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POSITION PAPER

Multimodality imaging in advanced heart failure. A clinical consensus statement of the Heart Failure Association of the ESC. Part 1: Multimodality imaging for the evaluation of patients with advanced heart failure

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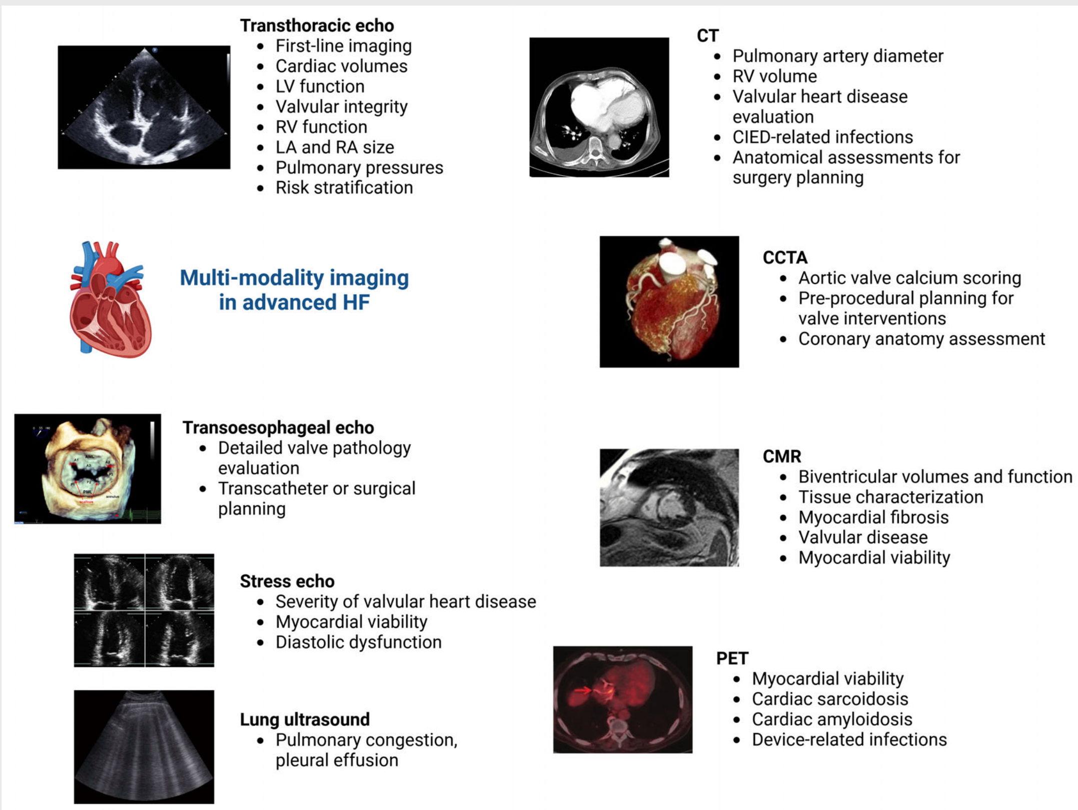
Heart failure (HF) represents a significant global health burden, with approximately 10% of patients progressing to advanced stages characterized by severe symptoms and recurrent hospitalizations despite conventional treatments such as guideline-directed medical therapy, devices, and surgery. This clinical consensus statement from the Heart Failure Association of the European Society of Cardiology discusses the applications of imaging modalities in patients with advanced HF. Transthoracic echocardiography remains the cornerstone for initial diagnosis and monitoring, providing critical insights into cardiac volumes, function, and valvular integrity, as well as congestion status. Transoesophageal echocardiography offers detailed evaluations of valve pathology, essential for surgical or transcatheter planning. Cardiovascular magnetic resonance provides comprehensive assessments of biventricular size and function, tissue characterization, and flow dynamics, proving particularly useful for diagnosing specific HF aetiologies. Computed tomography offers valuable insights into pulmonary artery diameter, right ventricular volume, and valvular anatomy, which are crucial for guiding percutaneous procedures. Nuclear imaging techniques allow assessing viability and diagnosing non-ischaemic HF conditions, guiding revascularization decisions. Advanced imaging techniques have expanded the understanding and management of right ventricular dysfunction. The integration of these advanced imaging modalities enhances diagnostic accuracy, risk stratification, and therapeutic decision-making, ultimately improving the prognosis and quality of life for patients with advanced HF. This clinical consensus statement highlights the critical role of various imaging modalities in managing patients with advanced HF, excluding those needing mechanical circulatory support or heart transplantation, emphasizing the multifaceted approach required for effective management.

Graphical Abstract



Role of different imaging modalities in advanced heart failure (HF). CCTA, coronary computed tomography angiography; CIED, cardiac implantable electronic device; CMR, cardiovascular magnetic resonance; CT, computed tomography; LA, left atrial; LV, left ventricular; PET, positron emission tomography; RA, right atrial; RV, right ventricular.

Keywords Advanced heart failure • Imaging • Echocardiography • Cardiovascular magnetic resonance • Computed tomography • Nuclear imaging • Diagnosis • Risk prediction • Management

Introduction

Heart failure (HF) is a cardiovascular disease with a significant global burden. Approximately 10% of HF patients progress to the advanced stage, characterized by severe symptoms and recurrent hospitalizations despite conventional treatments such as guideline-directed medical therapy (GDMT), devices, and surgery.[1] This clinical consensus statement from the Heart Failure Association of the European Society of Cardiology discusses the applications of imaging modalities in advanced HF. The statement is structured into a first document providing an overview of different imaging modalities, including specific scenarios, and a second document discussing mechanical circulatory support (MCS) and heart transplantation (HT).

Imaging modalities for diagnosis and risk prediction

Transthoracic echocardiography

Cardiac dysfunction requiring advanced therapeutic strategies is a critical aspect in the definition of advanced HF. In recent years, various techniques have been developed to accurately assess the aetiology and severity of myocardial dysfunction. Echocardiography has emerged as the cornerstone technique due to its flexibility, low cost, and easy access. It is essential for estimating disease severity, stratifying risk, guiding clinical decisions, and determining the best therapeutic strategies.[2] Some of the main parameters from standard and speckle-tracking echocardiography, with the possible findings in patients with advanced HF, are reported in *Figure 1*.

