Multimodality imaging for the evaluation and management of patients with long-term (durable) left ventricular assist devices

A Clinical Consensus Statement of the European Association of Cardiovascular Imaging (EACVI) of the ESC

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Abstract

Left ventricular assist devices (LVADs) are gaining increasing importance as therapeutic strategy in advanced heart failure (HF), not only as bridge to recovery or to transplant, but also as destination therapy. Even though long-term LVADs are considered a precious resource to expand the treatment options and improve clinical outcome these patients, these are limited by peri-operative and post-operative complications, such as device-related infections, haemocompatibility-related events, device mispositioning and right ventricular failure. For this reason, a precise pre-operative, peri-operative and post-operative evaluation of these patients is crucial for the selection of LVADs candidates and the management LVADs recipients. The use of different imaging modalities offers important information to complete the study of patients with LVADs in each phase of their assessment, with peculiar advantages/disadvantages, ideal application and reference parameters for each modality. This clinical consensus statement sought to guide the use of multimodality imaging for the evaluation of patients with advanced HF undergoing LVADs implantation.

Keywords: left ventricular assist device, heart failure, cardiac imaging, echocardiography, cardiac magnetic resonance, computed tomography

Abbreviations

2D = bidimensional
3D = tridimensional
AV = aortic valve
CAD = coronary artery disease
CCTA = coronary CT angiography
CF = continuous flow
CMR = cardiac magnetic resonance
CT = computed tomography
EACVI = European association of cardiovascular imaging
FDG = fluoro-deoxy glucose
HF = heart failure
HFrEF = heart failure with reduced ejection fraction
ILS = intermittent low speed
EF = ejection fraction
FAC = fractional area change

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fwRVLS = free wall right ventricular longitudinal strain
GLS = global longitudinal strain
IVS = interventricular septum
LGE = late gadolinium enhancement
LV = left ventricle
LVADs = left ventricular assist devices
LVEDD = left ventricular end diastolic diameter
LVESD = left ventricular end systolic diameter
LVOT = left ventricular outflow tract
MCS = mechanical circulatory support
MMI = multimodality imaging
MRI = magnetic resonance imaging
PET = positron emission tomography
PFO = patent foramen ovale
PT = pump thrombosis
RV = right ventricle
RVF = right ventricular failure
SPECT = single photon emission computer tomography
TAH = total artificial heart
TAPSE = tricuspid annular plane systolic excursion
TOE = trans-oesophageal echocardiography
TR = tricuspid regurgitation
TTE = trans-thoracic echocardiography
UEA = ultrasound enhancing agent
WBC = white blood cells

1. Introduction

Mechanical circulatory support (MCS) is a major breakthrough in heart failure (HF) management. Left ventricular assist devices (LVADs) may be considered in patients with advanced heart failure already on optimal medical and device therapy, with reduced functional capacity and frequent hospitalizations. Also, dependence on inotropic therapy or short-term MCS as well as progressive end-organ dysfunction are potential indications. Of note, no absolute

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contraindications should be present, such as right ventricular dysfunction, contraindications to oral anticoagulation and absence of psychosocial support.

Mechanical circulatory support devices continue to evolve with advances in technology. Long-term (durable) LVADs is a form of MCS that has undergone considerable advances over the last two decades. Besides LVADs, Total Artificial Hearts (TAHs) are gaining their relevance in the field, but their diffusion is still limited to highly specialized centers worldwide. By replacing both ventricles, TAHs represent a completely different MCS system from a physiological standpoint.

The high incidence of HF, with consequent expansion in the number of patients with advanced disease [1] has led to increased use of long-term LVADs. However, these long-term (or "durable") devices are subject to peri-operative and post-operative complications, such as device-related infections, haemocompatibility-related events, device mispositioning and right ventricular failure (RVF), which may affect the long-term survival of patients [2,3]. Systematic evaluation during the pre-operative, peri-operative and post-operative periods is therefore necessary for these patients in routine clinical practice.

In addition to clinical and haemodynamic assessments of patients with HF, non-invasive imaging plays a pivotal role in the selection of LVAD candidates, the pre- and peri-operative management and the long-term management of patients with durable LVADs. Traditionally, echocardiography has been regarded as the preferred non-invasive technique for the assessment of LVAD recipients [4-6]. However, in the current era of multimodality imaging[7], it is timely to review the contribution of each of the various imaging modalities to highlight their relative advantages and pitfalls, not only for LVAD implantation centres, but also for primary and secondary care centres who may also encounter these patients.

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This European Association of Cardiovascular Imaging (EACVI) clinical consensus statement aims to provide a comprehensive guide for the use of echocardiography and multi-modality imaging (MMI) in the evaluation of patients with long-term LVADs in clinical practice. This document will describe (i) the role and pitfalls of each imaging modality; and (ii) the use of different imaging modalities to complement clinical and invasive assessments to guide patient selection, and both the peri-operative and post-operative management of patients with LVADs.

Key points (Box 1)
HF epidemic is growing, resulting in an increasing demand for durable LVADs.
Non-invasive MMI plays a crucial role in the work-up of patients considered for LVAD, as well as in their peri-operative and post-operative assessment and management
In addition to clinical and haemodynamic assessment, multimodality imaging plays a pivotal role in the selection of LVAD candidates and in the management of patients with durable LVADs.
The identification and evaluation of LVADs complications (such as thromboembolism, valvular heart disease, bleeding, device mispositioning and importantly, right ventricular failure) is crucial
The use of a systematic MMI approach is essential to ensure early recognition of LVAD complications

HF, heart failure; LVAD , left ventricular assist device; MMI, multimodality imaging

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2. Left Ventricular Assist Devices

2.1 Different generations of LVADs

Shortage of donor organs and limited access to heart transplantation has contributed to the increased interest in LVADs for patients with end-stage left ventricular failure. The first major clinical trial of durable LVADs started in the 1990s with the first-generation of pulsatile LVADs. The development of smaller second-generation continuous flow axial LVADs led to easier device implantation as well as improved durability. The Heartmate II device was one of the most commonly used second-generation axial flow LVADs in the 2000s.

The third-generation centrifugal pump HeartMate 3 LVAD was introduced in 2015. The HeartMate 3 LVAD has an 'artificial pulse' and several features to improve haemocompatibility. In the MOMENTUM-3 randomized trial, the centrifugal flow HeartMate 3 device was associated with lower incidence of mortality, stroke and pump thrombosis compared to the axial flow HeartMate II device [8], and a 58% 5-year survival was recently documented in the long-term follow-up of the trial cohort.

2.2 LVAD anatomy

The LVAD consists of an intrathoracic part: (i) the pump with the associated inflow cannula (in the LV apex) and the outflow graft (from the pump to the ascending aorta); and external components (ii) the pump controller; and (iii) the cables connected to a pair of external batteries or power source. Blood is drawn from the LV via the inflow cannula into the pump and delivered via the outflow graft to the ascending aorta (**Fig. 1**). The outflow graft is typically positioned at

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the lower margin of the RV and courses along the right heart border to anastomose at the ascending aorta. In occasional cases, the outflow graft may be anastomosed to the descending aorta.

2.3 LVAD physiology

The LVAD competes with the LV for preload and provides a parallel circulation from the LV to the aorta. It continuously drains blood from the LV and deliver it to the aorta, with: (i) reduction in LV size and filling pressures (commonly accompanied by improvement in functional mitral regurgitation); and (ii) reduction in LV native stroke volume and work, (iii) loss of isovolumic phases in the cardiac cycle. In general, these effects are directly related to the programmed pump speed.

The flow generated by the LVAD is preload-dependent and afterload-sensitive. Hypovolaemia and/or RV failure at an unchanged pump speed will lead to reduction in LV chamber volume (i.e. LV and LVAD preload), which may result in (i) reduced intrinsic LV stroke volume, stroke work and LVAD flow ; (ii) loss of aortic valve opening if the LV fails to overcome aortic pressure; and (iii) trigger 'suction events' (i.e. events where the pump speed automatically and transiently drops to a pre-set lower level). Excessive emptying of the LV may also result from inappropriately high pump speed, this may trigger ventricular arrhythmias and compromise RV function. LVAD flows are also afterload sensitive. Therefore, increased LV afterload (raised mean arterial pressure) can compromise LVAD flows.

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2.4 Considerations for imaging

Candidates to LVADs therapy may be administered with inotropic/vasopressor drugs to maintain adequate end-organ perfusion, especially if on INTERMACS class 3 or higher. Therefore, imaging examinations in these patients should always consider the potential impact of medical therapy on findings and possibly state the specific drug and posology in the examination report. Many considerations should be taken into account when performing imaging examinations in these cases: the observed systolic function of both ventricles could be influenced leading to an overestimation of it; positive chronotropic effect and arrhythmias may potentially limit the quality of second level examinations; ischemia evaluation and heart valves functioning may be unreliable in these patients as well since oxygen demand/supply and preload/afterload may vary. The same precautions should be considered also in the perioperative period.

The objectives of LVAD therapy are: (i) improving systemic cardiac output (combination of LV native stroke volume and LVAD flow); (ii) unloading the LV; (iii) without inducing complications associated with a non-physiological parallel blood flow circuit (such as RV failure and aortic regurgitation). Imaging assessment of a patient with LVAD should exploit these anatomical and physiological concepts of heart-LVAD interaction to facilitate effective delivery of LVAD therapy. The three essential components of imaging assessment are the study of LVAD outflow (by Doppler imaging), LV unloading and LVAD-related complications. However, multimodality imaging of LVADs currently represents a challenge for clinicians and there are many issues, such as suboptimal acoustic windows, artefacts, interference for Doppler imaging, magnetic resonance incompatibility and blooming artefacts which strongly limit the evaluation of these patients.

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Key points (Box 2): LVAD flow
Contemporary LVADs are continuous flow devices
LVAD flow is preload-dependent and afterload-sensitive. Preload is dependent on volume status and right heart function and afterload is dependent on mean arterial pressure.
LVAD flow may be interrogated by Doppler imaging of the outflow graft

3. Pre-implantation: Multimodality imaging in selection of LVAD candidates

3.1 Echocardiography

3.1.1 2D Echocardiography

3.1.1.1 Left and right ventricular dimensions and function

Pre-operative transthoracic echocardiography (TTE) is the key imaging modality for assessing LV and RV function and dimensions in the evaluation and selection of patients for LVAD implantation [9] (**Table 1**).

The first thing to evaluate is the existence of the primary indication for LVAD implantation, which is end-stage HF due to ischaemic or non-ischaemic dilated cardiomyopathy with severe LV systolic dysfunction, an LV ejection fraction (LVEF) <25% and the presence of an appropriate space for an LVAD inflow cannula [10].

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The second key point to evaluate in the selection of LVAD candidates is RV function, another major determinant of a successful LVAD implantation[11]. Indeed, RV failure is currently considered the "Achilles heel" of contemporary LVAD devices. For tailored risk assessment, appropriate quantification of the RV function is therefore of paramount importance.

The echocardiographic assessment of the RV remains challenging due to technical difficulties in RV imaging, in addition to its complex geometry and function [12]. Key points in the echocardiographic assessment of RV are its structure, function, and tricuspid regurgitation. The most useful parameters to evaluate are shown in **Key Points Box 3** [13-17]. Importantly, RV in this situation must be as accurate as possible and requires a multiparametric approach ideally completed by CMR in case of doubt.

Key points (Box 3): Echocardiographic assessment of LV and RV function in LVAD candidates
LV severe dysfunction assessed by LV EF < 25% is a major criterion for LVAD implantation
The evaluation of LV geometry (to exclude the absence of space for LVAD cannula) and volumes measurement is also advisable
RV structure may be estimated by mid-cavitary diameter [13] and RV sphericity index (as the ratio of the short diameter at the mid-ventricular level to the long diameter in end-

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diastole, usually < 0.5) in apical 4 chamber view, and RV/LV diameter ratio (usually >0.7)
RV function may be estimated by tricuspid annular plane systolic excursion (TAPSE), TDI-derived tricuspid lateral annular systolic velocity wave (S’), RV fractional area change (FAC, usually > 35%), RV longitudinal strain and RV ejection fraction quantified by 3D echocardiography.

3.1.1.2 TOE: valvular heart disease, intracardiac thrombi or shunts

Transoesophageal echocardiography (TOE) should be always performed during LVAD candidates’ selection when TTE findings are inconclusive or incomplete or when a TOE is more appropriate, as for example in urgent cases or emergency scenarios. TOE provides added value for the assessment of valvular heart disease and for the exclusion of intracardiac thrombi and intracardiac shunts (**Table 2**) [18] .

TOE provides a good assessment of the heart valves and can be essential for the assessment of prosthetic valves function and paravalvular regurgitation. TOE can help quantify native or prosthetic valve mitral stenosis and aortic regurgitation, quantification of which is crucial prior to LVAD implantation and which could be affected by the existence of low-flow in the left ventricle (LV) and elevated LV end-diastolic pressures. Moderate or severe mitral stenosis prevents LVAD cannula inflow, and more than mild aortic regurgitation could lead to recirculation of blood flow from the ascending aorta, reducing LVAD effectiveness [19]. In patients with HF with reduced ejection fraction (HFrEF), the mitral mean diastolic gradient does not reflect mitral stenosis severity, being lowered by the existence of both low-flow and high LV pressure; consequently, inspection of the valve and calculation of effective valve orifice area are required to help elicit

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the diagnosis. Vena contracta measurements, with the benefit of the higher resolution of TOE can help in the diagnosis of regurgitant lesions. Inspection of the aortic valve and aortic root morphology can help in the evaluation of co-existent significant aortic regurgitation, even though the possible underestimation of aortic regurgitation due to increased LV diastolic pressures should be considered. The regurgitant volume can be low because of low flow in the LV; the calculated regurgitant fraction might therefore better reflect the severity of aortic regurgitation.

Mitral regurgitation of any severity usually improves following LVAD implantation and LV unloading. On the contrary, moderate or severe tricuspid regurgitation may necessitate tricuspid repair or replacement at the time of LVAD implantation, to protect the RV. Pulmonary regurgitation can contribute to RV volume overload and consequent RV systolic dysfunction, particularly when LV unloading is unsuccessful.

