal aortic valve, chronic LVAD support can result in leaflet tethering and subsequent AR, which may play a critical role in determining the hemodynamic clinical improvement among patients receiving LVAD therapy. Serial echocardiographic and pathologic studies have demonstrated that despite normal aortic valve function at the time of LVAD insertion, AR develops in a high percentage of patients 1 year after LVAD insertion [73], particularly when the aortic valve is noted to be persistently closed throughout the cardiac cycle. Moreover, pre-implant AR could be worsened by LVAD activation because of pressure overload above the aortic leaflets, which causes impaired leaflet function, aortic root dilatation, and altered leaflet coaptation at the central portion of the aortic valve [74]. A significant regurgitation volume causes an LVAD preload increase and reduces the forward flow. Thus, patients with more-than-mild aortic regurgitation should be considered for aortic valve surgery during device implantation [4]. Real-time 3D echocardiography should be considered the technique of choice during the perioperative assessment of aortic valve function because it guarantees a higher accuracy and sensitivity compared with 2D for AR quantification [75]. Furthermore, Kellman et al. recently found that none of the parameters obtained from intraoperative 2D TEE seemed to predict development of at least moderate postoperative AR in their cohort of patients [76]; therefore, the prognostic role of 3D echocardiography in this setting should be tested.

Mitral Valve

Mitral regurgitation (MR) is a very common finding in patients with end-stage HF and a dilated LV. LVAD implantation usually improves MR severity, decompressing the LV and reducing its size; thus, MR does not routinely require surgical repair or valve replacement [4]. On the other hand, persistence of significant MR after LVAD insertion can suggest inadequate LV decompression and should be carefully considered. The assessment of MR could be obtained with 2D TTE and

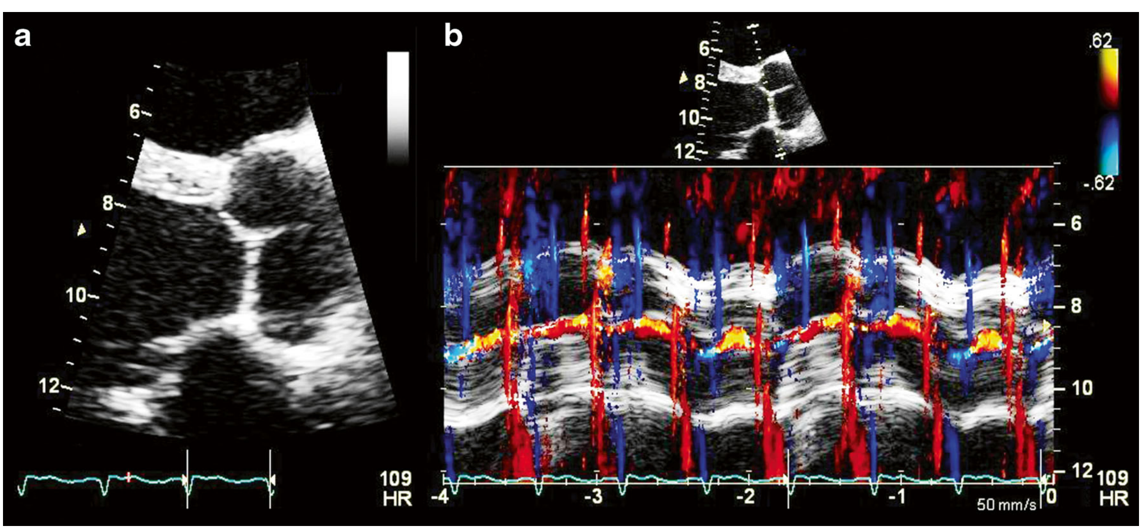
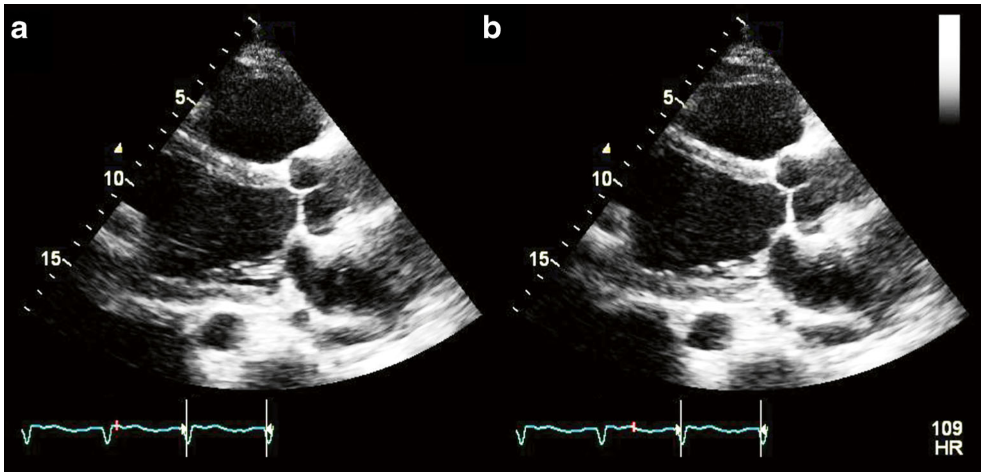


Fig. 5 **a** Parasternal long-axis view focused on the aortic valve (AV) in a patient with normal left ventricular assist device. Note that the AV is remaining closed for multiple beats and is not opening during systole. Panel **b** demonstrates a color M-mode image through the AV with continuous mild aortic regurgitation

Fig. 6 Parasternal long-axis view of a 56-year-old ischemic cardiomyopathy patient with a left ventricular assist device. Note the aortic valve is not opening, unchanged end-diastolic and end-systolic volumes, and a midline left ventricular septum (**a** and **b**)



TEE echo-Doppler. However, real-time 3D echocardiography provides a better accuracy, sensitivity, and specificity compared with 2D TTE and TEE in detecting etiology, mechanisms, and severity of MR [77].