The assessment of left ventricular (LV) function is fundamental, as LV functional impairment is central to the pathophysiology of advanced HF. Various parameters, such as ejection fraction (EF), stroke volume, and cardiac output, can be used to evaluate LV function. Pulsed-wave Doppler is typically employed to measure stroke volume and cardiac output at the aortic annulus. LVEF is a widely used index of systolic cardiac function, crucial for diagnosis, classification, and risk stratification. It is also crucial for guiding management, including medical therapy and interventions like valvular surgery and defibrillator implantation. Nonetheless, LVEF has several limitations: it is influenced by loading conditions, operator expertise, and image quality[3]; it underestimates HF severity in cases of moderate or severe mitral regurgitation (MR),[4] does not correlate well with functional capacity, and LVEF as sole parameter does not allow the diagnosis of HF with preserved EF (HFpEF),[5] which constitutes nearly half of HF cases and can progress to advanced stages.[1] Speckle-tracking echocardiography (STE) is a non-invasive, semi-automated technique that tracks the displacement of 'speckles' in echocardiographic images, offering parameters such as global longitudinal strain (GLS). GLS is a robust marker for myocardial mechanics and early LV dysfunction, reflecting the gradual development of LV impairment and serving as an early diagnostic and prognostic marker in HF.[6]

Impaired diastolic relaxation may result from intrinsic myocardial damage leading to reduced LV compliance. Several echocardiographic parameters may be used to give an estimate of intracardiac pressures. The E/e′ ratio, derived from tissue Doppler imaging, is particularly useful in assessing LV end-diastolic pressure and predicting HF prognosis.[7]

Echocardiography also evaluates LV geometry, as progressive myocardial damage in HF leads to LV dilatation, a sign of advanced disease. LV geometry assessment includes measuring volumes, diameters, and the sphericity index. Three-dimensional (3D) echocardiography offers more accurate and reliable measurements, providing a focused view with superior spatial and temporal resolution.[8]

Right ventricular (RV) function assessment is equally important, especially as RV dysfunction often accompanies advanced HF, and is a strong predictor of outcome.[9] Several conventional and non-conventional parameters of RV function have been evaluated in clinical trials and found to have prognostic implications for patients with HF (*Table 1*).[3,10–16]

Tricuspid annular plane systolic excursion (TAPSE) is a simple and reproducible parameter exploring the longitudinal systolic motion of the right ventricle at the level of the lateral tricuspid annulus. In patients with dilated cardiomyopathy (DCM), a TAPSE <14 mm independently predicts the need for urgent HT, and a TAPSE <15 mm is a predictor of major cardiac events at 1 and 2 years.[12] A systolic velocity (RVS′) of the lateral tricuspid annulus <9.5 cm/s indicates RV systolic dysfunction. In patients with DCM, RVS′ has prognostic value beyond other echocardiographic parameters.[13] RV fractional area change (FAC) is calculated from the RV end-diastolic and end-systolic areas in a 4-chamber view. A FAC <27% was independently associated with death or need for HT.[14] STE measures deformational parameters of the right ventricle, such as RV free wall longitudinal strain (RVFWLS). An RVFWLS >−20% indicates dysfunction, with values >−16% having prognostic implications for patients with HF and reduced EF (HFrEF).[15] RVFWLS may provide more prognostic information than RV GLS, which includes the interventricular septum.[16] Impaired RVFWLS in