Moreover, mechanical valves need to be identified (if not known) so that they can be replaced with a bioprostheses at the time of surgery in order to prevent additional risk of blood stasis and thrombosis.

TOE is also essential for exclusion of left atrial appendage thrombus in patients with atrial fibrillation. It can also help exclude LV apical thrombus and aneurysm formation, although the LV is often foreshortened on TOE with suboptimal visualization of the LV walls.

A comprehensive assessment for intracardiac shunts is essential prior to LVAD implantation, and can be performed with TOE using saline contrast, comprising exclusion of ventricular septal defects in patients with ischaemic cardiomyopathy, exclusion of atrial septal defects, partial anomalous venous drainage and a patent foramen ovale (PFO). Flow through an atrial septal defect or PFO can reverse following LVAD implantation, causing right-to-left shunt and

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subsequent arterial hypoxaemia, because of the reduction in left atrial pressure following left heart offloading. Identification and correction of an interatrial shunt is therefore essential before/during LV implantation [20].

Key points (Box 4) : TOE for pre-operative evaluation of LVAD candidates
TOE provides added value for the assessment of valvular heart disease and recognition of mechanical valves in LVAD candidates
Calculation of mitral valve area and aortic regurgitant fraction by TOE allow a better assessment of mitral stenosis and aortic regurgitation respectively in patients with low flow and high LV pressure
To investigate the presence of intracardiac shunts or masses by TOE is advisable before LVAD implantation.

3.1.2 Speckle tracking echocardiography

Speckle tracking echocardiography (STE) allows the analysis of myocardial deformation i.e. ‘strain’ of all cardiac chambers [21].

STE is particularly useful for RV evaluation in patients referred for LVADs, allowing the detection of subclinical RV dysfunction which may predispose to the development of post-LVAD RV failure. Two parameters may be measured for this purpose: RV global longitudinal strain (GLS), which analyses the deformation of the whole RV wall divided into six segments, and free-wall RV longitudinal strain (fwRVLS), which analyses three RV segments limited to the RV

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free-wall. FwRVLS is considered the most accurate, as it focuses on RV physiological function in which the RV free wall contributes to 80% of RV output (**Fig.2**). By contrast, RV GLS also includes the interventricular septum (IVS) which may be influenced by LV kinetics and could therefore underestimate RV function in HFrEF patients, although it can be argued that the IVS contributes to RV systolic function, and that therefore impaired IVS function is an important component of impaired RV function [22,23].

Both preoperative RV GLS and fwRVLS have been found to be reduced in patients undergoing LVAD implantation who develop subsequent RVF, as confirmed in a recent meta-analysis [34]. RV strain has also demonstrated superior prognostic information to conventional echocardiographic parameters of LV and RV function in patients with chronic HF [24,25].

Moreover, as compared to invasive techniques, fwRVLS (usually < -22%) has been shown to have good correlation with RV stroke work index which is the most used invasive measurement of RV impairment assessed by right heart catheterization [26], and has been shown to be a marker of RV fibrosis as well [27].

In previous studies, fwRVLS emerged as a prognostic marker in patients being considered for an LVADs, predicting of early RVF [28, 29] and was included in highly-sensitive prognostic scores together with haemodynamic, echocardiographic, and clinical parameters [30-33] with a cutoff value > -14%.

Therefore, fwRVLS may be considered the most sensitive echocardiographic parameter to identify those patients referred for an LVAD who are at greatest risk of developing postoperative RVF and therefore to aid in patient selection and determination of further management strategies. However, larger multicentre studies, such as the ongoing EuroEchoVAD trial (ClinicalTrials.gov

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NCT03552679), a EUROMACS approved study including 600 patients, are needed to establish optimal reference values to aid decision-making in routine clinical practice.

Key points (Box 5) : Speckle tracking echocardiography for pre-operative evaluation of LVAD candidates
The evaluation of RV strain by speckle tracking echocardiography is advisable to detect subtle RV dysfunction possibly leading to post-implant RV failure
RV strain quantification by free wall strain rather than global RV strain should be preferred since it analyzes better RV intrinsic function independent from LV function

3.1.3 Three-dimensional echocardiography

Echocardiographic assessment of LV and RV size and function is key for candidate selection and detection of possible LVAD complications. Due to the complex shape and mechanics of the RV, 2D echocardiography (2DE) cannot reliably measure RV volumes and EF.

In the presence of adequate acoustic windows and local expertise, three-dimensional echocardiography (3DE) is the most accurate method to quantify ventricular volumes and EF [34]. Feasibility of 80-92% is reported for RV-focused 4 chamber views [35]. 3DE can circumvent all the potential limitations associated with 2DE including limited visualization, incorrect geometric assumptions, and cavity foreshortening [36]. 3DE permits a more accurate and reproducible analysis of LV and RV volumes and function than 2DE [37]. This is particularly useful in borderline cases, such as when LV EF is around 25% or RVFAC is 30-35%. In LVAD implantation candidates, 3D RV volumes and EF were associated with postoperative outcome

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and were superior predictors of RV failure compared to conventional parameters such as 2D RV volumes and RV/LV ratio [38-40].

Following LVAD implantation, 3DE becomes more technically challenging due to poor image quality and artefacts due to the LV apical cannula (50-56% feasibility in LVAD patients vs 85% in non-LVAD patients) [41-43]. When feasible, 3DE was helpful to reliably identify the "cross-over point" during ramp testing (see par.7.2), which corresponds to the LVAD speed at which there was excessive LV unloading and risk of RV dilation due to septal shift towards the LV) [44], as well as to quantify the LV reverse remodelling and shape changes that occur early after LVAD implantation [45]. New 3D technologies under development, such as 3D intracardiac echocardiography, may assist in the future with the point-of-care implantation of percutaneous LVADs in critical care settings [46].

Key points (Box 6): 3D echocardiography for LVAD pre-operative evaluation
In the presence of adequate acoustic window and local expertise, 3D echocardiography may be performed for a more reliable assessment of biventricular structure and ejection fraction
Further investigations will have to clarify whether 3DE quantification improves clinical outcomes of LVAD patients, compared to conventional echocardiographic parameters.

3.2 Cardiovascular Magnetic Resonance

CMR advantages are unrestricted planes and high spatial resolution and tissue contrast [47]. Current European Society of Cardiology (ESC) guidelines for the management of HF assign CMR Class 1 indications for patients with suboptimal echocardiography and suspected

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myocardial infiltration; and Class 2 indications for detection of ischaemia and scar [48]. Although CMR thus offers clear potential for the selection of candidates for LVAD therapy, the current evidence for the use of CMR in this scenario is sparse and recommendations in this document are therefore necessarily largely based on expert opinion. Moreover, the use of CMR is limited in patients with chronic kidney failure (for contraindication to the use of gadolinium with eGFR < 30 ml/min/m2) and with non-magnetic resonance compatible devices (e.g. implantable cardioverter defibrillator).

In the selection of candidates for LVAD, CMR will generally be considered when echocardiography is either of insufficient quality or shows findings that require more detailed assessment; when information on myocardial ischaemia and viability is required or in patients with complex anatomy including those with congenital heart disease. However, obtaining high quality CMR images requires patients to lie supine within the MRI scanner usually for 30-45 minutes and to be able to hold their breathing for several seconds. Many of the patients considered for LVAD therapy may therefore not able to tolerate a CMR scan during their acute presentation. Rapid CMR protocols are in development and may improve the use of CMR in these patients in the future. CMR image quality may also be affected by the presence of implantable cardiac devices, but most of these devices do not pose a contraindication to CMR.

A routine CMR scan will include anatomical images that identify the main cardiac and vascular structures and can detect mediastinal and pulmonary pathology that may be relevant in the triage for LVAD. Cine images are acquired in standardized orthogonal long axis and short axis planes that cover the entire heart and provide highly reliable measurements of left and right ventricular dimensions, regional and global contractile function [47]. In particular, in patients with abnormal cardiac morphology, CMR is more accurate than 2D echocardiography in measuring ventricular

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size and function and can thus help guide decisions on the appropriateness of LVAD therapy in borderline cases [49,50]. LGE CMR has become the reference standard for the detection, localization and quantification of myocardial infarction and focal fibrosis due to its high spatial resolution and tissue contrast, which closely match and provide direct anatomical correlation of viable and non-viable myocardium [51]. The combined assessment of regional LV function, ischaemia and scar by CMR offers accurate assessment of the potential for regional and global functional recovery to guide the need for revascularization in patients with known or suspected ischaemic heart disease considered for LVAD therapy [52]. Moreover, CMR and PET imaging for example could be used to rule-out inflammatory heart disease in patients undergoing heart transplantation diagnosed as idiopathic dilated cardiomyopathy. In some patients, LGE CMR can be complemented by low dose Dobutamine cine imaging to determine functional reserve similar to stress echocardiography [53]. Early and late gadolinium-enhanced CMR is also highly sensitive for the detection of intracardiac thrombi, providing essential information prior to cannulation of the LV [54]. Further tissue characterization can be achieved with parametric mapping, which provides information on myocardial oedema and diffuse fibrosis and where available may be used as a contrast-free alternative to LGE [55]. Flow-velocity encoded CMR can be used as an adjunct to echocardiography to estimate the severity of valvular disease as an important predictor of outcome following LVAD [56]. Finally, MRI angiography delineates the anatomy of the great vessels and excludes pathology such as aortic aneurysms similar to CT and can help procedure planning of concomitant vascular intervention [57].

The limited literature on the use of CMR before LVAD implantation includes a study that compared CMR with echocardiography and right heart catheterization for the prediction of

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significant right heart failure post-LVAD, a common complication with associated poor outcome [58].

Key points (Box 7): The use of CMR for LVAD pre-operative evaluation
CMR allows accurate measurements of left and right heart dimensions and function in patients considered for implantation of LVAD
MR angiography can be used to assess the vascular anatomy in pre-operative assessment
Contrast enhanced CMR allows the detection of intracardiac thrombi with high accuracy
Specific evidence of using CMR pre LVAD therapy is sparse and more prospective research is needed

3.3 Computed tomography

Data concerning the use of CT in the planning phase of LVAD implantation are scarce, being mostly related to the post-procedural follow-up and assessment of device-related complications [59]. Currently, CT is not routinely performed in all patients who are considered for LVAD therapy. However, recent results have shown a promising potential role in the pre-procedural evaluation of patients' eligibility and feasibility for device implantation.

The principal value of CT concerns its accurate definition of the thoracic anatomy. Imaging with CT can provide a detailed overview of the mediastinum, accurately defining the spatial

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relationships of the LV with the surrounding non-cardiac structures. Evaluation of the anatomical course of the great vessels, exclusion of aortic aneurysms and congenital alterations are of fundamental importance before LVAD implantation [34]. Pre-operative assessment with CT is appropriate in patients with known congenital heart diseases to evaluate the safety and feasibility of the surgical procedure [60]. In patients with known aortic disease, pre-operative CT should be performed to exclude the need for concomitant aortic surgery [61].

Recently, new softwares have been developed to achieve virtual device reconstruction and simulation of implantation through semi-automatic segmentation and three-dimensional reconstruction of pre-operative CT scans before LVAD surgery [62, 63] .

Identification of patients who may still benefit from myocardial revascularization is also fundamental prior to LVAD implantation [63]. An attempt to treat haemodynamically significant coronary stenosis should be fully addressed, as every single opportunity of myocardial recovery may strongly influence LVAD planning. According to latest guidelines, coronary CT angiography (CCTA) is appropriate to exclude the presence of coronary artery disease (CAD) in HF patients with low to intermediate pre-test probability of CAD or in cases when results from other non-invasive stress tests are uncertain [64]. In these patients, beyond pure anatomical definition of coronary stenosis, advanced techniques, such as fractional flow reserve-CT and myocardial perfusion imaging with computed tomography perfusion, could be considered to unmask haemodynamically significant coronary lesions and presence of myocardial ischaemia, as an alternative to other functional imaging stress tests [48].

Another important issue before LV cannulation concerns the detection of intracardiac thrombi, which is fundamental to avoid thromboembolic events in the peri- and post-operative phase. On cardiac CT, thrombi typically appear as hypodense lesions that persist on delayed acquisition

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sequences (60–90 s after contrast injection) [48]. Cardiac CT is considered an appropriate alternative to transoesophageal echocardiography (TOE) to rule-out left atrium and left atrial appendage thrombosis thanks to its high sensitivity and specificity [65]. Moreover, CT can provide a multiplanar view of all cardiac structures and is not limited by acoustic windows or acoustic shadowing like echocardiography. However, the possible CT artefacts which may mimic left atrial appendage thrombus should be considered and excluded.

As already mentioned, before LVAD implantation, the presence of significant aortic or tricuspid regurgitation, RV dysfunction, and intracardiac shunts should be evaluated to avoid post-implant complications [63]. However, according to a recent consensus document, cardiac CT could be helpful to assess ventricular volumes and function in selected cases where echocardiographic data are uncertain and/or CMR is limited or contraindicated [48], as many of these patients are already implanted with cardiac defibrillators [66].

In contrast to larger echocardiographic data, specific CT parameters, which prognostically can represent predictors of post-operative complications, increased morbidity and mortality after LVAD implantation, have not yet been defined. Moreover, no data is available on the use of CT delayed enhancement for scar assessment [67] in planning LVAD surgery. Further larger studies are warranted to explore the role of CT in these scenarios.

Moreover, technological advances and strategies for radiation dose reduction could further help expanding the role of CT in the selection of patients for LVAD therapy as a complementary test to other imaging modalities (**Table 3**). However, like CMR, this resource remains limited in patients with severe reduction of renal function.