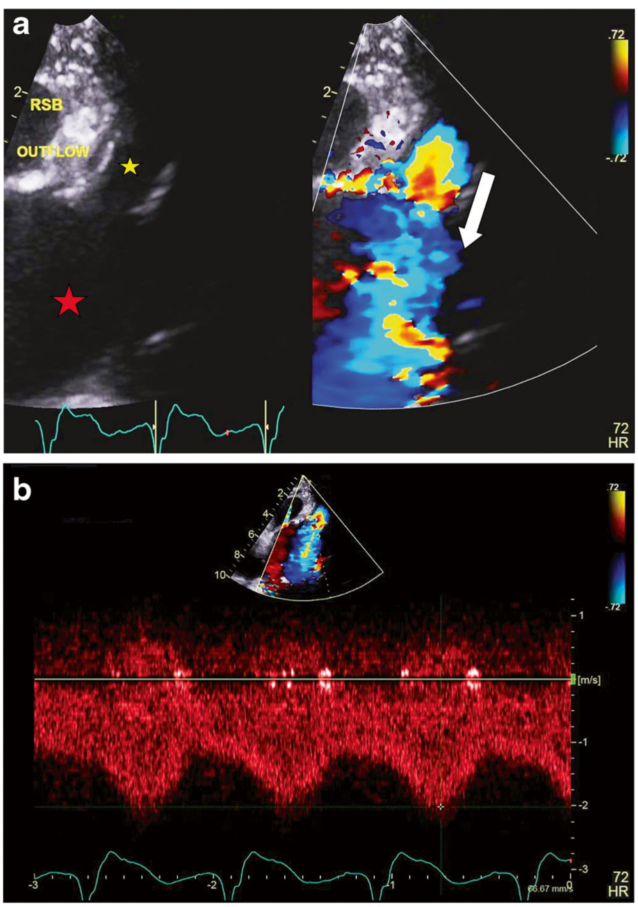


Fig. 7 **a** Color comparison high right parasternal image demonstrating outflow graft (*yellow asterisk*) with anastomosis to ascending aorta (*red asterisk*). Note the color flow blue jet (*white arrow*) is going away from the transducer position. **b** Continuous Doppler outflow graft velocity demonstrating a peak velocity of 2.02 m/s. This flow demonstrates a typical appearance of an unobstructed outflow graft

Mitral valve stenosis is a rare finding in LVAD-eligible patients. When found, it should be carefully evaluated by 2D and 3D [78] echocardiography because it can reduce LV filling, leading to low device output. Valve replacement with a tissue valve should be considered for more-than-mild mitral valve stenosis [4].

Tricuspid Valve

Tricuspid regurgitation is a common finding in patients with progressive HF and is an independent predictor of negative outcomes after LVAD implantation [79]. As previously mentioned, LVAD implantation may improve or worsen tricuspid regurgitation depending on the degree of pressure unloading of the LV and pulmonary circuit and/or concomitant volume loading and geometric disturbances of the RV. Therefore,

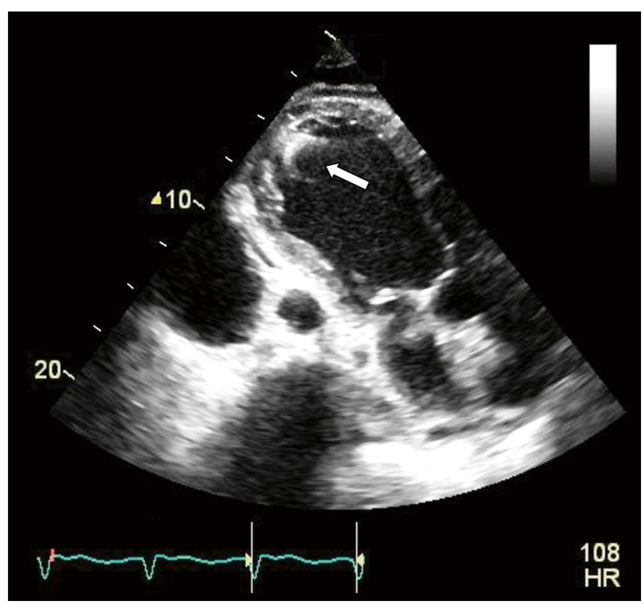


Fig. 8 Apical long-axis view demonstrating the inlet cannula (*arrow*) of the left ventricular assist device