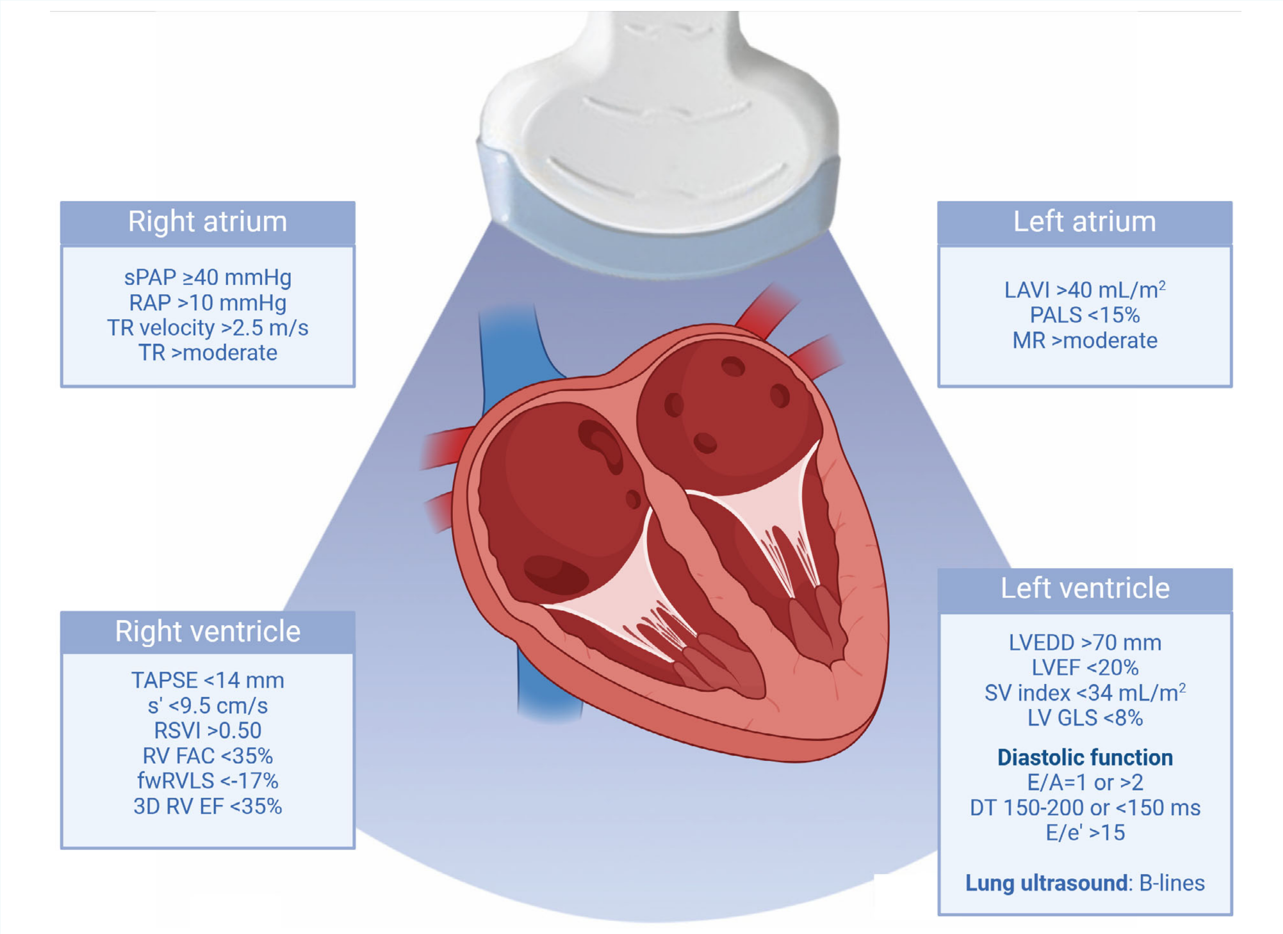


Figure 1 Possible echocardiographic findings in patients with advanced heart failure. 3D RV EF, three-dimensional right ventricular ejection fraction; DT, deceleration time; E/A, peak early diastolic E wave velocity to peak late diastolic A wave velocity ratio; E/e′, early diastolic mitral inflow velocity (E wave) to early diastolic mitral annular velocity (e’) ratio; fwRVLS, free wall right ventricular longitudinal strain; LAVI, left atrial volume index; LVEDD, left ventricular end-diastolic diameter; LVEF, left ventricular ejection fraction; LV GLS, left ventricular global longitudinal strain; MR, mitral regurgitation; PALS, peak atrial longitudinal strain; RAP, right atrial pressure; RV FAC, right ventricular fractional area change; RVSI, right ventricular sphericity index; s’, peak systolic tricuspid annular velocity; sPAP, systolic pulmonary artery pressure; SV, stroke volume; TAPSE, tricuspid annular plane systolic excursion; TR, tricuspid regurgitation. Modified with permission from Pastore *et al.*[2]

patients with preserved TAPSE values indicates a worse outcome.[17] 3D echocardiography correlates well with cardiovascular magnetic resonance (CMR)-based RV volumes and EF measurement, although it tends to underestimate volumes. In DCM patients, a 3D RVEF <43% was independently associated with outcomes.[17]

None of these RV function parameters reflect RV contractility. As afterload increases, RV contractility initially increases to compensate but eventually deteriorates, leading to a decline in RV function. All of these parameters are pre- and afterload sensitive, making their interpretation challenging, especially when RV function is borderline.

Non-invasive measurements of RV to pulmonary artery coupling provide incremental prognostic value by focusing not only on RV function but also on its adaptation to pulmonary circulation. A decreased TAPSE and pulmonary artery systolic pressure (PASP) ratio is a potent independent predictor of pre-capillary pulmonary hypertension and prognosis in HF, with a prognostic cut-off value of 0.36 mm/mmHg.[18] RV strain indexed to estimated PASP has been shown to be a stronger predictor than the TAPSE/PASP ratio. The 3D RVEF/PASP ratio also demonstrated a prognostic value at least equal to the TAPSE/PASP ratio.[16,19] Finally, serial evaluation of RV function is also crucial in patients undergoing MCS implantation, as discussed in Part 2 of this clinical consensus statement.[20]

The right atrium and left atrium also play crucial roles in the assessment of patients with advanced HF. Right atrial (RA) pressure and the presence of pulmonary hypertension can be evaluated using echocardiography. Left atrial (LA) size and function are assessed through LA volume index (LAVI) and strain measurements, providing insights into LA remodelling and its impact on LV filling pressures.[2]

Contrast echocardiography may be helpful to rule out or identify intracardiac masses, particularly thrombi in advanced HF.

Table 1 Parameters to assess right ventricular function and prognostic implications

Parameter	Strengths	Weaknesses	Cut-off for RV dysfunction[3,10,11]	Prognostic role
TAPSE	• Easy to obtain • Widely available	• Angle-dependent • Only assesses longitudinal function • Less reliable in the presence of severe tricuspid regurgitation	≤17 mm	TAPSE <14 mm predictive of death and heart transplantation in patients with LVEF <35% ($n = 140$)[12]
RV S′ wave velocity	• Easy to obtain • Widely available	• Angle-dependent • Only assesses longitudinal function • Less reliable in the presence of severe tricuspid regurgitation	< 9.5 cm/s	RV S′ <9.7 cm/s predictive of cardiovascular death in patients with LVEF <45%[13]
RV FAC	• Easy to obtain • Widely available • Provides a global assessment of RV function	• Poor reproducibility that depends on image quality • Limited by RV shape assumptions	<35%	RV FAC <27% predictive of death or LVAD implantation in patients with LVEF <35% ($n = 68$)[14]
RVFWLS	• Less angle-dependent • Evaluates the whole free RV wall	• Requires dedicated software • Requires adequate imaging quality	>−20%	143 patients with DCM and LVEF <45%. RVFWLS <−16.5% predictive of death and HF hospitalization[15]
RV GLS	• Less angle-dependent • Provides a global measure of RV function	• Requires dedicated software • Requires adequate imaging quality	>−17%	RV GLS >−12.5% was predictive of cardiac death, non-fatal cardiac arrest and HF hospitalization in patients with non-ischaemic DCM and LVEF <40% ($n = 50$)[16]
3D RVEF	• Provides comprehensive RV function assessment • More accurate volume measurements compared to 2D echo	• Requires adequate quality imaging	<45%	RVEF <43.3% predictive of cardiac death, non-fatal cardiac arrest and HF hospitalization in patients with non-ischaemic DCM and LVEF <40% ($n = 50$)[16]

2D, two-dimensional; 3D, three-dimensional; DCM, dilated cardiomyopathy; FAC, fractional area change; HF, heart failure; LVAD, left ventricular assist device; LVEF, left ventricular ejection fraction; RV, right ventricular; RVEF, right ventricular ejection fraction; RVFWLS, right ventricular free wall longitudinal strain; RV GLS, right ventricular global longitudinal strain; TAPSE, tricuspid annular plane systolic excursion.

Finally, echocardiography is crucial to select patients for advanced HF therapies, such as MCS or HT, as discussed in Part 2 of this clinical consensus statement.[20]

Transoesophageal echocardiography

Transoesophageal echocardiography (TOE) is often performed as part of the workup of patients with mitral or tricuspid valve disease evaluated for possible surgery or percutaneous interventions.[21,22] It allows exploring the entire valve and its apparatus in multiple views. Both two-dimensional (2D) and 3D TOE offer detailed insights into the mechanisms and aetiologies of mitral and tricuspid valve diseases. TOE can predict the likelihood of successful transcatheter or surgical valve repair or the necessity for valve replacement. It also enables a more detailed quantification of the severity of regurgitation. TOE is also valuable in the evaluation of mitral stenosis by enabling direct planimetry of the valve area.[21–23]