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Key points (Box 8): The use of cardiac CT for LVAD pre-operative evaluation
Cardiac CT allows accurate definition of thoracic anatomy and assessment of congenital alterations or aortic aneurysms before LVAD surgery
Cardiac CT with delayed imaging can exclude the presence of intracardiac thrombi with high sensitivity and specificity
CT angiography can be used to assess the vascular anatomy in pre-operative assessment
Further studies are needed to evaluate the role of CT to prevent post-procedural complications

4. Peri-implantation assessment

The assessment of LVAD recipients in the peri-LVAD implantation period predominantly involves (i) TOE which should always be performed during the LVAD implantation surgery and (ii) TTE which, in conjunction with TOE, is used early post-operatively in the intensive care unit. Other imaging modalities are seldomly utilized in this peri-operative period.

4.1. Preimplantation TOE

A comprehensive TOE evaluation of LVAD candidates in the operating theatre should precede LVAD implantation and is typically an extension of prior comprehensive multimodality imaging performed during assessment of LVAD candidacy and preoperative planning. The immediate

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preimplantation TOE should include, but should not be limited to, the evaluation of potential intracardiac thrombi and shunts, as well as RV size and function and aortic valve structure and function [6, 68]. A thorough assessment of a potential PFO should thus be undertaken, including colour Doppler evaluation of the fossa ovalis at low settings of the Nyquist limit and intravenous injection of agitated saline, which in some cases may be required in conjunction with a ventilator-driven Valsalva manoeuvre to unmask shunting [6,67]. Despite such attempts, in some cases only a decrease in left atrial pressure following LVAD initiation will unmask the existence of a PFO [6]. In regard to thrombi, all cardiac chambers should be examined, particularly the left atrial appendage (of note, some centres perform concomitant surgical left atrial appendage occlusion) and the LV apex (particularly around the site of the apical cannulation, where an apical thrombus needs to be brought to the surgeon's attention). Other relevant points to assess should be based on prior imaging examinations as well as the clinical status of the patient, e.g.: 1) in case of any suspicion of endocarditis, possible vegetations should be excluded (if confirmed, endocarditis is a contraindication for LVAD implantation); 2) in some cases an extended evaluation of the aortic valve may be required (however the degree of aortic regurgitation is best assessed prior to surgery, as it may be underestimated in the context of general anaesthesia) [6, 68]; 3) the assessment of the morphology of the ascending aorta for dissection, aneurysm, plaques and calcifications may also be needed in planning the location of the outflow graft anastomosis.

4.2 TOE during implantation

The perioperative TOE examination during LVAD implantation includes the guidance of the site of apical coring for the insertion of the inflow cannula of the LVAD. This is performed by imaging the heart in the mid-oesophageal 4 chamber view during external compression of the apical area (by surgical instrument or finger), directed towards the mitral valve orifice, with the aim of positioning the inflow cannula in this direction [69]. Further procedures include continuous monitoring for possible air bubbles in left-sided chambers (including the LV apex

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and inflow cannula area), aorta and the outflow graft anastomosis during the implantation and de-airing procedures [6]. Complete closure and lack of residual communication between the left atrium and appendage should be confirmed by TOE in those undergoing left atrial appendage occlusion [70]. The monitoring of RV function is described in the following subsection.

4.3 TOE during LVAD activation and pump speed optimization

TOE is an irreplaceable tool in haemodynamic monitoring during LVAD implantation, complementing invasive haemodynamic monitoring. During LVAD activation and pump speed optimization, LVAD settings (speed and flow) should be documented on the echocardiographic images. One of the primary determinants of the speed of cardiopulmonary bypass weaning (in those implanted on-pump) and increment in LVAD speed is the balance between left and right heart loading conditions, as evidenced by the position of the interatrial and IVS, as well as the size and function of left- and right-sided chambers. This predominantly entails the assessment of RV size and function, along with the assessment of tricuspid regurgitation, which could determine the capability of the RV to accommodate the increase in preload after LVAD activation. Additionally, LVAD speed settings which are excessive in the setting of a failing RV may induce a "sucked-down" underfilled /over-decompressed LV [6]. Depending on the intraoperative TOE and haemodynamics, in conjunction with the assessment of RV function prior to the LVAD implantation, the occurrence of RV dysfunction during LVAD activation may require pulmonary vasodilators to reduce RV afterload, lower LVAD speed settings to reduce RV preload, short-term inotropic support or perioperative temporary RVAD implantation in patients unresponsive to these attempts. In cases of brief and transient RV dysfunction, a careful and slower speed optimization of the LVAD may allow for restoration of RV function and the possibility of restoring medial positions of the interatrial septum and IVS.

Another indication of an appropriate LVAD speed setting is the opening of the aortic valve, which should be assessed in conjunction with the RV and LV size and function (**Fig. 3**).

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In patients with Heart Mate II or 3 or HeartWare HVAD, a constantly closed AV may indicate maximal LV unloading; intermittent AV opening usually indicates good LV unloading; while a constantly opened AV may indicate inadequate offloading which suggests additional escalation of LVAD speed in order to increase LV unloading – the ultimate choice among these strategies is centre-specific.

Nevertheless, patients with LVADs characterized by a different pump system that lowers device work for 9 seconds each minute (intermittent low speed, ILS, phase, typical of Jarvik 2000 device), have a different aortic valve opening pattern. In case of correct function, aortic valve should open only during the ILS phase.

A dilated RV with TR, septal shifts towards the left-sided chambers, and a small LV with a closed aortic valve suggests the need for a reduction in LVAD speed; a dilated LV with a septal shift towards an unenlarged RV and a fully opening aortic valve suggest the need for an increase in LVAD speed. In some case, looking at the atrial septal shift may be useful for this purpose as well. The presence and severity of aortic regurgitation should be assessed in addition, as previously described - in the event of unmasked significant aortic regurgitation after LVAD activation, an additional surgical procedure may be considered [69].

It is also important to assess the position of the inflow cannula and the outflow graft. The inflow cannula should be positioned within or near the LV apex, parallel to the IVS, with its opening directed towards the mitral valve – an excessive angulation towards the IVS or the LV free wall might require surgical revision. Doppler interrogation of the inflow cannula and outflow graft should be performed. This could be done by pulsed Doppler interrogation adjacent to the structure of interest, using a four-chamber apical view for inflow cannula and left or right (in right lateral decubitus) parasternal views or suprasternal view for outflow graft.

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Key points (Box 6): Peri-implantation assessment of LVAD recipients
Peri-procedural imaging predominantly involves TOE (during LVAD implantation surgery) and TTE (both may be used early post-operatively), while other modalities are typically not utilized in this period
The preimplantation TOE involves (but is not limited to) the evaluation of potential intracardiac thrombi and shunts, RV size and function and AV structure and function
Perioperative TOE during LVAD implantation includes: - guidance of the site of apical coring for the insertion of the inflow cannula, - monitoring for intracavitary / intra-aortic air bubbles
Perioperative TOE during LVAD activation and pump speed optimization focuses on the balance between left and right heart loading conditions by assessing: - position of the interatrial septum and IVS - size and function of left- and right-sided chambers, - AV opening, - assessment of tricuspid regurgitation

5. Early post-implant complications

5.1 Cardiac tamponade

Cardiac tamponade associated with cardiac surgery may occur within the first 24 hours, or late (arbitrarily defined as >5-7 days) after cardiac surgery. Early tamponade is usually related to bleeding, while late tamponade is often multifactorial [71]. Patients undergoing LVAD

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implantation have higher risk of early tamponade because of (i) pre-implantation coagulopathy related to anti-thrombotic therapy or temporary mechanical circulatory support; (ii) early postoperative anticoagulation and antiplatelet therapies; and (iii) acquired (LVAD-related) coagulopathy.

Haemodynamic parameters such as raised right atrial pressure and low cardiac output unresponsive to fluid challenge cannot distinguish tamponade from RVF following LVAD implantation. TTE is sometimes difficult in the early post-operative setting, and TOE may be helpful. However, the diagnostic value (e.g. sensitivity and specificity) of echocardiographic parameters for cardiac tamponade has not been systematically evaluated in patients with LVADs.

Traditional echocardiographic criteria such as exaggerated respiratory variation in mitral inflow pattern have limited utility during positive pressure ventilation [72]. In addition, inferior vena cava diameter and hepatic venous flow may not differentiate tamponade from RVF, especially with concomitant tricuspid regurgitation. Continuous LV drainage by the LVAD may further complicate the diagnosis. For example, pulsus paradoxus and changes in aortic flow velocity cannot be appreciated in the absence of pulsatility and LV ejection. Leftward shift in the IVS and LV collapse may be features of excessive pump speed and RVF.

In the face of these challenges, diagnosis must rely on high index of clinical suspicion and serial clinical, haemodynamic and echocardiographic assessments. Increasing pericardial effusion with right heart chamber collapse can distinguish tamponade from right heart failure. M-mode imaging may identify the timing and duration of right atrial and RV collapse. In general, the longer the

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duration of compression, the more severe the tamponade [73]. Finally, clinicians should be cognisant that RVF and tamponade may coexist; the diagnosis of one does not preclude the other.

5.2 RV failure

RV dysfunction is one of the main adverse consequences after LVAD implantation. Right heart failure is a major cause of mortality early post-LVAD implant. Right ventricular dysfunction may be transient following cardiopulmonary bypass or transient RV ischaemia from air emboli. However, persistent RV dysfunction may develop for various reasons. Excessive increase in RV preload, perioperative elevations in the pulmonary vascular resistance, a shift in the IVS position altering RV geometry and function or the function of the tricuspid valve annulus, ischaemic injury of the RV and atrial dysrhythmias can all lead to worsening RV function following LVAD implantation [74]. Alternatively, RV function can improve after LVAD implantation, in particular in patients with end-stage heart failure who have a degree of RV dysfunction due to post-capillary pulmonary hypertension.

RV dysfunction can develop due to excessively high LVAD pump speeds which can lead to (i) excessive RV preload (ii) impairment of LVAD flows and consequently an LV suction event when the LVAD inflow cannula 'sucks down' on the LV wall, potentially causing haemolysis or ventricular arrhythmias .

Imaging parameters should always be assessed in conjunction with clinical and haemodynamic features of RV failure. Echocardiography is the primary imaging modality in evaluating RV function in LVAD patients. Assessment of the RV includes an assessment of RV shape, size, volume, wall thickness, radial and longitudinal contractility, IVS shift towards left or right

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ventricle, evaluation of the right atrial size, main pulmonary artery and its branches, inferior vena cava size and its respiratory alterations, tricuspid valve annulus, and degree of TR [75]. Increased RV size and worsening tricuspid regurgitation indicates worsening RV function after LVAD. TAPSE becomes less sensitive in assessing RV function after cardiothoracic surgery. The improvement in RV afterload and contractility could lead to reduction of TAPSE due to increase in RV stroke volume. However, reduced TAPSE along with RV dilatation and worsening TR indicates worsening RV function [76].

Echocardiographic parameters correlated with RV failure after LVAD implantation include quantitative RV dysfunction, TAPSE, FAC, RV short-axis to long-axis ratio, RV end-diastolic dimension to LV end-diastolic dimension ratio, tricuspid annular dilatation without significant TR, TR duration corrected for heart rate, Peak systolic (S') velocity of the right ventricular free wall at the tricuspid annulus assessed with tissue Doppler, early diastolic (E') velocity of the right ventricular free wall at the tricuspid annulus assessed with tissue Doppler, RV index of myocardial performance, RV systolic and diastolic longitudinal strain, right ventricular E/E' ratio, TAPSE increase in response to dobutamine infusion, severity of tricuspid regurgitation and 3-dimensional right ventricular end-systolic and end-diastolic volume index [77].

5.3 Inadequate or excessive LV unloading

LVADs are excellent at unloading the LV, as reflected by subsequent reductions of LV size, and improvements in IVS position and LV systolic function. The ability of LVADs to provide haemodynamic offloading is dependent on preload, afterload and pump speed.

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IVS shift to the right could be due to inadequate LV unloading due to low pump speed, whereas IVS shift to the left could indicate excessive LV offloading due to high pump speed (**Fig.4**). Improvement in the degree of mitral regurgitation – or lack thereof - is a marker of the adequacy of LV offloading, as it reflects changes in LV end-diastolic pressures.

Assessment of aortic valve opening is crucial for the evaluation of LV unloading. Aortic valve opening is affected by LVAD pump speed, native LV function, LV preload and afterload. Low pump speed often leads to normal or intermittent opening of the aortic valve in relation to the cardiac cycle accompanied by larger LV dimensions. Aortic valve opening is best assessed by M-mode echocardiography at the aortic valve level. It is worthy to mention that the choice of optimum LVAD pump speed varies between centres as some prioritize intermittent aortic valve opening while others aim at optimizing best LV unloading while leaving aortic valve closed [6]. It is advised that LVAD speed be set as low as possible to allow at least intermittent valve opening, however, this may not be possible in the context of severely impaired native LV function, therefore, pump speed should not be set so low to allow AV opening at the expense of adequate LV unloading and HF symptoms.

Excessive offloading of the LV with high LVAD pump speeds can lead to a suction event in which the LVAD inflow cannula sucks down on the LV cavity leading to an abrupt drop in LVAD flows. This can develop due to the excessive decompression by the LVAD and / or subsequent RV dysfunction which impairs LVAD filling. Accurate assessment of the frequency of AV opening requires recording of multiple cardiac cycles (5-6) at a slow sweep speed (25-50 mm/sec). Assessing AV opening requires using both M-mode and 2D assessment as M-mode

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assessment alone could give a false impression of AV opening (pseudo-opening) due to off-axis imaging which should be suspected if AV opening appears fusiform [6]. Colour M-mode can also be used in the presence of aortic regurgitation (**Fig.5**).

If the AV is closed, it important to evaluate for the presence of AV and root thrombosis which can develop with or without commissural fusion as well as evaluation for new onset aortic regurgitation.

5.4 Infections

Device infection is a common complication after LVAD implantation. This may involve the device driveline, the pump itself, the inflow cannula or outflow graft, and the pump pocket [78]. The LVAD driveline is frequently involved as the initial source of infection (10-35% of all cases), especially at the entry site in the skin [79]. Additionally, fibrin deposition on the device and cannulae surfaces favours bacterial colonization [80]. Vegetations can be observed, as well as destructive valve lesions and abscesses in the surrounding cardiac structures, typically develop adjacent to the device. Presence of fever, leukocytosis, elevated inflammatory markers and a purulent drainage around the driveline should strongly raise the suspicion for LVAD infection [81].