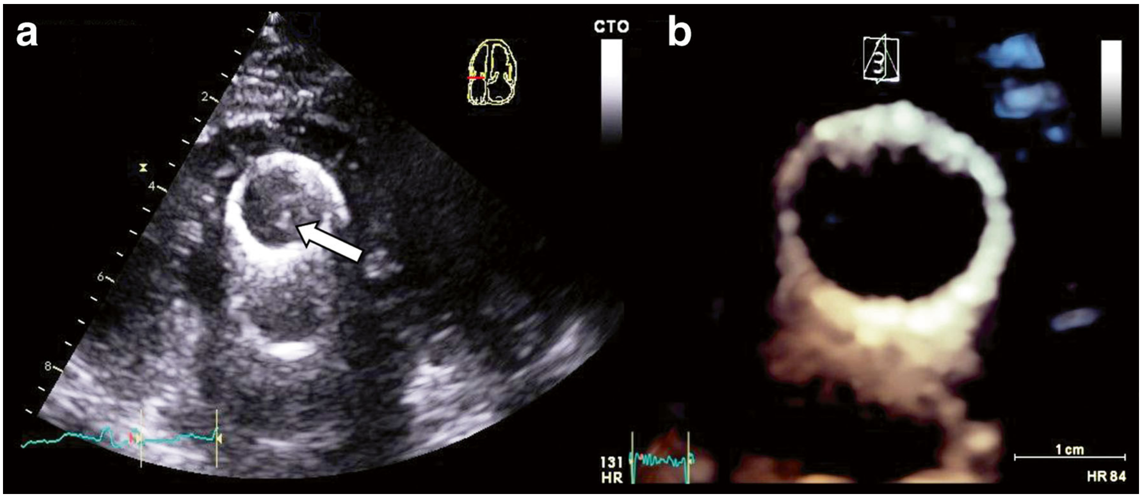


Fig. 9 Panel **a** shows a two-dimensional transthoracic echocardiographic short-axis view of the left ventricular assist device inlet cannula. Note the hyperechoic density (*arrow*) within the cannula. Panel **b** is a 3D transthoracic echocardiogram demonstrating the short-axis view of the left ventricular assist device inlet cannula without a hyperechoic density within the cannula; the 3D picture disproves the hypothesis of cannula thrombosis

moderate or greater tricuspid regurgitation should be considered for surgical repair at the time of implantation [4]. Tricuspid regurgitation can be successfully evaluated by 2D TTE and TEE with conventional Doppler measurements;

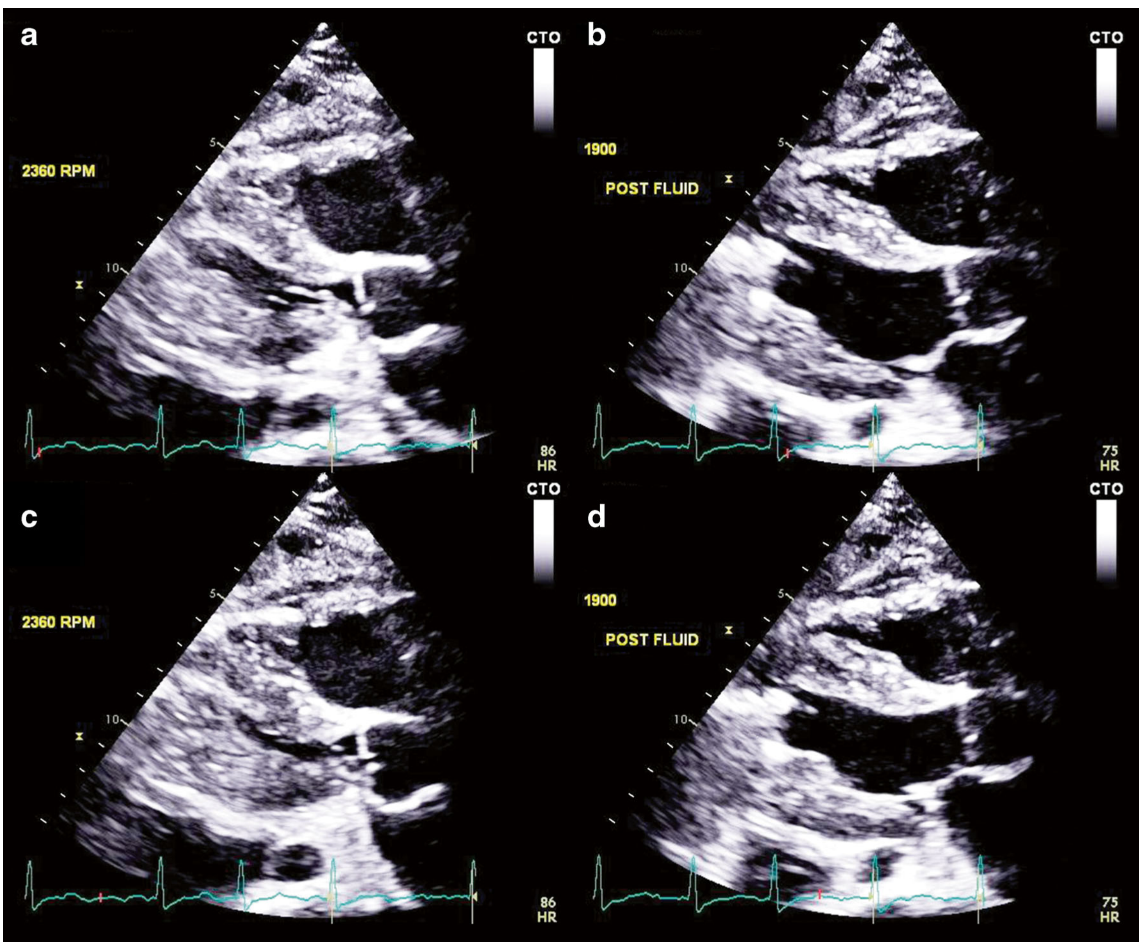


Fig. 10 Panels **a** and **c** demonstrate an underfilled, hypovolemic left ventricle ("suction cascade effect") with a left ventricular assist device (LVAD) speed of 2360 rpm. Panels **b** and **d** demonstrate an increase in left ventricle preload with a bolus of intravenous fluids and a slower LVAD speed of 1900 rpm