Stress echocardiography

Exercise echocardiography can be used to ascertain the severity of valvular heart disease in patients who have discordant echoardiographic features.[21] Low-dose dobutamine stress echocardiography (DSE) is particularly important for individuals with aortic stenosis (AS) and LV dysfunction, where the calculated aortic valve area (AVA) may be less than 1 cm^2 (indicative of severe AS), but the transvalvular gradient is low. DSE can differentiate true AS (low-flow, low-gradient [LFLG] AS) from pseudo-severe AS. Besides measuring transvalvular gradient and AVA at rest and during low-dose dobutamine, DSE also assesses contractile reserve, which can help predict the response to treatment.[21]

Stress echocardiography is also valuable in ischaemic HF for determining the presence of myocardial viability and ischaemia. Both exercise and pharmacological stress (e.g. dobutamine or vasodilator) can be used. This technique assesses myocardial regional wall motion and thickening, identifying areas of hypokinesis or akinesis. A fixed wall motion abnormality at rest and during stress indicates infarcted myocardium. Low-dose dobutamine imaging can identify stunned or hibernating (i.e. viable) myocardium that may improve with revascularization.[24]

Heart failure with preserved EF is characterized by exercise intolerance, and some physiological abnormalities, such as diastolic dysfunction, may become apparent only during exercise. The HFA-PEFF diagnostic algorithm includes a diastolic stress test, such as exercise echocardiography, in cases where the HFA-PEFF score indicates an intermediate probability of HFpEF. Diagnostic criteria include an average E/e′ ≥15 and/or tricuspid regurgitation (TR) velocity >3.4 m/s, which are consistent with HFpEF.[5] Stress echocardiography may also be combined with cardiopulmonary exercise testing, which is referred to as cardiopulmonary exercise

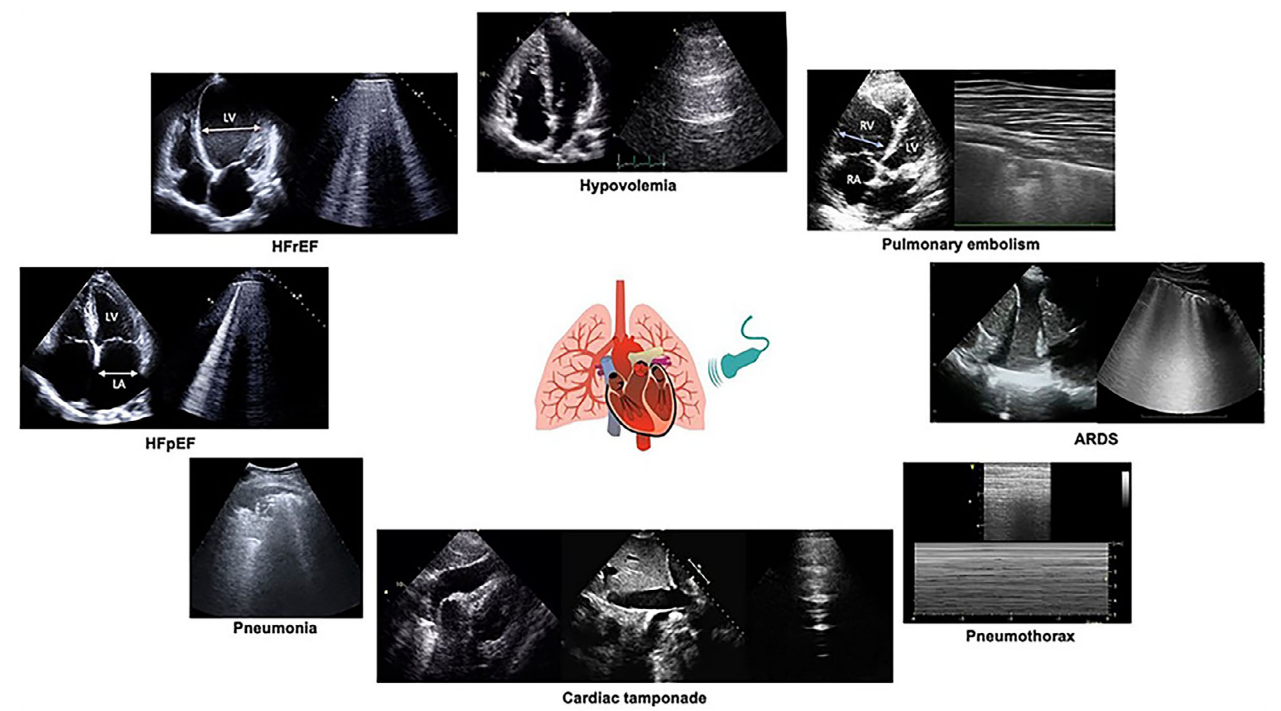


Figure 2 Integrated cardiopulmonary ultrasound for the differential diagnosis of respiratory and circulatory failure. ARDS, acute respiratory distress syndrome; HFpEF, heart failure with preserved ejection fraction; HFrEF, heart failure with reduced ejection fraction. Reprinted with permission from Gargani *et al.*[26]

testing echocardiography, and may be useful to diagnose HFpEF. For example, a steeper mean pulmonary artery pressure/cardiac output slope may be a sensitive parameter to identify HFpEF.[25]

Lung ultrasound echocardiography

Lung ultrasound (LUS) is increasingly recognized as a valuable tool in the evaluation of patients with HF. It is highly sensitive and specific for detecting pulmonary congestion, which is common in HF patients, and to distinguish it from other conditions (*Figure 2*).[26] B-lines, which are vertical comet-tail artefacts extending from the pleural line, indicate pulmonary congestion.[27] The number of B-lines can be used to detect, semi-quantify, and monitor the degree of pulmonary congestion, providing prognostic information. LUS is also effective in detecting pleural effusions.[27]

Focused cardiac ultrasound

Echocardiography plays a central role in identifying potential underlying causes of cardiogenic shock (CS) and associated pathophysiology. Without identification and treatment of the underlying cause, the outcome is usually fatal.[28] A standard echocardiographic evaluation can quickly provide sufficient information to confirm or exclude conditions such as tamponade, mechanical complications of myocardial infarction, LV outflow tract obstruction, and severe valvular lesions. The evaluation may also include an assessment of LV and RV function and an estimation of left and right filling pressures.[29] When echocardiography is not immediately available, focused cardiac ultrasound (FoCUS) can provide useful preliminary information and is typically followed by a comprehensive echocardiographic evaluation as soon as possible. The Rapid Ultrasound in Shock (RUSH) examination protocol helps to determine the specific aetiology of undifferentiated shock by evaluating the heart, the inferior vena cava/intra-abdominal and pleural compartments, and large vessels including the aorta (*Figure 3*).[30,31] The RUSH protocol is both sensitive and specific (0.89 and 0.97, respectively) in diagnosing CS, but it is advisable not to use it to exclude CS.[32]

Cardiovascular magnetic resonance

Cardiovascular magnetic resonance offers a detailed evaluation of biventricular volumes, systolic function, cardiac flows, masses, and myocardial tissue composition. CMR capability in volume and function assessment is important, as different methods of LVEF and volume assessment have varying performances. CMR uses Simpson's disk summation method for LVEF analysis, which is more accurate and reproducible than other techniques like TTE and radionuclide ventriculography.[33] Furthermore, LA conduit strain on CMR was a strong independent prognostic predictor, superior to LV GLS, LVEF, and LAVI and incremental to late gadolinium enhancement (LGE), in patients with DCM.[34] Nonetheless, advanced HF represented only a minority of these study populations.