Echocardiography should be firstly performed to confirm clinically suspected device infection. TTE allows the detection and sizing of vegetations, can assess involvement of the surrounding cardiac structures and should also be repeated after device extraction to rule out residual vegetations [82]. TOE demonstrated a higher sensitivity and specificity for LVAD infection than

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TTE and should be performed when transthoracic findings are uncertain and/or the clinical suspicion is high. False negative findings for TTE are mainly due to inadequate acoustic windows, presence of reverberation artefacts due to metallic components and limited planar views [83].

Second-level imaging with cardiac CT can help confirm the diagnosis and assess the extent of the infected sites. Typically, on CT imaging infections present as gas or fluid-collections around the cannulae or on the device surface, while masses within the cannulae may be imaged as well. Additional, highly suggestive features are the presence of rim-enhancement and soft tissue components as signs of inflammation [84]. Detection of LVAD infection with CT may, however, also be limited by artefact due to the device and driveline.

When diagnostic uncertainty persists regarding possible LVAD-related infections and risks of surgical exploration are high, then fluorodeoxy-glucose (FDG) positron emission tomography (PET)/CT may be useful. In fact, although TTE, TOE and CT are characterized by good sensitivity for the detection of LVAD infections, these provide non-specific information regarding increased wall thickness, fluid accumulation, abscess formation, fistula.

FDG PET/CT has shown high diagnostic accuracy in localizing device infection and its internal extension, with an overall sensitivity and specificity of 92% and 83% respectively [85]. Indeed, PET/CT can distinguish between the wide range of LVAD-related infections, such as those related to pump and cannula, pump pocket, and superficial and deep driveline infections. Combined use of PET and CT helps identifying areas with increased metabolic activity with high spatial resolutions. Therefore, knowing the precise localization and extension of an infection source may guide subsequent treatment, whether prolonged anti- microbial therapy, LVAD

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exchange, or heart transplant. It has also shown higher diagnostic accuracy compared to radiolabeled leucocyte scintigraphy single-photon emission computed tomography [86].

Beyond its high diagnostic power, the PET/CT pattern of radiotracer uptake has demonstrated important prognostic value and is relatively unaffected by device related artefact [87]. Inaccurate results may occur during the perioperative period because of the possible uptake of pledgeted surgical suture material in typical locations. Also, attenuation correction used to enhance image quality can produce artifacts surrounding LVAD metallic components, therefore possible uptake should be confirmed in non-attenuated images as well. On the contrary, antibiotic use may lead to underestimation of the FDG uptake in areas of infection. Finally, careful metabolic preparation to drive myocytes metabolism towards fatty acids instead of glucose should be performed prior the examination [88].

5.5 Aortic regurgitation

A competent aortic valve is a pre-requisite for optimal LVAD function. First of all, aortic valve opening prevents aortic root thrombosis and reduces tissue remodeling and cusps fusion which represent the main cause of LVAD-related aortic regurgitation. Aortic regurgitation creates a ‘short-circuit’ in the LVAD-aortic blood flow pathway, and results in a drop in antegrade flow and ineffective unloading of the LV. Current consensus recommends concomitant bioprosthetic aortic valve replacement surgery for moderate or severe aortic regurgitation during LVAD implantation [89]. Assessment of the aortic valve is mandatory pre- and intra-operatively. Thus, severe aortic regurgitation in the early post-operative period is unusual and largely preventable.

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In some cases, aortic regurgitation may develop following aortic valve replacement due to paravalvular leak. The assessment of the severity of paravalvular leaks is especially challenging in patients with LVAD due to the nature of continuous blood flow. Several echocardiographic features of significant aortic paravalvular leak have been described [90], such as short pressure half time, "dense" regurgitation jet on continuous wave Doppler imaging, vena contracta >0.6cm, descending aorta diastolic flow reversal, regurgitant fraction >50% and increased systolic transvalvular gradient despite normally functioning prosthesis. However, many of these parameters are not applicable in the setting of LVAD and may also underestimate the severity as regurgitation may span the cardiac cycle. Dynamic assessment with ramp testing showing the lack of reduction in LV volume with increase in LVAD flow also provides supportive evidence of severe aortic regurgitation. In ramp test, echocardiography is repeatedly performed at incremental pump speed. A typical protocol starts with a pump speed of 8000 rpm, which is then increased by 400 rpm every 2 min.

5.6 Thrombosis

According to MOMENTUM 3 trial five-year results, thrombosis is reported in 10% patient/year with axial-flow pump devices and 1% patient/year with centrifugal-flow pump devices after LVAD implantation [91]. The pump system, the inflow and the outflow cannula may all be involved, as well as the cardiac cavities and the aortic root. Continuous-flow (CF) systems favour patterns of shear stress which activate the thrombogenic cascade, whilst dislocation or kinking of cannulas may also facilitate thrombosis [92]. Clinical suspicion arises with decline of pump performance, increase of pump consumption, and signs of overt haemolysis or ischaemic stroke.

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The first-line imaging modality to assess device thrombosis is echocardiography. Inflow cannula thrombosis can result in cannula obstruction, which is characterized by elevated flow velocities and turbulent flow on colour Doppler [93, 94]. Relevant pump thrombosis should be suspected in the presence of LV dilatation and severe (or worsening) mitral regurgitation, insufficient LV unloading with continuous opening of the aortic valve, and regurgitation through both cannulae with increased systolic-to-diastolic velocity ratio [6].

Laminated thrombi may develop even on the aortic root due to a persistently closed aortic valve, generally involving the non-coronary cusp but sometimes causing massive thrombosis of the whole aortic root with high embolic risk. At this level, TOE may be particularly advantageous, and valvular thrombosis typically appears with thickening and restricted motion of valve leaflets [95]. Maintenance of intermittent valve opening through modification of LVAD speed may be useful in non-pulsatile LVADs to avoid this complication [96], but the valve may not open adequately even with reduction of pump speed in some case. Use of ultrasound enhancing agents (UEAs) can also help interpretation of other important TTE features such as inflow cannula inlet malposition and intracardiac and/or aortic root thrombus [97].

CT can accurately confirm and assess the extension of thrombosis (**Fig.6**). Most devices are not MRI compatible, while CT can allow complete visualization of the inflow and outflow cannulae with the sites of anastomosis [98] (**Table 4**). The thrombi typically appear as low attenuation areas with focal filling defects on contrast-enhanced CT scans [99]. CT has demonstrated a high sensitivity and specificity of 85% and 100% respectively, in detecting cannula thrombi when using surgical findings as reference standard [100]. Moreover, when a pump exchange is being

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considered, CT may not only help confirm which structures are mechanically compromised but can also facilitate planning of surgical device exchange [101].

5.7 Inflow cannula / outflow graft abnormalities

Several complications have been described in relationship to or involving the LVAD inflow cannula, which can lead to adverse outcomes. Proper positioning of the inflow cannula within the apex and in relation to the IVS is crucial to avoid septal shift, and consequently RVF. Importantly, inflow cannula depth and angulation in relation to the long-axis of the LV can change during the course of LVAD support and play a role in reducing intraventricular thrombosis and/or pump thrombosis [102-104].

Likewise, the LVAD outflow graft is a site for several, potentially serious complications including narrowing, kinking, obstruction, infection, and thrombosis. The accumulation of biodebris has been reported within and around the outflow graft in patients with CF-LVAD such as Heart Mate 3. Jain and colleagues recently reported outflow graft narrowing in one-third of Heart Mate 3 recipients. Furthermore, the longer the duration of support the higher the chance for an outflow graft narrowing. Significant outflow graft narrowing (due to biodebris) could be defined as any hypodense material accumulation of at least 3 mm at any point along the outflow graft, either within or distal to the bend relief [105-107]. The Heart Mate 3 pump includes a bend relief structure premade with a radiopaque Gore-Tex (W.L. Gore & Associates) tube surrounding the proximal portion of the outflow graft to prevent graft kinking [108]. This radiopaque material facilitates fluoroscopic and CT assessment of kinking.

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Overall, TTE and TOE using colour and spectral Doppler modes allow for the assessment of blood flow via the inflow cannula and the outflow graft. Chest CT angiography with 3D reconstruction may be of additional use in all LVAD recipients postoperatively to assess inflow cannula position, thrombus formation or obstruction [109] (**Fig. 7**). Likewise, chest CT angiography allows the assessment of outflow graft patency, twist, kinking, and position. In addition, ramp test and machine logfiles analysis is advised in all cases with suspected inflow or outflow graft complications.

Key points (Box 7): Short-term complication assessment of LVAD recipients
Serial echocardiographic evaluation, together with clinical and haemodynamic monitoring, is fundamental to recognize cardiac tamponade. Increasing pericardial effusion with right atrial / RV collapse is the most helpful feature for diagnosis and severity assessment
Echocardiography is the first imaging modality in evaluating early RV failure after LVAD implantation and is advisable to perform it in all patients. Advanced echocardiography (speckle tracking, 3D) may offer additional information about RV early dysfunction and size.
IVS shift, mitral regurgitation and aortic valve opening must be assessed to recognize inadequate or excessive LV unloading
Echocardiography, particularly TOE has shown high sensitivity and specificity to detect LVAD infections. However, CT and PET/CT may be used in doubtful cases for higher diagnostic accuracy, or to assess the extension of device infection.
A ramp test demonstrating a lack of reduction in LV volume with an increase in LVAD

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flow is highly suggestive of severe aortic regurgitation in LVAD patients.
Echocardiography is the first line modality to assess thrombosis and cannula obstruction. TOE may be useful in case of valvular thrombosis. UEAs may help recognizing thrombosis and inflow cannula malposition. CT may be appropriate to confirm and assess the extension of thrombosis or in cases of ongoing clinical uncertainty.
TTE and TOE using colour and spectral Doppler modes, possibly completed with a ramp test, is advisable to assess blood flow via the inflow cannula and the outflow graft. Chest CT angiography with 3D reconstruction may be appropriate in all LVAD recipients postoperatively to assess inflow and outflow cannula malpositioning.

6. Post-implantation: Follow up

Follow-up of LVAD-carriers is expected to be performed by LVAD centres and non-specialized centres in a shared manner, as patients may not have easy access to LVAD centres. Clinical follow-up may be carried out by non-specialized centres while comprehensive evaluations should be routinely performed in LVAD centres. Timing of follow-up vary depending on time from intervention, being more frequent in the first year. Echocardiography plays a major role in follow-up visits, by providing important information regarding hemodynamic status, heart valves functioning, reverse remodelling and guiding treatment optimization (**Table 5**).

6.1.1 Left ventricular unloading

LV unloading with an LVAD results in reduction of LV dimensions and volume compared to pre-implantation measurements. The most used parameter for serial assessment at follow-up is

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the ECG-gated diastolic LV internal diameter measured in the parasternal long axis view. This is because the inflow cannula can obscure the LV apex endocardial border in apical views, reducing the accuracy of LV volume calculation in bi-plane views and resulting in underestimation of the LV volume. The ECG-gated systolic LV internal diameter is also measured in parasternal long axis view and compared to the diastolic diameter. A smaller diastolic than systolic diameter suggests excessive LVAD unloading. However, it can be also the result of severe volume overload of an impaired RV, with consequent displacement of the IVS towards the unloaded LV.

LV unloading results as well in a reduction in mitral regurgitation severity and drop in trans-mitral E wave velocity and estimated left atrial pressure based on E/e' ratio.

Impaired unloading due to LVAD dysfunction will be suggested by an increase in dimensions and volumes of the left ventricle, increase in mitral regurgitation severity and/or in E/e' [6].

6.1.2 Aortic valve opening

Continuous flow through the LVAD into the aorta simultaneously pressurizes the aortic root and reduces LV preload (lowers LV pressure and stroke volume), a combination that reduces the frequency and magnitude of aortic valve opening. This can be observed on two-dimensional transthoracic or transoesophageal imaging and can be recorded on M-mode through the long axis of the aortic valve, to allow high frame rate imaging and consequent accurate and reproducible measurement of leaflet separation and of the duration of opening. Importantly, differences among LVADs devices should be taken into account (**Fig.4**): Jarvik 2000 has an ILS mode during which

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aortic valve opening occurs, while in patients with HeartMate 3, the aortic valve should open each 3-4 beats, in normal conditions. Colour M-mode provides the added value of assessing the existence and duration of actual forward flow through the aortic valve, particularly when only minimal separation of cusps is observed. Increased opening, more regular opening or opening at every cardiac cycle of the aortic valve suggests decrease in LV unloading, recovery of LV contractility and / or reduction in systemic peripheral resistances. Ideally, the LVAD pump speed should be programmed at a level that is high enough to provide adequate unloading and flow, yet low enough to allow some intermittent aortic valve opening. However, when the LV contractility is extremely poor, aortic valve opening may not happen at all at the LVAD speed needed to achieve unloading.

If the aortic valve remains closed in all cardiac cycles, aortic root thrombosis and fusion of the aortic valve cusps can be observed, and it must be excluded at every assessment during follow-up. LVAD speed reduction to facilitate intermittent aortic valve opening should not be attempted in case of suspected thrombosis of the aortic root, to avoid embolization.

LV unloading creates haemodynamic settings favourable for the development of new aortic regurgitation or worsening of pre-existent aortic regurgitation, because of higher pressure in the aortic root and ascending aorta than in the LV outflow tract. This aortic regurgitation can be continuous and not only diastolic resulting in a higher regurgitant volume for a certain regurgitant area, and difficulties in accurate quantification or estimation. New aortic regurgitation is more common in cases of complete lack of aortic valve opening in systole and aortic root thrombosis [6].