Table 4 Role of emerging technologies in the echocardiographic assessment of left ventricular assist device patients

Technique	Diagnostic and prognostic role
3D echocardiography	Accurate and reliable quantification of LV and RV volumes and EF with diagnostic and prognostic relevance for risk stratification of patients with HF before LVAD implant
	Accurate and reliable assessment of RV volumes and EF with high prognostic relevance for risk stratification of post-LVAD implant RV failure
	Sensitive and accurate detection of intraventricular clots and intracardiac shunts before and after LVAD activation
	Detailed evaluation of cannula position, flow pattern, and velocities
	Accurate and reproducible assessment of cardiac valve function with reliable indication for surgical management
	Improved detection of air bubbles in the LV, ascending and descending aorta, anastomotic sites, and inflow and outflow cannulas before LVAD activation
	Real-time sensitive and accurate assessment of LV and RV volumes and IVS position and LV and RV hemodynamics for the evaluation of proper LV unloading after LVAD activation
	Highly sensitive detection of pericardial effusion and characterization of its nature
	Easy and repeatable assessment of LV and RV volumes and function during follow-up
2D strain and strain rate	More sensitive and accurate evaluation of LV and RV function compared with conventional parameters, with diagnostic and prognostic relevance for risk stratification of HF patients
	More sensitive and accurate evaluation of RV function compared with conventional parameters, with increased prognostic relevance for risk stratification of post-LVAD implant RV failure
	Feasible and repeatable quantification of LV function during follow-up

2D two-dimensional, *3D* three-dimensional, *EF* ejection fraction, *HF* heart failure, *IVS* interventricular septum, *LV* left ventricle, *LVAD* left ventricular assist device, *RV* right ventricle

however, real-time 3D echocardiography has been shown to better identify septal leaflet tethering, septal-lateral annular dilatation, and the severity of pulmonary hypertension [80].

Echocardiographic Evaluation of LVAD Components

Perioperative TEE assessment plays a key role in the correct placement of inflow and outflow cannulas during LVAD implantation. The inflow cannula is usually positioned in the LV apex and oriented within the LV toward the P2 segment of the mitral valve. A properly aligned inflow cannula should have laminar and unidirectional flow from the ventricle to the device, which can be evaluated by TEE Doppler. The normal peak velocity in axial-flow LVAD ranges from 1 to 2 m/s and power Doppler shows a consistently phasic, slightly pulsatile flow pattern. The presence of elevated velocities should suggest cannula obstruction, which could be due to cannula thrombus, cannula angulation into the myocardium, or other cannula malposition; in addition, regurgitation flow suggests an LVAD pump malfunction.

The outflow cannula is usually anastomosed along the ascending aorta and shows a flow pattern similar to the inflow cannula (Fig. 7). The ascending aorta should be interrogated for significant atheromatous disease, aneurysms, and dissection, which should be repaired before the cannula placement.

2D TEE commonly is used for the assessment of inflow and outflow cannula position and flow during the perioperative assessment, whereas 2D TTE commonly is used during the follow-up period (Fig. 8). However, reliable evaluation of the inflow cannula and surrounding structures is not always possible and some new-generation LVADs can generate a Doppler artifact that precludes interrogation of the inflow cannula velocities [81]. Moreover, the assessment of the ascending aorta can be challenging and the study of outflow patterns might not be possible with 2D TEE. Real-time 3D TTE and TEE can provide a detailed and accurate assessment of inflow cannula structure and flow [82] by cropping away the basal regions of the LV and enabling the echocardiographer to obtain an en face view of the inflow cannula as it enters the LV. 3D echocardiography has shown a greater sensitivity compared with 2D in detecting cannula thrombi [83, 84] (Fig. 9).

Detection of LVAD Dysfunction and Complications: a Brief Road Map

The main LVAD alterations and post-implant complications include pump failure, inflow and outflow cannula obstruction, RV failure, and inadequate LV filling and emptying. All these conditions, previously discussed in detail, can be broadly classified in well-defined categories.

Evidence of low pump flow with increased power should suggest pump failure or increased afterload. The typical scenario includes a dilated LV, rightward deviation of the IVS, MR, and permanent opening of the aortic valve. Pump failure is usually due to pump thrombosis, whereas mechanical malfunction is rare. The echocardiographic diagnosis of pump thrombosis can be challenging because of the high echogenicity of the LVAD. Therefore, alternative algorithms—e.g., some ramp test protocols that evaluate the patient's left ventricular end-diastolic dimension (LVEDD), frequency of aortic valve opening, valvular insufficiency, blood pressure, and CF-LVAD parameters at increments of 400 rpm from 8000 to 12,000 rpm—have been proposed [41]. In patients with pump thrombosis, LVEDD changed only minimally with changes in revolutions per minute. However, the effectiveness of these protocols should be further tested. The main causes of increased afterload are kinking or obstruction of the outflow cannula and hypertensive emergencies. Loss of Doppler flow signal or Doppler velocities >2 m/s with color Doppler aliasing at the cannula orifice indicate the former, whereas high blood pressure with normal echocardiographic findings suggests the latter.