Cardiovascular magnetic resonance also provides comprehensive flow measurements through phase-contrast sequences, useful

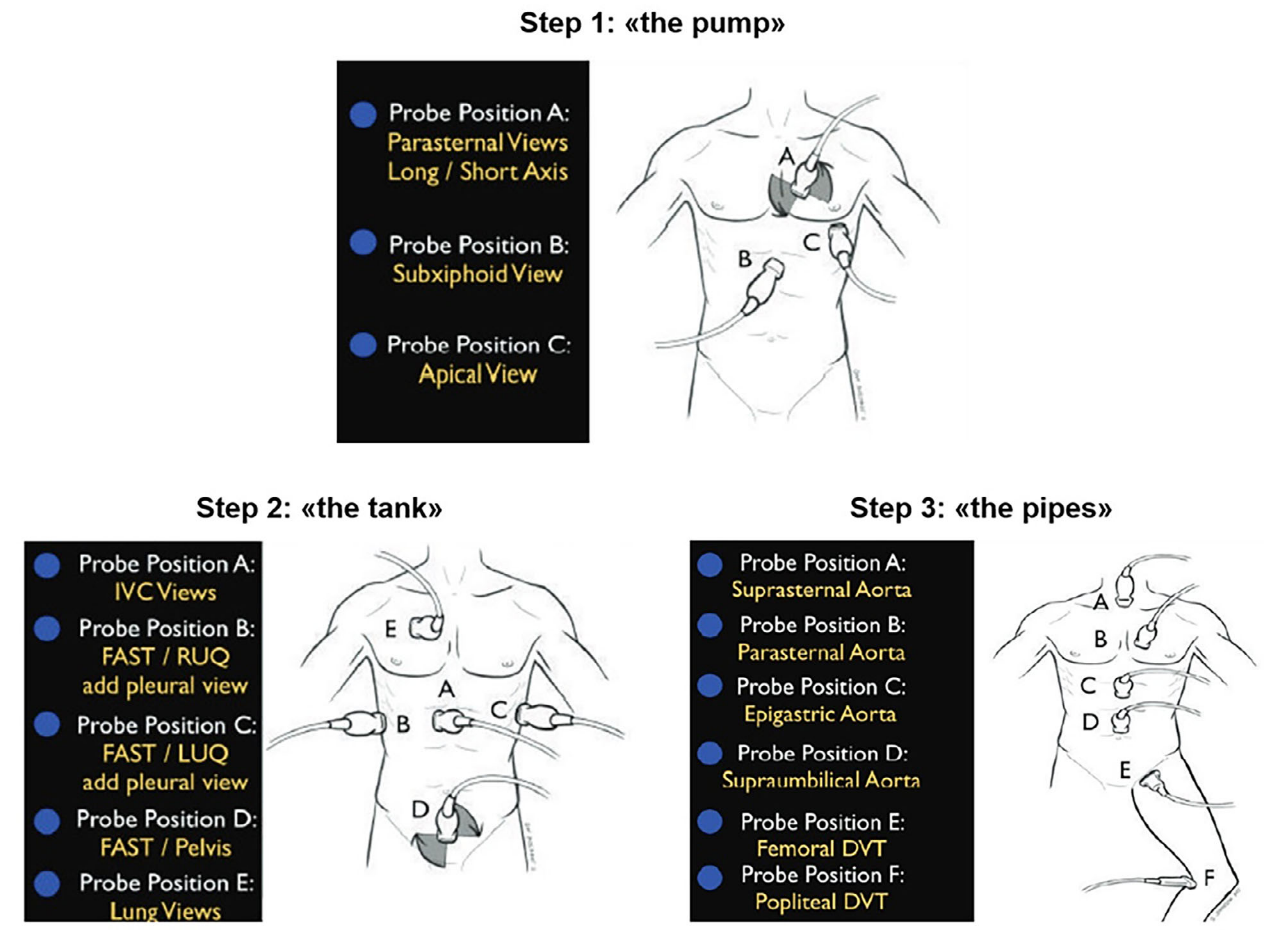


Figure 3 The Rapid Ultrasound in Shock (RUSH) protocol. DVT, deep vein thrombosis; FAST, Focused Assessment Sonography in Trauma; IVC, inferior vena cava; LUQ, left upper quadrant; RUQ, right upper quadrant. Modified with permission from Seif *et al.*[31]

for evaluating valvular heart disease and secondary MR in advanced HF patients. Pulmonary transit time by first-pass perfusion CMR was specifically studied in advanced HF patients and shown to independently predict mortality, with stronger prognostic value than clinical and other CMR parameters, including LVEF, RVEF and GLS.[35] Emerging four-dimensional (4D) flow CMR allows for detailed study of flow dynamics, wall shear stress, and vortex formation, potentially aiding in the evaluation of diastolic dysfunction and valvular heart diseases.

Tissue characterization by CMR includes LGE and parametric mapping techniques, essential for assessing fibrosis, oedema, and myocardial composition. This information may be relevant to establish the aetiology of HF, which has prognostic implications. Moreover, the intramural extent of LGE, wall thickness and motion are possible indicators of myocardial viability in patients with ischaemic cardiomyopathy.[36] LGE presence and extent is related to risk of all-cause mortality, HF hospitalization, and sudden cardiac death in patient with non-ischaemic cardiomyopathy,[37] while it predicts survival, response to cardiac resynchronization therapy (CRT) and to coronary revascularization.[38,39] LGE is also a powerful predictor of ventricular arrhythmias in patients with LV dysfunction, including those with non-ischaemic HF.[40] CMR is also a good technique to detect intracardiac thrombi, and may be helpful in patients being evaluated for surgical ventricular reconstruction.