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6.3 Myocardial recovery

Significant myocardial recovery with subsequent successful LVAD explantation has excellent outcomes but was possible only in 1.4% in the recent analysis of EUROMACS Registry [110]. In a preliminary multicentre prospective study, aggressive pharmacological and regular monitoring of cardiac function to maximally unload the LV resulted in a high rate (40%) of successful LVAD explantation [111]. For these goals, regular low-speed echocardiograms and invasive right heart haemodynamic measurements were obtained to test the myocardial reserve.

LVAD explantation was deemed achievable if the following echocardiographic and haemodynamic criteria were met:

- Regression of the LV dilatation (LV end-diastolic diameter (LVEDD) <60 mm, LVESD <50 mm) and significant improvement in LV function (LVEF >45%),
- LV end-diastolic pressure or pulmonary capillary wedge pressure ≤15 mmHg,
- Resting cardiac index >2.4 L/min/m^2,
- Maximal exercise oxygen consumption >16 mL/ kg/min (optional criterion).

However, protocols for LVAD weaning are heterogenous with no consensus or standardization [112-114]. A recent review summarized the evidence in the literature and formulated an approach to the assessment of potential myocardial recovery and LVAD explantation [115]. Progressive pump speed up-titration during outpatient follow-up is probably needed for optimal LV unloading, to promote recovery and prevent the LVAD-related RVF [116]. However, right ventricular function does not always improve concomitantly with LV offloading, and the prevalence of AV regurgitation progressively increases during LVAD pump speed up-titration.

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Given the increasing number of patients with LVAD as a destination therapy, and yet with relatively limited survival compared to heart transplantation (median survival of approximately 5 versus 15 years, respectively), further studies are urgently needed to define the optimal pharmacological treatment, mechanical unloading and weaning protocols for patients with LVADs [117].

Key points (Box 8): Short-term follow-up of LVAD recipients for complications
The evaluation of TE LV internal diameter, mitral regurgitation and estimated left atrial pressure based on pulsed-wave and tissue Doppler measures is advisable to assess LV unloading.
The assessment of aortic valve opening and thrombosis is advisable, even though differences among different devices should be taken into account
Serial echocardiographic exams and right heart catheterization are advisable after LVAD implantation to evaluate possible myocardial recovery and criteria for LVAD explantation

7. Long-term complications

7.1 Right ventricular failure

It has long been recognized that a subset of patients fails to thrive after LVAD implantation, and this failure to thrive may be related to late right heart failure [118]. A number of studies have described late right heart failure [119] but uniform diagnostic criteria are lacking. In a recent registry study, right HF was simply defined as documented evidence of manifestations of

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elevated central venous pressure (e.g. peripheral oedema, ascites or abnormal liver biochemistry) and documentation of elevated central venous pressure (e.g. directly measured right atrial pressure or distended inferior vena cava). Based on this registry, right heart failure requiring inotropes or RV assist device at 3 months following LVAD implantation was associated with poorer survival at a year [120]. In practice, right HF is usually diagnosed on the basis of clinical features of congestion, low LVAD flow, suction events, in conjunction with echocardiographic features such as RV and inferior vena cava dilatation and tricuspid regurgitation.

Late right HF may be related to intrinsic RV cardiomyopathy or arrhythmias, excessive LVAD output but even inadequate unloading of the LV should be excluded. Causes of inadequate LVAD unloading include inappropriate LVAD settings, aortic regurgitation or outflow graft obstruction. Echocardiographic assessment during follow-up, including ramp studies should be performed to optimize LVAD function and LV unloading. Finally, the use of combined echocardiographic and haemodynamic ramp studies has been shown to optimize the assessment of LV and RV loading status and LVAD speed settings [121]. CT imaging of the outflow graft may be appropriate in the setting of reduced LVAD flow.

In case of poor acoustic window, recent investigations showed that the use of UEAs provides substantial improvement in the examination of RV dimension, global and regional contraction with the use of UEAs, replacing some measurements from normal to abnormal leading to an improved echocardiographic assessment of the patients [24].

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7.2 Pump thrombosis

Late pump thrombosis (PT) is reported in 2-6% of cases (HeartMate II device) and it is associated with increased risk of stroke and mortality, in addition to prolonged hospital readmissions [122].

PT may occur in the circuit and/or in the pump resulting in increased afterload, low flow and high-power alarms on the controller [116]. If unidentified and untreated with intensified anticoagulation, PT may result in worsening clinical or haemodynamic instability, requiring surgical device exchange or urgent heart transplantation [123].

PT is often associated with changes in device parameters such as increased pump power (≥2 W above the baseline) and decreased pulsatility index (normal values 1-10) accompanied by acute increases in serum lactate-dehydrogenase (≥2-fold above the baseline) and elevated plasma-free haemoglobin (>12 mg/dl) in the absence of other causes of haemolysis [124].

In addition to clinical, haemodynamic and laboratory parameters, echocardiography plays a pivotal role in recognizing PT (**Table 6**), starting from the evaluation of inflow and outflow cannula systolic velocities. Sometimes, LV contraction may attempt to increase to speed blood-flow through the pump, resulting in an increased systolic cannula velocity, although this partially depends on the site of thrombus - inflow cannula velocities may be increased or reduced, while there can even be backflow (in pump stop) [6]. Diastolic velocity, which is generated by the LVAD alone, decreases concomitantly in correlation with the degree of thrombus interference with pump function, suggesting impaired device contribution to flow. The ratio of systolic/diastolic flow velocity is therefore increased [12].

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A too frequent and wide aortic valve opening may indicate a sub-optimal LVAD speed or pump dysfunction [125], although opening of the a reduces the risk of thrombus formation. Spontaneous opening of the aortic valve V is particularly important when the outflow graft is located in the descending aorta (e.g. in Jarvik-2000) as the aortic valve is not washed by the blood flow. Aortic root thrombosis can also occur in patients with CF-LVADs.

Finally, the ramp test may be helpful in aiding in the diagnosis of PT [126].

The presence of pulsatility index (PI) slope in the lower quartile, aortic valve closure at higher speed, LVEDD flat slope, and a dramatically high-power slope are suggestive of device thrombosis.

As a future perspective, a protocol for ramp testing should become widely established and validated. Cardiac CT can also be used to evaluate LVAD thrombosis, which appears as low-attenuating material that creates a focal filling defect. Contrarily, normal CT appearance of the pump can be seen as circumferential, hypoattenuating material with variable thickness around the outflow cannula [69].

7.3 Aortic regurgitation

Late aortic regurgitation may develop in up to the 30% of patients in the first year after LVAD implantation [127], reducing pump efficiency mostly due to inadequate LV unloading and peripheral hypoperfusion. LVAD settings should allow a residual aortic valve opening which can be constant, at every cardiac cycle, or at least intermittent (for example during low intermittent speed in CF-LVAD) [128]. M-mode or B-mode at aortic valve should include the registration of 5-7 cardiac cycles to investigate cusps' excursion. Significant aortic regurgitation can be defined as at least moderate regurgitation [129]. Echocardiographic assessment can be technically

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challenging in apical views so it should rely mostly on the parasternal long axis view. First, aortic regurgitation duration is a key point: a continuous vs diastolic regurgitation (more common in continuous flow LVAD) is usually more severe and consequently correlated with a worse outcome in terms of symptoms, hospitalization, and survival [130]. The aortic jet *vena contracta* width, with a cut off > 6 mm denotes severe regurgitation. AR jet height /LVOT diameter ratio might represent another useful parameter (being > 30% indicative for relevant AR). On the contrary, pressure half time and effective regurgitant orifice area are usually not assessable. Aortic root dimensions and LV end-diastolic and end-systolic diameters must be included in each echocardiographic report. To improve aortic regurgitation quantification in continuous flow LVADs, two recent parameters have been proposed: peak systolic-to-diastolic velocity ratio of the outflow graft (with values of <5.0 indicating at least moderate aortic regurgitation) and diastolic acceleration of the outflow graft (significant aortic regurgitation for acceleration > 49 cm/sec)[131,132]. Aortic regurgitation assessment should be repeated with different LVAD pump speeds, although speed reduction should be avoided in cases of suspected or know aortic root thrombosis in order to prevent cusp opening and possible embolization.

7.4 Mechanical complications (inflow/outflow cannulae malpositioning/kinking, graft twisting, driveline issues)

One of the dreaded complications of LVAD implantation is mechanical obstruction of the device, which may be secondary to pump thrombosis, as discussed in the previous paragraph, or to mechanical obstruction. Obstruction of a cannula is a cause of low device flow and in some

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instances is due to improperly positioned cannula or kinking or twisting of the outflow graft [133].

The inflow cannula should be aligned with the mitral valve opening and should not have any contact with the LV walls. Misalignment can lead to obstruction of the inflow cannula at rest and with activities and can provoke clinical symptoms. Turbulent flow with elevated velocities via continuous-wave Doppler should raise a suspicion of cannula obstruction [134]. The normal filling velocity is between 1 and 2 m/s, depending on the preload and the intrinsic LV function. The outflow graft anastomosis to the ascending aorta can be visualized approximately at the level of the right pulmonary artery [135]. Evidence of high velocities (>2.0 m/s) can be indicative of obstruction of the outflow graft [6]. The angle of insertion of the LVAD outflow graft into the native aorta can influence flow patterns and velocities. Placing the outflow graft at a shallower angle, can improve forward blood flow and reduce turbulence [136]. In a similar way, mal-angulation of the inflow cannula away from the LV apical axis leads to markedly unfavourable haemodynamics within the LV, impairs effective unloading, and thus significantly diminishes the overall benefit of device support [137]. Moreover, this strongly impacts platelet activation and increases risk of thrombosis [138]. The outflow graft may also be subject to external obstruction, in this case early diagnosis is fundamental [139].

Acoustic shadowing on TTE may limit Doppler interrogation of the inflow and outflow cannulae and sometimes TOE is required to obtain valid, reliable velocities; when echocardiography is not sufficient to make the diagnosis, patients may need to undergo CT angiography or ventriculography.

Outflow graft twisting is a rare complication, as demonstrated in the 2-year experience of the MOMENTUM 3 trial [88], and represents a slowly progressive condition, leading to a drop

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of the pump flow without signs of pump thrombosis. When low flows are encountered, and obvious causes excluded, the diagnostic approach should immediately focus on detection of a potential outflow graft obstruction. This should typically include a chest radiography, to look for a change in pump position over time to detect pump migration or re-orientation, and an echocardiogram, to exclude alternate causes of low flow states. Finally, the confirmation of the diagnosis requires use of contrast imaging, best done with CT angiography and conventional angiography [140,141].

Damage to the driveline that interferes with the operation of the pump is a rare, but life-threatening complication. It is often caused by fracture due to accidental mechanical impact but intentional cutting or disconnection of the driveline from the controller has also been described. The most typical clinical findings associated with driveline failure are the red heart alarm and a drop in the pump speed below the auto-speed–low set limit. Radiography showing driveline kinking or fraying in patients with unexplained alterations in LVAD performance, suggests driveline damage and requires surgical management [142,143].

7.5 Infections

Late LVAD infection is an important, challenging and potentially serious complication following LVAD implantation, which is associated with high morbidity and mortality and might require pump exchange. Infection rates in the EUROMACS Registry were higher in the early period (<3 months) compared to the late period (1.44 vs 0.45 events/person-year) [144] While in the INTERMACS Registry, half of LVAD patients developed infection, which was associated with excess mortality. The 2-year unadjusted all-cause mortality of LVAD recipients with infection was 41.0% compared with 25.2% for those without infection [145].

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Nuclear imaging relies on the fact that infection stimulates neutrophils and other inflammatory cells with high metabolic requirements around the site of infection creating "hot spots". These cells are characterized by high level of glucose utilisation and so they also demonstrate avid uptake of the glucose-analoge and radiotracer 18-FDG. The process of immune cell migration takes place early during infection, which make 18-FDG PET/CT a very sensitive tool to early detect infection, although careful differentiation from physiological uptake of 18F-FDG by the myocardium (glucose is a major energy source for myocytes) and careful dietary preparation to minimise this is required. The use of 18F-FDG PET/CT in the assessment of cardiac infection has been recognized in the 2015 infective endocarditis guidelines [146] (**Fig.8**). Several studies have demonstrated that FDG-PET/CT can accurately localize the site and extent of the late LVAD infection across the peripheral driveline and the involvement of the central portion of the pump [147]. Furthermore, it predicts clinical outcomes of patients with LVAD infection better than CT [148]. Tam et al. reported a pooled sensitivity of 92% and specificity of 83% for FDG PET/CT in the diagnosis of LVAD infections.

In cases of a non-diagnostic Echo and PET/CT in patients with suspected LVAD infection (**Fig. 9**), radiolabeled white blood cell scintigraphy (WBC SPECT/CT) can be used to assess LVAD infection. Overall, this technique is less sensitive but more specific than FDG PET/CT to detect LVAD infections. Whilst it involves a much more complicate imaging protocol and local expertise WBC SPECT/CT can also help to differentiate infection from inflammation, particularly in patients with equivocal FDG-PET/CT [149-151].

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Key points (Box 9): Long-term follow-up complication assessment of LVAD recipients
Serial echocardiographic assessment, if possible with a ramp test, is advisable in LVAD recipients to assess LV and RV function and loading over long term follow up. Ultrasound-enhanced agents (UEAs may be used to help assess RV dimensions and function. Cardiac CT should be may be used in case of reduced LVAD flow.
Echocardiography is the first imaging modality to assess pump thrombosis. Systolic and diastolic velocities of inflow cannula should always be assessed. Ramp testing and cardiac CT should be used for their additional diagnostic value.
AR quantification by echocardiography at different pump speeds is advisable in all LVAD recipients. Due to challenging apical views, not all the parameters are available. Vena contracta>6mm and AR jet height/LVOT>30% is usually assessable. In continuous flow LVAD, peak systolic-to-diastolic velocity ratio of the outflow graft and diastolic acceleration of the outflow graft could be used for AR quantification.
TTE may be limited by acoustic shadowing on TTE for the assessment of LVAD mechanical complications (e.g. cannula malpositioning) and sometimes TOE may be required for inflow/outflow cannula interrogation. CT angiography or ventriculography should be applied when TTE/TOE do not offer sufficient information.
Echocardiography is the first imaging modality to assess LVAD infections, however, 18-FDG PET/CT is the most sensitive tool to investigate infection localization and extension and provides prognostic information. In doubtful cases, WBC SPECT CT could be used as more specific.