RVF, hypovolemia, severe tricuspid regurgitation, inflow cannula obstruction, and cardiac tamponade are all conditions that cause a reduction of pump filling and output, despite normal rotor speed and power. The combination of a small LV with a leftward deviation of the IVS, dilated RV, decreased RV systolic function, increased right atrial pressure, and increased tricuspid regurgitation suggests RVF (Fig. 10). On the other hand, increased LV volumes with high Doppler velocities or loss of signal at the inflow cannula suggest cannula obstruction. High pump flow with a low cardiac output raises concern about de novo, severe AR. A large regurgitant volume results in reduced forward flow and an increased LVAD preload. The presence of a pericardial effusion and distortion or compression of one or more cardiac chambers is consistent with tamponade.

Conclusions

The role of 2D echocardiography in the assessment of LVAD-eligible patients is well established; however, the role of newer technologies is currently underappreciated. Real-time 3D echocardiography has great diagnostic and prognostic relevance in all phases of LVAD implantation, being able to provide more accurate and reliable quantification of LV and RV volumes, evaluation of valves and pericardial alterations, and detection of LV or cannula thrombi and intracardiac shunts. Moreover, 2D strain measurements provide incremental value in risk stratification for patients with end-stage HF and for post-implantation RVF and could be a useful tool for the estimation of LV function during follow-up (Table 4). Therefore, we suggest the routine use of these tools in the evaluation of patients eligible for LVAD implantation.

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Compliance with Ethical Standards

Conflict of Interest Luca Longobardo, Christopher Kramer, Scipione Carerj, Concetta Zito, Renuka Jain, Valentin Suma, Vinay Thohan, Nasir Sulemanjee, Frank X. Downey, and Bijoy K. Khandheria declare that they have no conflict of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

References

Papers of particular interest, published recently, have been highlighted as:
- • Of importance
- •• Of major importance

1. Rose EA, Moskowitz AJ, Packer M, et al. The REMATCH trial: rationale, design, and end points. Randomized evaluation of mechanical assistance for the treatment of congestive heart failure. Ann Thorac Surg. 1999;67:723–30.
2. Mozaffarian D, Benjamin EJ, Go AS, et al. Heart disease and stroke statistics—2015 update: a report from the American Heart Association. Circulation. 2015;131:e29–322. Erratum in: Circulation. 2015;131:e535.
3. Kirklin JK, Naftel DC, Pagani FD, et al. Seventh INTERMACS annual report: 15,000 patients and counting. J Heart Lung Transplant. 2015;34:1495–504.
4. Feldman D, Pamboukian SV, Teuteberg JJ, et al. The 2013 International Society for Heart and Lung Transplantation Guidelines for mechanical circulatory support: executive summary. J Heart Lung Transplant. 2013;32:157–87.
5. Carluccio E, Dini FL, Biagioli P, et al. The 'Echo Heart Failure Score': an echocardiographic risk prediction score of mortality in systolic heart failure. Eur J Heart Fail. 2013;15:868–76.
6. Cintron G, Johnson G, Francis G, et al. Prognostic significance of serial changes in left ventricular ejection fraction in patients with congestive heart failure. The V-HeFT VA Cooperative Studies Group. Circulation. 1993;87:VI17–23.