In patients with a cardiac implantable electronic device (CIED), CMR can still be performed with precautions, although magnetic susceptibility artefacts may complicate image interpretation. Techniques like wideband inversion pulses and specific imaging protocols help mitigate these artefacts, ensuring diagnostic efficacy.[41]

Nuclear imaging

Along with DSE and CMR, single-photon emission computed tomography (SPECT) with ^{99m}Tc-marked tracers and ^{18}F-fluorodeoxyglucose positron emission tomography (^{18}F-FDG-PET) may be used to evaluate and distinguish between viable, stunned, and hibernating myocardial tissue.[42] Increased ^{18}F-FDG-PET mismatch correlate with improved outcomes following revascularization, particularly when the mismatch is $\geq$7%.[43] On the other hand, the 10-year follow-up of the Surgical Treatment for Ischemic Heart Failure (STICH) trial did not show a long-term prognostic benefit of a revascularization strategy guided by viability testing through SPECT and DSE.[44] Similarly, the Revascularization for Ischemic Ventricular Dysfunction (REVIVED-BCIS2) trial found that revascularization by percutaneous coronary intervention plus optimal medical therapy did not result in a lower incidence of death from any cause or hospitalization for HF compared to optimal medical therapy alone in patients with HFrEF who had viability in at least four segments of the left ventricle assessed through DSE, CMR, SPECT, or FDG-PET.[45] ^{18}F-FDG-PET can also be used to assess myocardial scar, and has been shown to be useful in estimating responders to CRT in patients with ischaemic cardiomyopathy.[46]

In non-ischaemic HF, nuclear imaging is primarily used for cardiac sarcoidosis,[47] cardiac amyloidosis,[48] and device-related infections. Most notably, ^{18}F-FDG-PET/computed tomography (CT) has a high sensitivity and specificity for device-related infections in advanced HF patients with MCS devices.[49]

Computed tomography

Computed tomography is a possible alternative to echocardiography when acoustic windows are poor, and CMR is not tolerated or contraindicated. With the use of CT, coronary anatomy can be assessed and the presence of coronary artery disease may be evaluated in patients with a low or intermediate pre-test likelihood.[50] As such, CT can be part of the initial evaluation of patients with unexplained LV dysfunction. Chest CT-derived pulmonary artery diameter and RV volume, as indicators of pulmonary hypertension, independently predicted all-cause mortality and HF events in patients with advanced HFrEF.[51] In addition, CT may be of great value in patients with HF and valvular heart disease, for patient selection and guidance of percutaneous procedures.[52]

Valve disease assessment: an application of multimodality imaging

In patients with advanced HF, valvular heart disease is often present and is typically treated to improve prognosis.[1] In the paragraphs below, the role of multimodality imaging in the assessment and treatment of valvular heart disease in patients with advanced HF will be discussed.

Aortic stenosis

As discussed above, low-dose DSE helps differentiate between truly severe AS and pseudo-severe AS. Aortic valve replacement is advised in patients with true severe AS and contractile reserve demonstrated by DSE.[21] Absence of contractile reserve predicts a high operative risk during aortic valve replacement, though it is less associated with long-term outcomes. For patients with pseudo-severe AS, optimization of HF therapy is the mainstay of management.

Computed tomography is essential to assess suitability to transcatheter aortic valve replacement and plan this intervention. CT provides detailed information on aortic valve anatomy, annular size and shape, extent and distribution of valve and vascular calcification, risk of coronary ostial obstruction, aortic root dimensions, optimal fluoroscopic projections for valve deployment, and feasibility of vascular access.[53]

Mitral regurgitation

Mitral regurgitation is a prevalent situation in patients with advanced HF. MR in the context of HF is often functional, resulting from LV dilatation, remodelling, and dysfunction rather than primary mitral valve disease. The main mechanisms include LV remodelling and dysfunction, LA dilatation, annular dilatation, and leaflet tethering. MR poses significant diagnostic and therapeutic challenges. It is crucial to accurately assess the presence and severity of MR in these patients, as it directly impacts their clinical management and prognosis.[54] Imaging plays a pivotal role in the evaluation of MR (*Figure 4*), guiding therapeutic decisions and helping to predict outcomes.

Transthoracic echocardiography is the first-line imaging modality for evaluating MR. It provides detailed information on valve morphology, LV size, function, and haemodynamics.[54] Colour Doppler imaging is used to assess the severity of MR, characterized by the regurgitant jet area and vena contracta width. Quantitative measures include regurgitant volume, regurgitant fraction, and effective regurgitant orifice area. TOE offers superior resolution of the mitral valve apparatus and is particularly useful for detailed assessment of the mechanism of MR, especially in candidates for surgical or percutaneous interventions. Advances in 3D echocardiography allow for comprehensive evaluation of the mitral valve structure and function, providing valuable insights into leaflet motion, coaptation, and the extent of annular dilatation.[55]

Cardiovascular magnetic resonance is highly accurate for assessing LV volumes, function, and mass. It is particularly useful in cases where echocardiographic windows are suboptimal. CMR can quantify the regurgitant volume and fraction and provides additional information on myocardial viability, fibrosis, and scarring.[56] CT imaging provides detailed anatomical information about the mitral valve, annulus, and surrounding structures. For example, CT can assess the extent of calcification in the mitral annulus and leaflets, which is crucial for planning percutaneous or surgical procedures.[56] SPECT and PET can assess myocardial viability, helping determine the potential benefit of coronary revascularization.[56]

Mitral regurgitation severity has significant prognostic implications in advanced HF. Severe MR is associated with increased mortality and higher rates of HF hospitalization.[57] Accurate quantification and characterization of MR using advanced imaging techniques are essential for risk stratification and guiding therapeutic decisions.[54]

Optimizing HF therapy, including the use of GDMT and, if indicated, CRT, can reduce the severity of functional MR in many patients. For patients with significant MR despite optimal medical management, surgical or percutaneous interventions may be appropriate. Imaging plays a critical role in selecting appropriate candidates, planning interventions, and guiding transcatheter interventions.[54]