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8. Conclusions

Survival in patients with advanced heart failure has improved significantly over the last two decades with LVAD therapy. However, patients with LVADs are burdened with troublesome and sometimes life-limiting complications. Multimodality cardiac imaging is fundamental for the pre-operative evaluation of LVAD candidates, the peri-operative evaluation of LVAD recipients and post-operative assessment of short- and long-term complications in patients with long-term LVADs (**Central illustration**). In this EACVI clinical consensus statement the role of each imaging modality in the possible clinical scenarios of LVAD implantation, with advantages and caveats, is explored, highlighting the need for close integration of the different imaging modalities to optimize the management of patients with LVADs.

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Figure Legend

Fig.1: The components of an LVAD (inflow cannula sits within the LV and is not shown here)

Fig.2 Echocardiographic evaluation of right ventricular (RV) function**.** *3D, three dimensional; LV, left ventricle; RVFAC, right ventricular fractional area change; TAPSE, tricuspid annular plane systolic excursion; TDI, tissue Doppler imaging*

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Fig. 3 Aortic valve opening pattern in different types of LVAD which is useful to recognize optimal and pathologic conditions, and relative possible causes of abnormalities. *ILS, intermittent low speed; AVO, aortic valve opening*

Fig.4 Evaluation of interventricular septum (IVS) position in patients with LVADs is fundamental to recognize different hemodynamic abnormalities possibly causing leftwards or rightwards IVS shift.

Fig.5 M-mode echocardiography and color Doppler application for the evaluation of aortic regurgitation in patient with LVADs : this figure shows pan-cardiac cycle aortic regurgitation in a patient with HeartMate 3.

Fig.6 Representative case : *75-year-old male with end-stage ischemic cardiomyopathy who underwent placement of a LVAD (Jarvik 2000; A). He was admitted to hospital because of repeated Jarvik alarms. Computed tomography angiography (CTA) of the chest showed an eccentric thrombus causing a severe stenosis at the distal portion of the outflow cannula (B: curved reconstruction; C: axial view; D: navigator view), subsequently treated by placement of Optimed Sinus-XL 6F 16x120 mm stent (E-F).*

Fig.7 Possible complications of outflow graft detected by cardiac computed tomography.

Fig. 8 example of FDG-PET/CT scan from a patient with LVAD infection. *Modified with permission from. Akin et al. 2018. Panel A: Case AI: 18F-FDG PET/CT images of a high FDG ring around the inflow cannula of the LVAD. Banded ring with high degree of accumulation in the connection part of the inflow cannula with the housing. Panel B: Case AI: Picture of the debris we found in the connection between inflow cannula and pump housing (hands of Dr. A.P.W.M. Maat). 18F-FDG PET/CT, 18F-fluorodeoxyglucose positron emission tomography/ computed tomography; LVAD, left ventricular assist devices.*

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Fig. 9 Diagnostic flow chart of a patient with suspected LVAD infection. Modified with permission from Dilsizian et al.[176] J Am Coll Cardiol Img 2022;15:891–911. FDG-PET/CT, fluorodeoxyglucose positron emission tomography/computed tomography; TEE, transesophageal echocardiography; TTE, transthoracic echocardiography; WBC, white blood cell count

Central illustration. Use of multimodality imaging for pre-operative, peri-operative and post-operative evaluation of patients with left ventricular assist devices. AR, aortic regurgitation; AV, aortic valve; CT, computed tomography; CMR, cardiac magnetic resonance; LV, left ventricular; LVAD, left ventricular assist device; PET, positron emission tomography; PFO, patent foramen ovale; RV, right ventricular; TOE, transoesophageal echocardiography; TR, tricuspid regurgitation; TTE, transthoracic echocardiography

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Table 1: Pre-implantation TTE checklist

Heart structure	**Parameters**
Left ventricle	LV dimensions (LV EDD, LV EDS, LV EDV, LV ESV -3D preferred-) LV systolic function (LV EF -3D preferred-, LV GLS) LV diastolic function (E/A, e’ septal, e’ lateral, E/E’, LAVI, LA strain)
Left atrium	LA dimensions (LA area and volume index) LA function (LA strain)
Heart valves (better by TOE)	Mitral annulus dimensions, leaflets and papillary muscles geometry, and mitral regurgitation degree Aortic valve morphology and regurgitation degree Tricuspid annulus dimensions and regurgitation degree Prosthesis position and function, paravalvular regurgitation
Right ventricle	RV dimensions (RV basal, longitudinal and medium diameter, RV volumes by 3D) RV function (TAPSE, TDI s’, RVFAC, RVSI, RV free-wall strain)
Pulmonary pressure	sPAP
Other	Intracardiac thrombi Intracardiac shunts Size of ascending aorta

EDD, end-diastolic diameter, ESD, end-systolic diameter; EDV, end-diastolic volume, ESV, end-systolic volume; E’, mitral annular velocity by tissue Doppler imaging; E/A, early diastolic wave / late diastolic wave ratio by pulsed-wave Doppler; LA, left atrium; LAVI, left atrial volume index; LV, left ventricle; sPAP, systolic pulmonary artery pressure; RV, right ventricle; RVFAC, right ventricular fractional area

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change; RVSI, right ventricular sphericity index; TAPSE, tricuspid annular plane systolic excursion; TDI s', systolic wave velocity by tissue Doppler imaging

Table 2: Pre-implantation TOE checklist

Heart structure	**Parameters**
Heart Valves	Mitral valve morphology and regurgitation and/or stenosis degree Aortic valve morphology and regurgitation degree Tricuspid annulus dimensions and regurgitation degree Pulmonary regurgitation
Prosthetic Valves	Prosthesis position and function, paravalvular leak
Intracardiac Shunts	Exclusion of ventricular septal defects, atrial septal defects, partial anomalous vein drainage and patent foramen ovale
Left Atrial Appendage Thrombus	For patients with atrial fibrillation
LV Apical Thrombus and Aneurysm (better by TTE)	Suboptimal visualization of LV walls

LV, left ventricle; TTE, transthoracic echocardiography

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Table 3: Role of different imaging modalities in the pre-operative assessment for LVAD

	Echo	CT	CMR
LV function	++	+	+++
LV filling pressures	+++	+	+++
RV function	++	+	+++
Thoracic anatomy	++	+++	++
Vascular anatomy	+	+++	++
Valves	+++	+	++
Shunt	++	+	+++
Ischaemia	+	+	+++
Scar	+	+	+++
Thrombus	++	+++	+++
Fibrosis	+	++	+++
Oedema	+	+	+++

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Table 4: LVAD related complications assessment by Echocardiography / computed tomography (CT) / Cardiac magnetic resonance (CMR)

	Echo	CT	CMR
Thrombosis	**Signs of cannula and pump dysfunction, laminated thrombi on the aortic root, intracardiac thrombi**	**Hypoattenuation areas on contrast-enhanced CT at delayed imaging (60-90 s)**	**Most devices are not CMR compatible**
Infections	**Vegetations on device and cannula surfaces, abscess, destructive valve lesions**	**Rim-enhancing fluid collections with gas locules and soft-tissue components on contrast CT**	**Most devices are not CMR compatible**
Aortic regurgitation	**Use of colour Doppler Measurements of quali-quantitative parameters Left ventricular enlargement**	**Classification of regurgitation type Quantification of aortic regurgitant orifice Exclusion of aortic dissection**	
Inflow/outflow graft abnormalities	Inflow cannula: turbulent flow with elevated velocities via continuous-wave Doppler should raise a suspicion of cannula obstruction. The normal filling velocity is between 1 and 2 m/s, depending on the preload		

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	and the intrinsic LV function. The outflow graft: anastomosis to the ascending aorta can be visualized approximately at the level of the right pulmonary artery. Evidence of high velocities (>2.0 m/s) can be indicative of obstruction of the outflow graft.		
Cardiac tamponade	Right heart chambers collapse IVC dilatation and abnormal hepatic venous flow		
Right ventricular failure	**2D echocardiographic assessment of RV size, function and interventricular septum position** **fwRVLS is most accurate in assessing RV function before and after LVAD implantation**		

2D, two-dimensional; fwRVLS, free-wall right ventricular longitudinal strain IVC, inferior vena cava; LV, left ventricle; LVAD, left ventricular assist device; RV, right ventricle

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Table 5: Follow-up TTE checklist

Heart structure	**Parameters**
Left ventricle	LV dimensions (LV EDD, LV EDS) LV systolic function (LV EF, LV GLS) LV diastolic function (E/A, e' septal, e' lateral, E/E', LAVI, LA strain)
Left atrium	LA dimensions (LA area and volume index) LA function (LA strain)
Heart valves	Mitral annulus dimensions, leaflets and papillary muscles geometry, and mitral regurgitation degree Aortic valve morphology, cusps' fusion, valve opening and regurgitation degree Tricuspid annulus dimensions and regurgitation degree Prosthesis position and function, paravalvular regurgitation
Right ventricle	RV dimensions (RV basal, longitudinal and medium diameter) RV function (TAPSE, TDI s', RVFAC, RVSI, RV free-wall strain)
Pulmonary pressure	sPAP
Other	Interventricular septum position Distance from inflow cannula and interventricular septum Aortic root thrombosis Pulsed-Doppler interrogation of inflow cannula and outflow graft

EDD, end-diastolic diameter, ESD, end-systolic diameter; E', mitral annular velocity by tissue Doppler imaging; E/A, early diastolic wave / late diastolic wave ratio by pulsed-wave Doppler; LA, left atrium; LAVI, left atrial volume index; LV, left ventricle; sPAP, systolic pulmonary artery pressure; RV, right ventricle; RVFAC, right ventricular fractional area change; RVSI, right ventricular sphericity index; TAPSE, tricuspid annular plane systolic excursion; TDI s', systolic wave velocity by tissue Doppler imaging

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Table 6. LVAD alarms troubleshooting by echocardiography

Reduced LVAD flow	
Echocardiographic finding	**Diagnosis**
RV dilatation **Reduced TAPSE and tissue Doppler velocity** **Atrial/ventricular septal shift to left** **Increase and triangular early peaking tricuspid regurgitation jet** **IVC dilatation and reduced/ reversed hepatic venous flow pattern**	**Right heart failure**
Pericardial effusion **Right heart chamber collapse** **IVC dilatation and abnormal hepatic venous flow**	**Tamponade**
Reduced LV size **No features of right heart failure**	**Hypovolemia** **Arrhythmia**
Inadequate LV unloading: • **Elevated filling pressure** • **Increased LV size** • **Recurrence of mitral regurgitation** **Increased LV ejection*** **Increased outflow graft flow velocity and turbulence**	**Inflow/ outflow graft obstruction**

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Inadequate LV unloading: • **Elevated filling pressure** • **Increased LV size** • **Recurrence of mitral regurgitation** **Increased LV ejection***	**Hypertension** **Inappropriately low pump speed**
Normal or increased LVAD flow	
Echocardiographic finding	**Diagnosis**
Aortic regurgitation **Increased LV size** **Recurrence of MR** **Elevated filling pressure**	**Aortic regurgitation**
Increased LVAD flow **Reduced pulsatility in flow (outflow graft Doppler)** **No change or reduced LV size**	**Vasodilatation** **(Eg: sepsis, vasodilators)**

*Increase in LV ejection dependent on LV contractile function and pump setting. *MR, mitral regurgitation ; LV, left ventricle; LVAD, left ventricular assist device; TAPSE, tricuspid annular plane systolic excursion*

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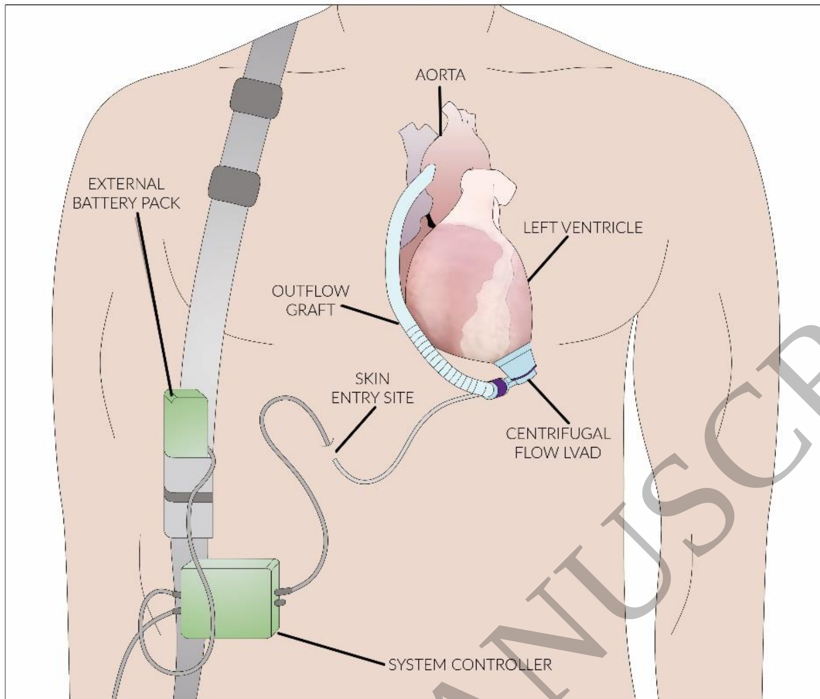