7. Wong M, Germanson T, Taylor WR, et al. Felodipine improves left ventricular emptying in patients with chronic heart failure: V-HeFT III echocardiographic substudy of multicenter reproducibility and detecting functional change. J Card Fail. 2000;6:19–28.
8. Todaro MC, Khandheria BK, Paterick TE, et al. The practical role of echocardiography in selection, implantation, and management of patients requiring LVAD therapy. Curr Cardiol Rep. 2014;16:468.
9. Kühl HP, Schreckenberg M, Rulands D, et al. High-resolution transthoracic real-time three-dimensional echocardiography: quantitation of cardiac volumes and function using semi-automatic border detection and comparison with cardiac magnetic resonance imaging. J Am Coll Cardiol. 2004;43:2083–90.
10. Dorosz JL, Lezotte DC, Weitzenkamp DA, et al. Performance of 3-dimensional echocardiography in measuring left ventricular volumes and ejection fraction: a systematic review and meta-analysis. J Am Coll Cardiol. 2012;59:1799–808.
11. Iacoviello M, Puzzovivo A, Guida P, et al. Independent role of left ventricular global longitudinal strain in predicting prognosis of chronic heart failure patients. Echocardiography. 2013;30:803–11.
12. Stanton T, Leano R, Marwick TH. Prediction of all-cause mortality from global longitudinal speckle strain: comparison with ejection fraction and wall motion scoring. Circ Cardiovasc Imaging. 2009;2:356–64.
13. Motoki H, Borowski AG, Shrestha K, et al. Incremental prognostic value of assessing left ventricular myocardial mechanics in patients with chronic systolic heart failure. J Am Coll Cardiol. 2012;60:2074–81.
14. Chang SN, Lai YH, Yen CH, et al. Cardiac mechanics and ventricular twist by three-dimensional strain analysis in relation to B-type natriuretic peptide as a clinical prognosticator for heart failure patients. PLoS One. 2014;9:e115260. Erratum in: PLoS One. 2015;10:e0123049.
15. Ma C, Chen J, Yang J, et al. Quantitative assessment of left ventricular function by 3-dimensional speckle-tracking echocardiography in patients with chronic heart failure: a meta-analysis. J Ultrasound Med. 2014;33:287–95.
16. Hamilton A, Huang SL, Warnick D, et al. Left ventricular thrombus enhancement after intravenous injection of echogenic immunoliposomes: studies in a new experimental model. Circulation. 2002;105:2772–8.
17. Fine NM, Abdelmoneim SS, Dichak A, et al. Safety and feasibility of contrast echocardiography for LVAD evaluation. JACC Cardiovasc Imaging. 2014;7:429–30.
18. Liao KK, Miller L, Toher C, et al. Timing of transesophageal echocardiography in diagnosing patent foramen ovale in patients supported with left ventricular assist device. Ann Thorac Surg. 2003;75:1624–6.
19. Patangi SO, George A, Pauli H, et al. Management issues during HeartWare left ventricular assist device implantation and the role of transesophageal echocardiography. Ann Card Anaesth. 2013;16:259–67.
20. Puskas F, Cleveland Jr JC, Singh R, et al. Detection of left ventricular apical thrombus with three-dimensional transesophageal echocardiography. Semin Cardiothorac Vasc Anesth. 2011;15:102–4.
21. Anwar AM, Nosir YF, Ajam A, et al. Central role of real-time three-dimensional echocardiography in the assessment of intracardiac thrombi. Int J Cardiovasc Imaging. 2010;26:519–26.
22. Sattiraju S, Masri SC, Liao K, et al. Three-dimensional transesophageal echocardiography of a thrombus entrapped by a patent foramen ovale. Ann Thorac Surg. 2012;94:e101–2.
23. Rana BS, Thomas MR, Calvert PA, et al. Echocardiographic evaluation of patent foramen ovale prior to device closure. JACC Cardiovasc Imaging. 2010;3:749–60.
24. Shanks M, Manawadu D, Vonder Muhll I, et al. Detection of patent foramen ovale by 3D echocardiography. JACC Cardiovasc Imaging. 2012;5:329–31.
25. Rana BS, Shapiro LM, McCarthy KP, et al. Three-dimensional imaging of the atrial septum and patent foramen ovale anatomy: defining the morphological phenotypes of patent foramen ovale. Eur J Echocardiogr. 2010;11:i19–25.
26. Sheinberg R, Brady MB, Mitter N. Intraoperative transesophageal echocardiography and ventricular assist device insertion. Semin Cardiothorac Vasc Anesth. 2011;15:14–24.
27. Ammar KA, Umland MM, Kramer C, et al. The ABCs of left ventricular assist device echocardiography: a systematic approach. Eur Heart J Cardiovasc Imaging. 2012;13:885–99.
28.• Estep JD, Vivo RP, Krim SR, et al. Echocardiographic evaluation of hemodynamics in patients with systolic heart failure supported by a continuous-flow LVAD. J Am Coll Cardiol. 2014;64:1231–41. **A useful, noninvasive and effective algorithm to predict LV filling pressures in patients with an LVAD**.
29. Andersen M, Gustafsson F, Madsen PL, et al. Hemodynamic stress echocardiography in patients supported with a continuous-flow left ventricular assist device. JACC Cardiovasc Imaging. 2010;3:854–9.
30. Topilsky Y, Hasin T, Oh JK, et al. Echocardiographic variables after left ventricular assist device implantation associated with adverse outcome. Circ Cardiovasc Imaging. 2011;4:648–61.
31. Martinez SC, Bradley EA, Novak EL, et al. Slope of the anterior mitral valve leaflet: a new measurement of left ventricular unloading for left ventricular assist devices and systolic dysfunction. Tex Heart Inst J. 2014;41:262–72.
32. McCarthy PM, Nakatani S, Vargo R, et al. Structural and left ventricular histologic changes after implantable LVAD insertion. Ann Thorac Surg. 1995;59:609–13.
33. Xydas S, Rosen RS, Ng C, et al. Mechanical unloading leads to echocardiographic, electrocardiographic, neurohormonal, and histologic recovery. J Heart Lung Transplant. 2006;25:7–15.
34. Moon MR, Bolger AF, DeAnda A, et al. Septal function during left ventricular unloading. Circulation. 1997;95:1320–7.
35. Topilsky Y, Price TN, Atchison FW, et al. Atypical tamponade hemodynamic in a patient with temporary left ventricular assist device. Interact Cardiovasc Thorac Surg. 2011;12:832–4.
36. Hernandez CM, Singh P, Hage FG, et al. Live/Real time three-dimensional transthoracic echocardiographic assessment of pericardial disease. Echocardiography. 2009;26:1250–63.
37. Gupta S, Woldendorp K, Muthiah K, et al. Normalisation of haemodynamics in patients with end-stage heart failure with continuous-flow left ventricular assist device therapy. Heart Lung Circ. 2014;23:963–9.
38. McDiarmid A, Gordon B, Wrightson N, et al. Hemodynamic, echocardiographic, and exercise-related effects of the HeartWare left ventricular assist device in advanced heart failure. Congest Heart Fail. 2013;19:11–5.
39. Morgan JA, Brewer RJ, Nemeh HW, et al. Left ventricular reverse remodeling with a continuous flow left ventricular assist device measured by left ventricular end-diastolic dimensions and severity of mitral regurgitation. ASAIO J. 2012;58:574–7.
40. Topilsky Y, Oh JK, Shah DK, et al. Echocardiographic predictors of adverse outcomes after continuous left ventricular assist device implantation. JACC Cardiovasc Imaging. 2011;4:211–22.
41. Uriel N, Morrison KA, Garan AR, et al. Development of a novel echocardiography ramp test for speed optimization and diagnosis of device thrombosis in continuous-flow left ventricular assist devices: the Columbia ramp study. J Am Coll Cardiol. 2012;60:1764–75.
42. Estep JD, Yarrabolu T, Win HK, et al. Median axial flow pump speed associated with cessation of aortic valve opening is an indicator of remission of chronic heart failure in patients supported by a left ventricular assist device. J Heart Lung Transplant. 2008;27:S185.
43. Mancini DM, Beniaminovitz A, Levin H, et al. Low incidence of myocardial recovery after left ventricular assist device implantation in patients with chronic heart failure. Circulation. 1998;98:2383–9.