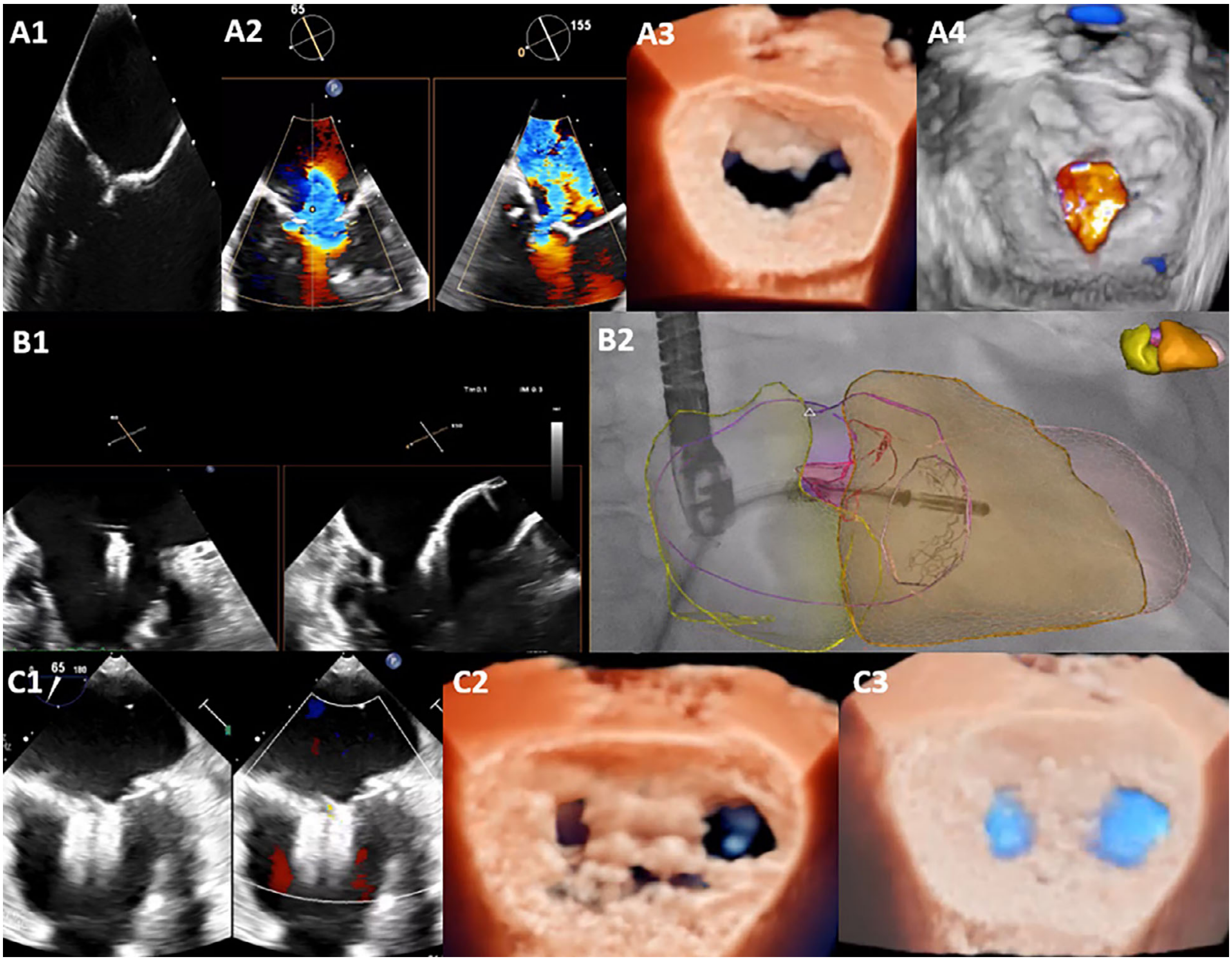


Figure 4 Contribution of imaging before and during transcatheter mitral valve edge-to-edge repair. Severe functional mitral regurgitation with leaflet tethering and a predominantly central jet, assessed by transoesophageal echocardiography (*A1*), including biplane (*A2*) and three-dimensional views with and without colour Doppler (*A3* and *A4*). Procedural guiding during transcatheter mitral valve edge-to-edge repair using live biplane transoesophageal views (*B1*) in addition to fluoroscopy with fusion imaging (*B2*). Immediate post-procedural result after implantation of two MitraClip devices at the A2/P2 (central) level assessed by transoesophageal echocardiography (*C1*), including three-dimensional views with and without colour Doppler (*C2* and *C3*).

Tricuspid regurgitation

Echocardiography is the first-line imaging modality for assessing tricuspid valve morphology,[58] which can vary greatly in terms of scallop numbers and regurgitant orifice shape.[59] It also evaluates the severity and mechanism of TR and its impact on the right ventricle. Assessing TR severity is critical but difficult and is best approached using a comprehensive multiparametric strategy with both 2D and 3D echocardiography.[60] Importantly, TR severity varies according to the patient's volume status. TR grades are classified as none, mild, moderate, severe, and possibly, as recently proposed, also massive or torrential.[60] A refined TR grading classification has been recently suggested, classifying the 'moderate' TR severity grade into 'mild-to-moderate' and 'moderate-to-severe', to align with the classification for MR and enhance accuracy in outcome prediction.[61] TR is mostly functional or secondary, with normal leaflet structure, and is mainly induced by left heart diseases. Functional TR is divided into atrial functional TR (caused by annular dilatation due to RA enlargement) and ventricular functional TR (caused by leaflet tethering due to RV enlargement). Organic TR, characterized by abnormal leaflet structure, is rare. A third entity, CIED-induced TR, has been proposed.[59]

An increasing number of symptomatic patients with severe TR undergo transcatheter interventions. TOE is the imaging modality of choice for patient selection by evaluating the mechanism of TR, the size and location of the gap, the location and impact of CIED leads on leaflets, and the device angle of approach.[62] TOE is also essential for guiding transcatheter interventions by ensuring safe device navigation into the right ventricle, imaging leaflet insertion, and confirming grasping. During these procedures, both mid/distal