Figure 1
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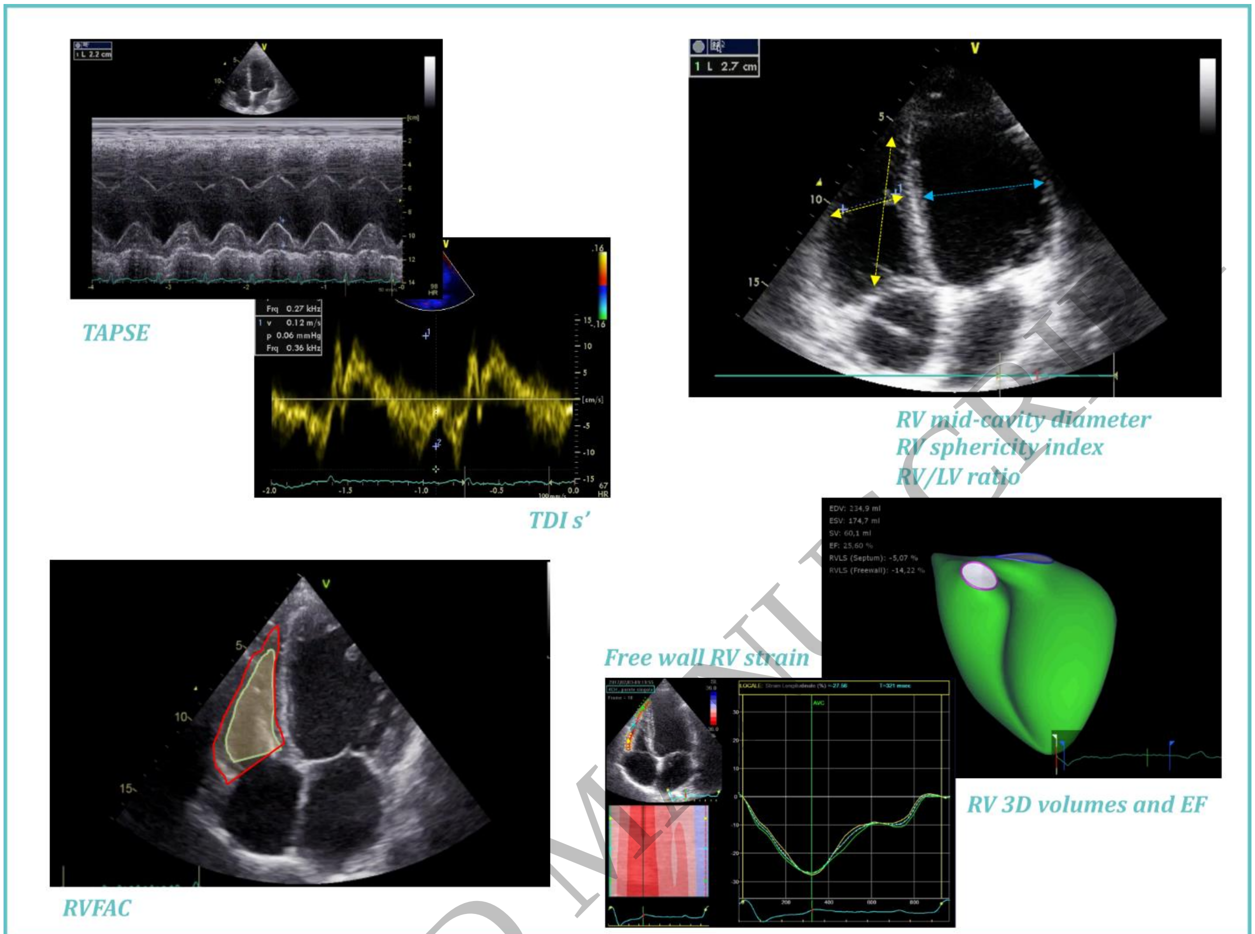

Figure 2
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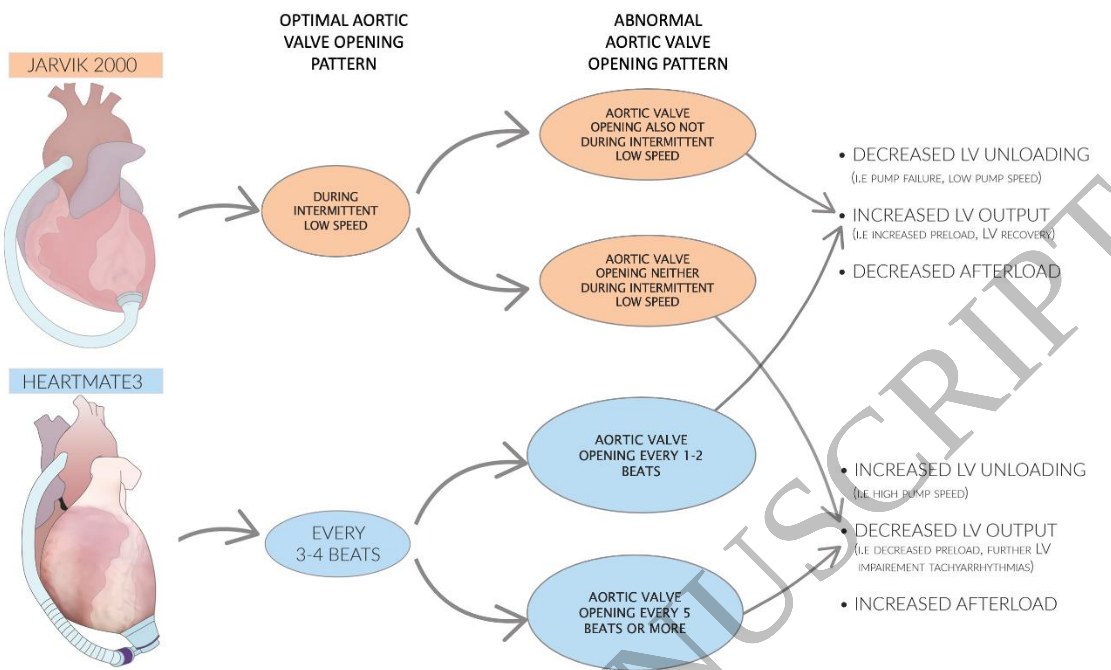

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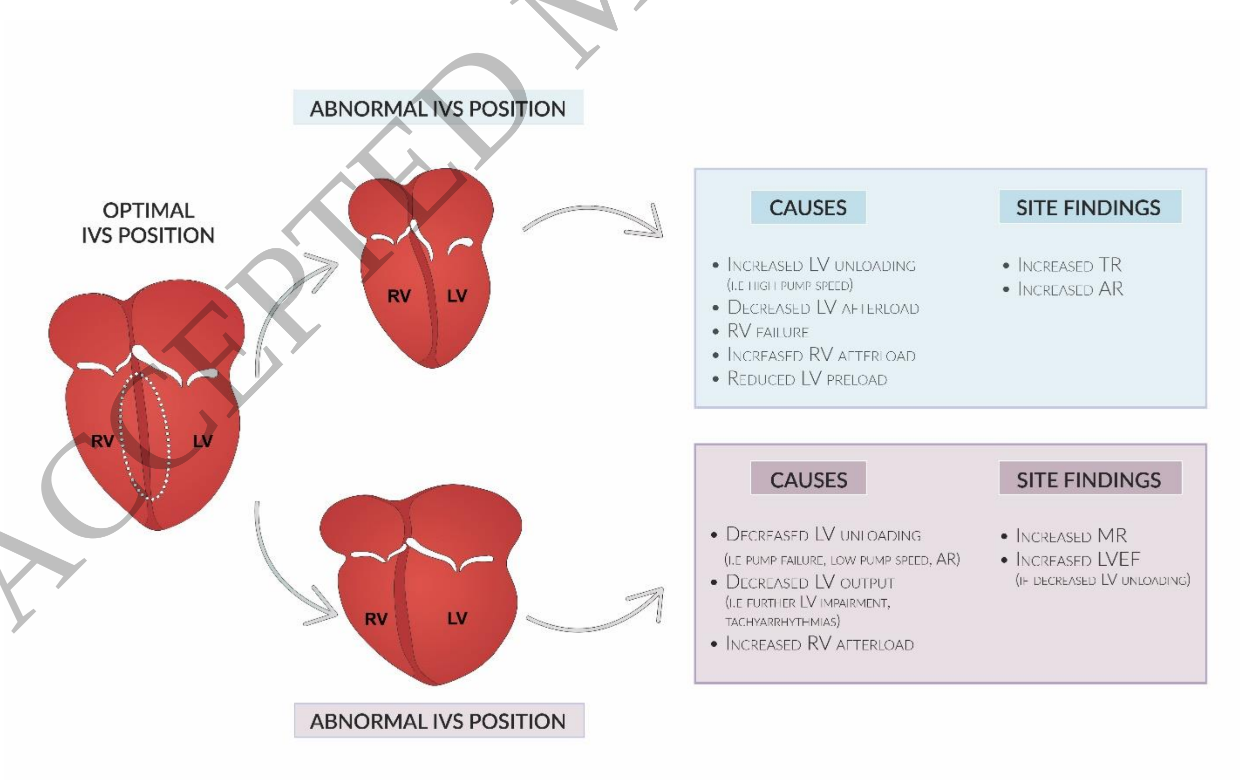

Figure 4
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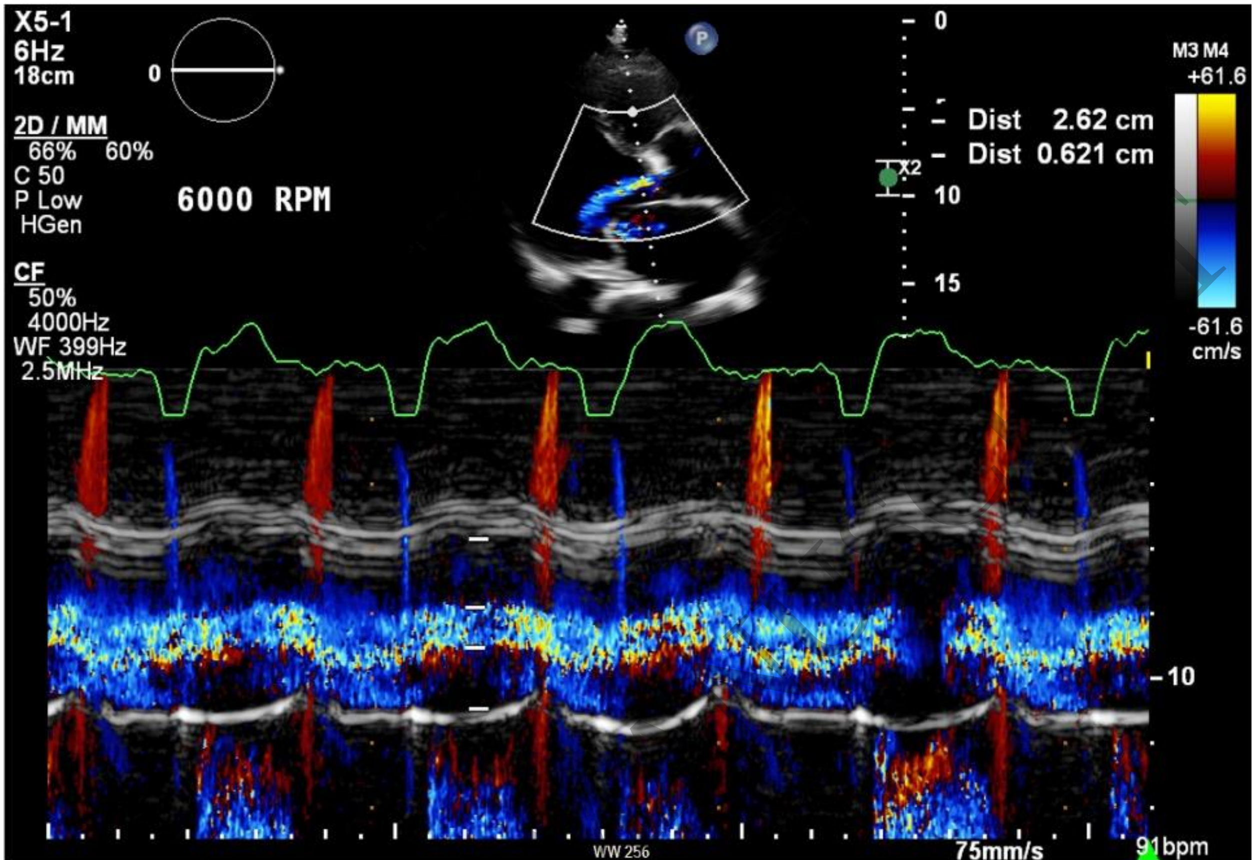

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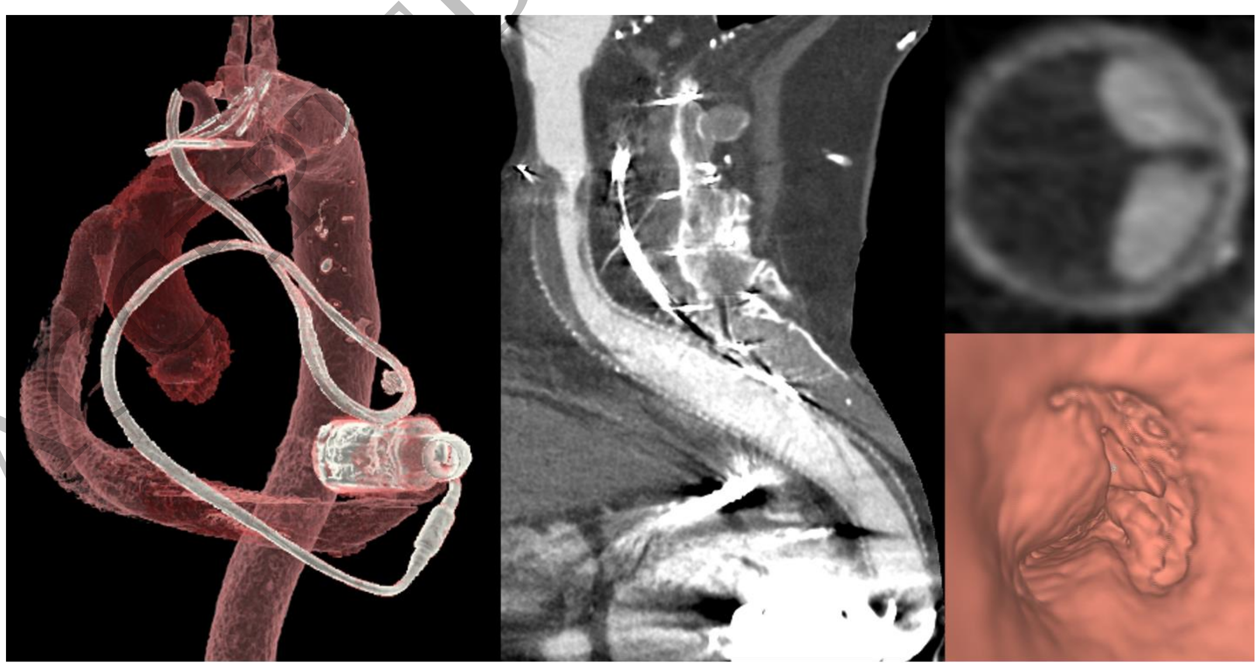