44. George RS, Sabharwal NK, Webb C, et al. Echocardiographic assessment of flow across continuous-flow ventricular assist devices at low speeds. J Heart Lung Transplant. 2010;29:1245–52.
45. Smiseth OA, Torp H, Opdahl A, et al. Myocardial strain imaging: how useful is it in clinical decision making? Eur Heart J. 2015. [Epub ahead of print].
46. Gupta DK, Skali H, Rivero J, et al. Assessment of myocardial viability and left ventricular function in patients supported by a left ventricular assist device. J Heart Lung Transplant. 2014;33:372–81.
47. St John Sutton M, Pfeffer MA, Moye L, et al. Cardiovascular death and left ventricular remodeling two years after myocardial infarction: baseline predictors and impact of long-term use of captopril: information from the Survival and Ventricular Enlargement (SAVE) trial. Circulation. 1997;96:3294–9.
48. Zornoff LA, Skali H, Pfeffer MA, et al. Right ventricular dysfunction and risk of heart failure and mortality after myocardial infarction. J Am Coll Cardiol. 2002;39:1450–5.
49. Damy T, Kallvikbacka-Bennett A, Goode K, et al. Prevalence of, associations with, and prognostic value of tricuspid annular plane systolic excursion (TAPSE) among out-patients referred for the evaluation of heart failure. J Card Fail. 2012;18:216–25.
50. Meris A, Faletra F, Conca C, et al. Timing and magnitude of regional right ventricular function: a speckle tracking-derived strain study of normal subjects and patients with right ventricular dysfunction. J Am Soc Echocardiogr. 2010;23:823–31.
51. Guendouz S, Rappeneau S, Nahum J, et al. Prognostic significance and normal values of 2D strain to assess right ventricular systolic function in chronic heart failure. Circ J. 2012;76:127–36.
52. Motoki H, Borowski AG, Shrestha K, et al. Right ventricular global longitudinal strain provides prognostic value incremental to left ventricular ejection fraction in patients with heart failure. J Am Soc Echocardiogr. 2014;27:726–32.
53. Cameli M, Bernazzali S, Lisi M, et al. Right ventricular longitudinal strain and right ventricular stroke work index in patients with severe heart failure: left ventricular assist device suitability for transplant candidates. Transplant Proc. 2012;44:2013–5.
54. Kim J, Cohen SB, Atalay MK, et al. Quantitative assessment of right ventricular volumes and ejection fraction in patients with left ventricular systolic dysfunction by real time three-dimensional echocardiography versus cardiac magnetic resonance imaging. Echocardiography. 2015;32:805–12.
55. Marzec LN, Ambardekar AV. Preoperative evaluation and perioperative management of right ventricular failure after left ventricular assist device implantation. Semin Cardiothorac Vasc Anesth. 2013;17:249–61.
56. Romano MA, Cowger J, Aaronson KD, et al. Diagnosis and management of right-sided heart failure in subjects supported with left ventricular assist devices. Curr Treat Options Cardiovasc Med. 2010;12:420–30.
57. Murali S, Kormos RL, Uretsky BF, et al. Preoperative pulmonary hemodynamics and early mortality after orthotopic cardiac transplantation: the Pittsburgh experience. Am Heart J. 1993;126:896–904.
58. Lam KM, Ennis S, O’Driscoll G, et al. Observations from non-invasive measures of right heart hemodynamics in left ventricular assist device patients. J Am Soc Echocardiogr. 2009;22:1055–62.
59. Raina A, Seetha Rammohan HR, Gertz ZM, et al. Postoperative right ventricular failure after left ventricular assist device placement is predicted by preoperative echocardiographic structural, hemodynamic, and functional parameters. J Card Fail. 2013;19:16–24.
60.•• Grant AD, Smedira NG, Starling RC, et al. Independent and incremental role of quantitative right ventricular evaluation for the prediction of right ventricular failure after left ventricular assist device implantation. J Am Coll Cardiol. 2012;60:521–8. **This is the first study that evaluated RV strain by STE to predict RVF outcomes in patients after LVAD implantation**.
61. Kato TS, Farr M, Schulze PC, et al. Usefulness of two-dimensional echocardiographic parameters of the left side of the heart to predict right ventricular failure after left ventricular assist device implantation. Am J Cardiol. 2012;109:246–51.
62. Dandel M, Potapov E, Krabatsch T, et al. Load dependency of right ventricular performance is a major factor to be considered in decision making before ventricular assist device implantation. Circulation. 2013;128:S14–23.
63. Kalogeropoulos AP, Al-Anbari R, Pekarek A, et al. The Right Ventricular Function After Left Ventricular Assist Device (RVF-LVAD) study: rationale and preliminary results. Eur Heart J Cardiovasc Imaging. 2015. [Epub ahead of print].
64. Cameli M, Lisi M, Righini FM, et al. Speckle tracking echocardiography as a new technique to evaluate right ventricular function in patients with left ventricular assist device therapy. J Heart Lung Transplant. 2013;32:424–30.
65. Kato TS, Jiang J, Schulze PC, et al. Serial echocardiography using tissue Doppler and speckle tracking imaging to monitor right ventricular failure before and after left ventricular assist device surgery. JACC Heart Fail. 2013;1:216–22.
66. Cameli M, Sparla S, Focardi M, et al. Evaluation of right ventricular function in the management of patients referred for left ventricular assist device therapy. Transplant Proc. 2015;47:2166–8.
67. Herod JW, Ambardekar AV. Right ventricular systolic and diastolic function as assessed by speckle-tracking echocardiography improve with prolonged isolated left ventricular assist device support. J Card Fail. 2014;20:498–505.
68. Kiernan MS, French AL, DeNofrio D, et al. Preoperative three-dimensional echocardiography to assess risk of right ventricular failure after left ventricular assist device surgery. J Card Fail. 2015;21:189–97.
69. Pal JD, Klodell CT, John R, et al. Low operative mortality with implantation of a continuous-flow left ventricular assist device and impact of concurrent cardiac procedures. Circulation. 2009;120:S215–9.
70. Vengala S, Nanda NC, Dod HS, et al. Images in geriatric cardiology. Usefulness of live three-dimensional transthoracic echocardiography in aortic valve stenosis evaluation. Am J Geriatr Cardiol. 2004;13:279–84.
71. Fang L, Hsiung MC, Miller AP, et al. Assessment of aortic regurgitation by live three-dimensional transthoracic echocardiographic measurements of vena contracta area: usefulness and validation. Echocardiography. 2005;22:775–81. Erratum in: Echocardiography. 2006;23:table of contents.
72. Rao V, Slater JP, Edwards NM, et al. Surgical management of valvular disease in patients requiring left ventricular assist device support. Ann Thorac Surg. 2001;71:1448–53.
73. Aggarwal A, Raghuvir R, Eryazici P, et al. The development of aortic insufficiency in continuous-flow left ventricular assist device-supported patients. Ann Thorac Surg. 2013;95:493–8.
74. Tuzun E, Pennings K, van Tuijl S, et al. Assessment of aortic valve pressure overload and leaflet functions in an ex vivo beating heart loaded with a continuous flow cardiac assist device. Eur J Cardiothorac Surg. 2014;45:377–83.
75. Ewe SH, Delgado V, van der Geest R, et al. Accuracy of three-dimensional versus two-dimensional echocardiography for quantification of aortic regurgitation and validation by three-dimensional three-directional velocity-encoded magnetic resonance imaging. Am J Cardiol. 2013;112:560–6.
76. Kellman SE, Feider AJ, Jeevanandam V, et al. Can intraoperative transesophageal echocardiography predict postoperative aortic insufficiency in patients receiving implantable left ventricular assist devices? J Cardiothorac Vasc Anesth. 2015;29:901–5.
77. Agricola E, Oppizzi M, Pisani M, et al. Accuracy of real-time 3D echocardiography in the evaluation of functional anatomy of mitral regurgitation. Int J Cardiol. 2008;127:342–9.