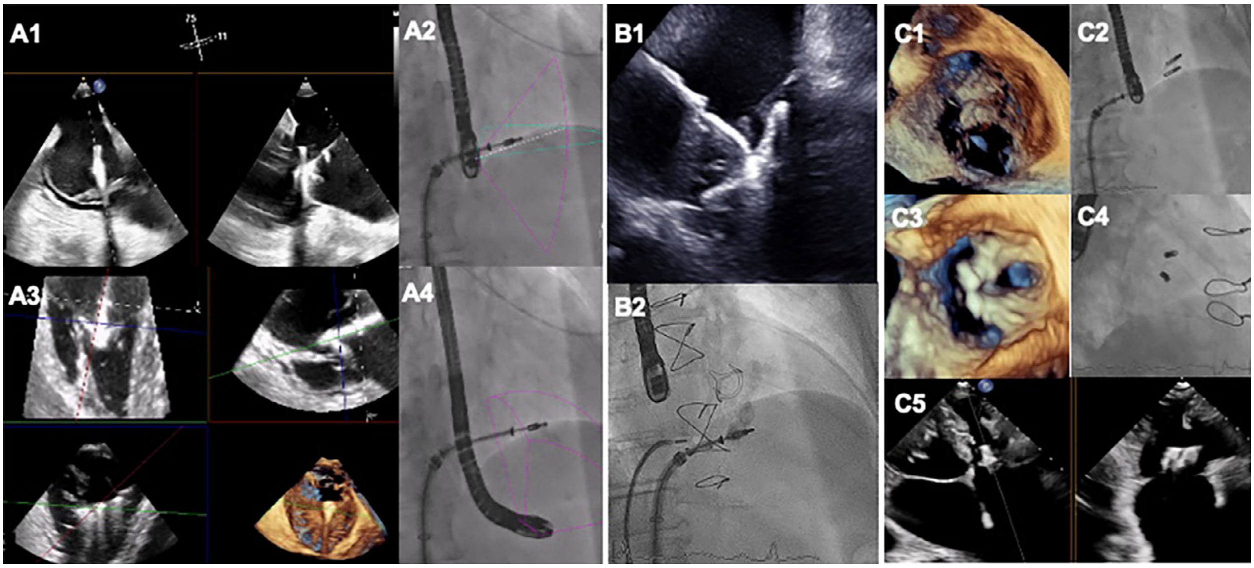


Figure 5 Contribution of imaging during transcatheter tricuspid valve edge-to-edge repair. Procedural guiding using live biplane transoesophageal views (*A1*) and transgastric views with multiplanar reconstructions (*A3*) in addition to fluoroscopy (*A2*, *A4*). Intracardiac echocardiography (*B1*) in addition to fluoroscopy (*B2*). Immediate post-procedural result using three-dimensional transoesophageal echocardiography (*C1*, *C3*), fluoroscopy (*C2*, *C4*) and biplane transthoracic echocardiography (*C5*).

Table 2 Clinical advice on multimodality imaging in advanced heart failure

1. Clinical advice based on published evidence
   - TTE is crucial for assessing disease severity, stratifying risk, guiding clinical decisions, and informing therapeutic strategies in advanced HF.
   - LVEF is a key index of systolic function used for diagnosis, classification, and risk stratification.
   - The E/e′ ratio assesses LV end-diastolic pressure and predicts HF prognosis.
   - Tricuspid annular plane systolic excursion <14 mm predicts mortality and heart transplantation in patients with LVEF <35%.
   - CMR enables accurate assessment of biventricular volumes, systolic function, cardiac flows, masses, and myocardial tissue composition.
   - CMR late gadolinium enhancement is of additional value in the risk assessment (all-cause mortality, HF hospitalization, and sudden cardiac death) in patients with non-ischaemic cardiomyopathy.
   - CT-derived pulmonary artery diameter and RV volume predict mortality and HF events.
   - Aortic valve replacement is recommended in patients with true severe aortic stenosis and contractile reserve.
   - Severe mitral and tricuspid regurgitation are linked to increased mortality and HF hospitalization, necessitating accurate quantification and characterization for risk stratification and therapeutic guidance.
2. Clinical advice based on uniform consensus of the Writing Group
   - Standard echocardiography can quickly confirm or exclude conditions such as tamponade, mechanical complications of myocardial infarction, LV outflow tract obstruction, and severe valvular lesions.
   - Multimodality imaging is essential for patient selection and procedural guidance in patients with advanced HF and valvular disease.
3. May be appropriate based on published evidence
   - FoCUS provides preliminary information and is generally followed by comprehensive echocardiography.
   - The RUSH protocol is sensitive and specific in diagnosing cardiogenic shock but not for exclusion.
4. May be appropriate based on consensus of the Writing Group
   - Emerging 4D flow CMR studies of flow dynamics, wall shear stress, and vortex formation, aiding in evaluating diastolic dysfunction and valvular diseases.
5. Area of uncertainty
   - The role of myocardial viability assessment via imaging modalities like ^{18}F-FDG-PET in guiding revascularization strategies in ischaemic cardiomyopathy remains debatable.

4D, four-dimensional; ^{18}F-FDG-PET, ^{18}F-fluorodeoxyglucose positron emission tomography; CMR, cardiovascular magnetic resonance; CT, computed tomography; E/e′, early diastolic mitral inflow velocity (E wave) to early diastolic mitral annular velocity (e′) ratio; FoCUS, focused cardiac ultrasound; LV, left ventricular; LVEF, left ventricular ejection fraction; HF, heart failure; RUSH, Rapid Ultrasound in Shock; RV, right ventricular; TTE, transthoracic echocardiography.

transoesophageal views and transgastric views with live 2D, 3D, or multiplanar reconstructions are used (*Figure 5*). For patients in whom image quality is insufficient or who are contraindicated for TOE, intracardiac echocardiography may be an alternative.[62]

Conclusions

The first part of this clinical consensus statement underscores the many roles of various imaging modalities in advanced HF, summarized in the *Graphical Abstract* and in *Table 2* with clinical advice. Echocardiography remains an indispensable tool, providing comprehensive information on LV function, geometry, diastolic pressures, and RV and atrial function. This facilitates early diagnosis, risk stratification, and the guidance of therapeutic strategies. The advent and integration of advanced imaging techniques such as STE and 3D echocardiography have further enhanced the accuracy and utility of echocardiographic evaluations in clinical practice. TOE complements TTE by offering detailed evaluations of mitral and tricuspid valve diseases, crucial for surgical or transcatheter planning. Stress echocardiography, including exercise and DSE, is valuable in assessing the severity of AS and myocardial ischaemia, guiding therapeutic interventions. In CS, echocardiography and FoCUS are indispensable for rapid diagnosis and management, guiding therapeutic interventions and improving patient outcomes. CMR plays a pivotal role in advanced HF by enabling a comprehensive evaluation of biventricular size and function, tissue characterization, and flow dynamics. It is particularly useful for diagnosing specific HF aetiologies. CT serves as an alternative when acoustic windows are poor and CMR is contraindicated, offering valuable insights into pulmonary artery diameter, RV volume, and valvular anatomy, which are crucial for guiding percutaneous procedures. Nuclear imaging techniques are essential for viability assessment, distinguishing between stunned, hibernating, and scarred myocardium, and thus guiding revascularization decisions. These modalities also diagnose non-ischaemic HF conditions like cardiac sarcoidosis and amyloidosis and detect device-related infections.

In summary, advanced imaging modalities enhance diagnostic accuracy, risk stratification, and therapeutic decision-making, ultimately improving prognosis and quality of life for patients with advanced HF.

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