Figure 6
338x176 mm (DPI)

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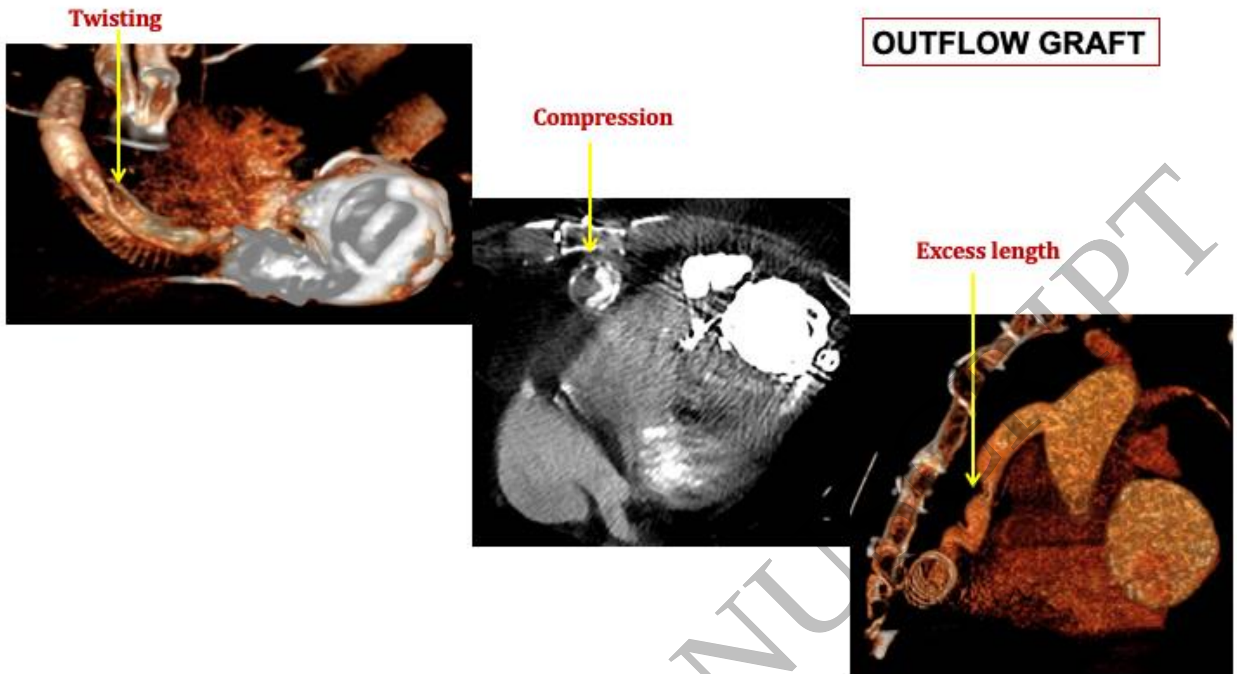

Figure 7
339x190 mm (DPI)

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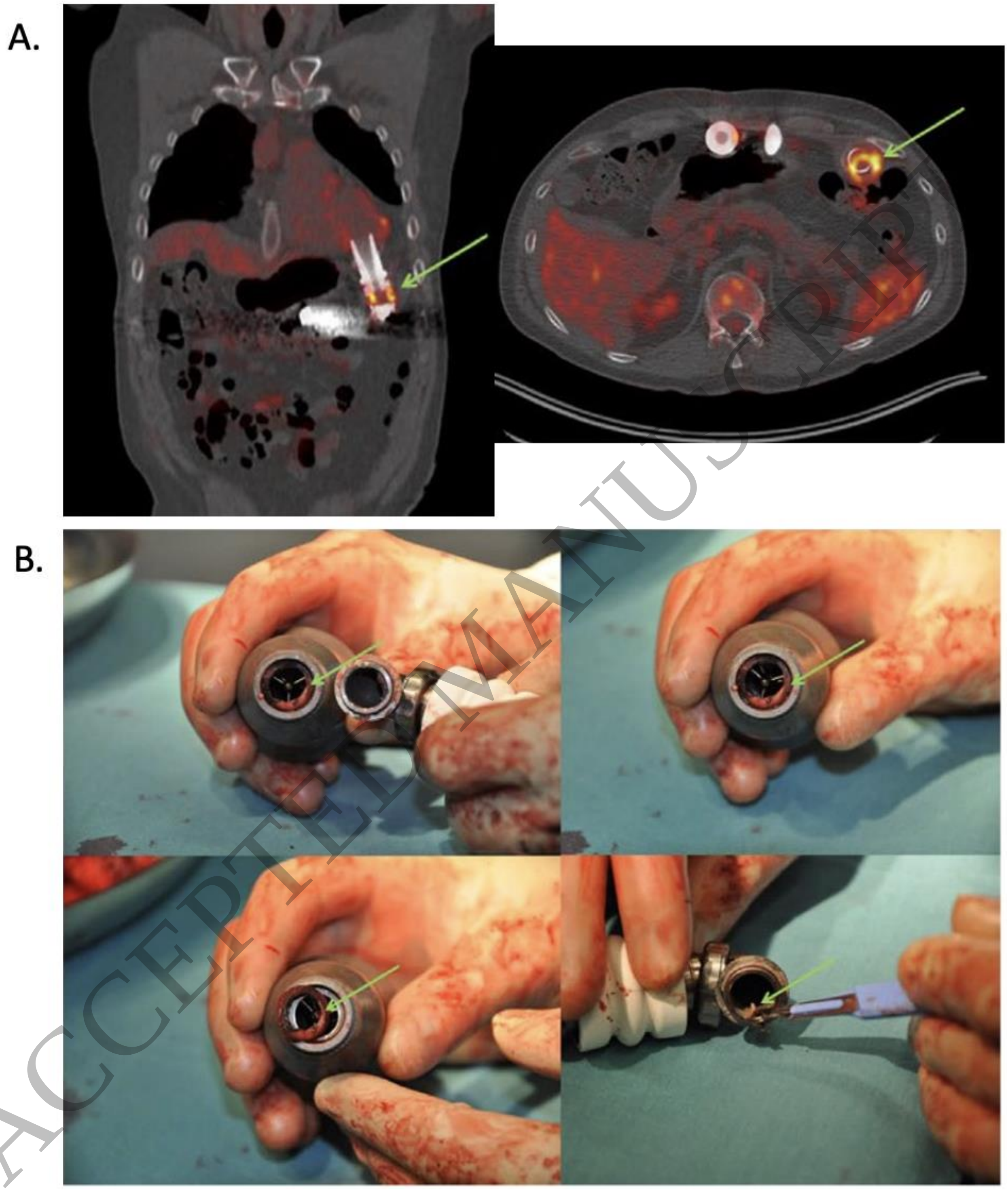

Figure 8
168x199 mm (DPI)

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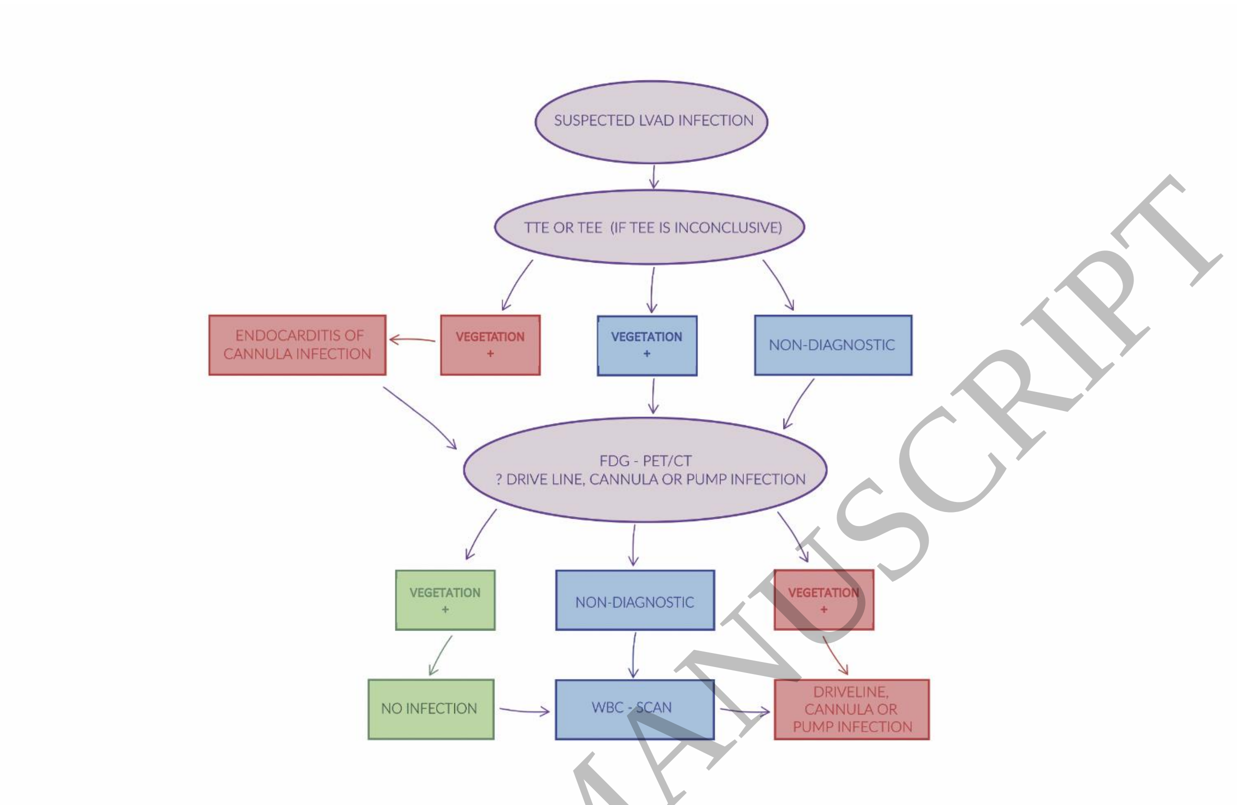

Figure 9

268x175 mm (DPI)

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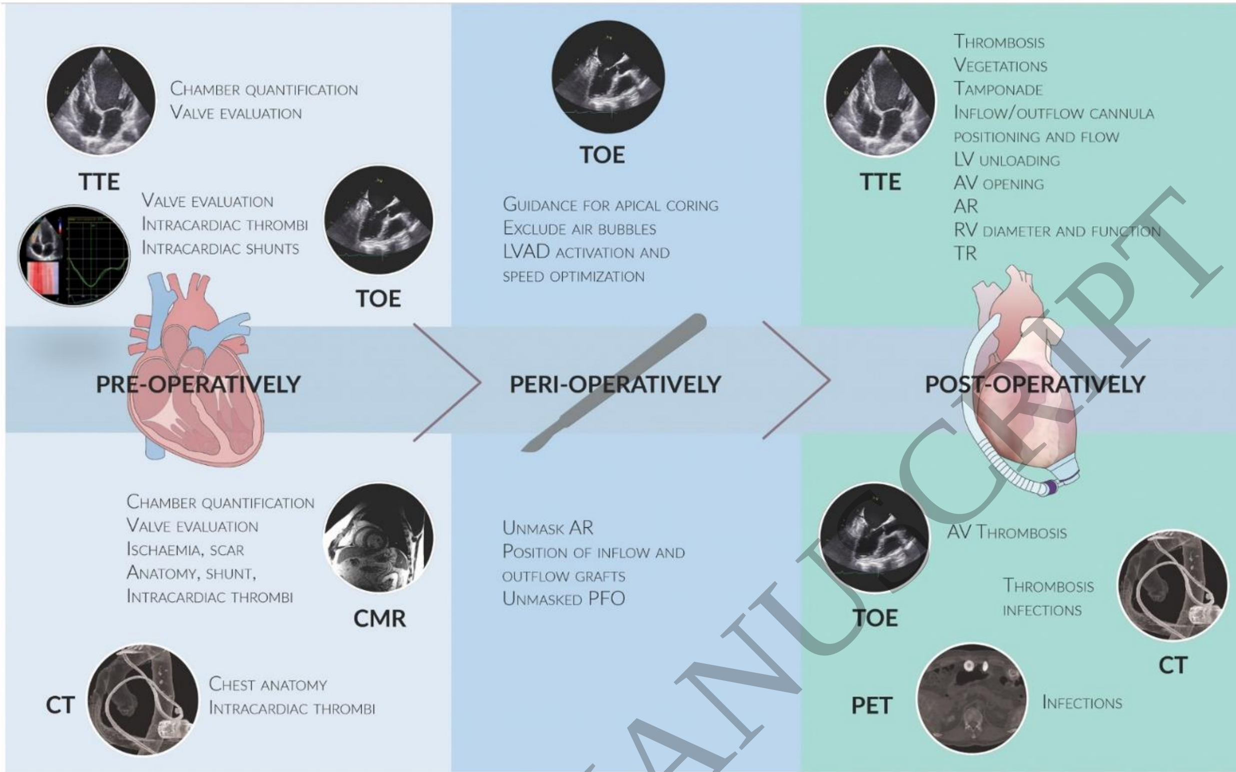

1

2 *Graphical Abstract*
3 *308x190 mm (DPI)*

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