78. Pérez de Isla L, Beńitez DR, Serra V, et al. Usefulness of real time 3D echocardiography in assessment of rheumatic mitral stenosis. Arch Cardiol Mex. 2005;75:210–21. Spanish.
79. Piacentino 3rd V, Williams ML, Depp T, et al. Impact of tricuspid valve regurgitation in patients treated with implantable left ventricular assist devices. Ann Thorac Surg. 2011;91:1342–6. discussion 1346-7.
80. Park YH, Song JM, Lee EY, et al. Geometric and hemodynamic determinants of functional tricuspid regurgitation: a real-time three-dimensional echocardiography study. Int J Cardiol. 2008;124:160–5.
81. Lesicka A, Feinman JW, Thiele K, et al. Echocardiographic artifact induced by HeartWare left ventricular assist device. Anesth Analg. 2015;120:1208–11.
82. Abusaid GH, Ahmad M. Transthoracic real time three-dimensional echocardiography in Impella placement. Echocardiography. 2012;29:E105–6.
83. Paluszkiewicz L, Schulte-Eistrup S, Körtke H, et al. Thrombosis of the LVAD inflow cannula detected by transthoracic echocardiography: 2D and 3D thrombus visualization. Echocardiography. 2011;28:E194–5.
84. Aissaoui N, Paluszkiewicz L, Koertke HH, et al. Echocardiography can be more sensitive than thoracic computed tomography in detecting a thrombus in the inflow cannula of a continuous left ventricular assist device. Echocardiography. 2011;28:E215–6.