European Heart Journal - Imaging Methods and Practice (2025) **3**, qyaf066
https://doi.org/10.1093/ehjimp/qyaf066

INVITED REVIEW

Cardiovascular imaging in 2024: review of current research and innovations

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Received 23 March 2025; accepted after revision 14 May 2025; online publish-ahead-of-print 17 May 2025

Abstract

Cardiovascular imaging saw significant advancements in 2024, impacting technology, pathophysiology, and clinical applications. This review provides a comprehensive summary of the most impactful research in cardiovascular imaging published in 2024, highlighting technological advancements, as well as research on ischaemic heart disease, valvular heart disease, cardiomyopathies, and heart failure. It emphasizes the crucial role of artificial intelligence, large-scale studies, and technical improvements across echocardiography, cardiovascular magnetic resonance, computed tomography (CT), and nuclear medicine. In the context of ischaemic heart disease, non-invasive imaging strategies improve patient management and reduce invasive coronary angiograms and unnecessary follow-up testing. Computed tomography plaque characterization is a

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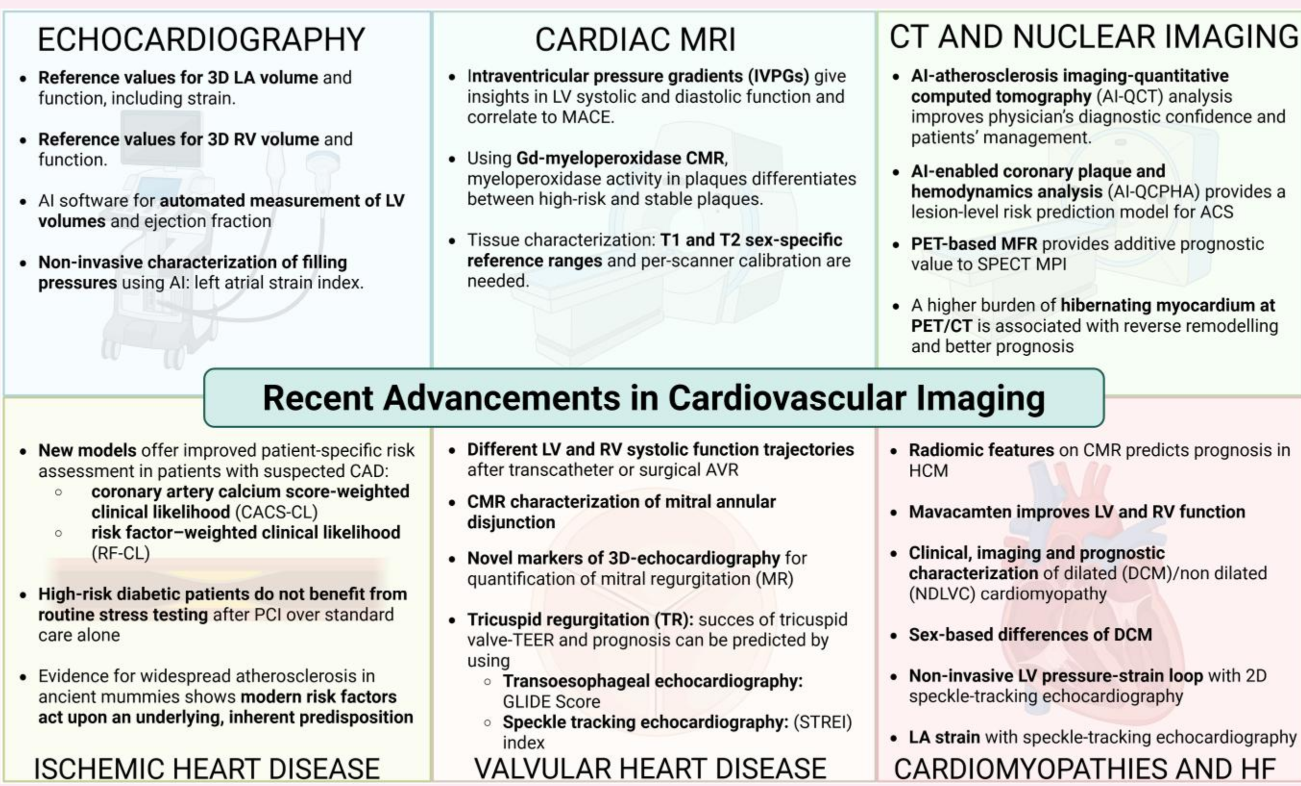
growing area of research, with potential for predicting disease severity, atherosclerosis progression, and clinical outcomes. In valvular heart disease, several imaging studies focused not only on transcatheter treatments for aortic stenosis, mitral regurgitation, and tricuspid regurgitation but also on specific conditions such as mitral valve prolapse and mitral annular disjunction. Finally, for heart failure and cardiomyopathies, imaging plays a vital role in early diagnosis and risk assessment, with newer techniques surpassing traditional methods in providing morpho-function characterization and in predicting long-term outcomes.

Lay summary

In 2024, heart imaging took big leaps forward, thanks to new technologies and research. Doctors now have better tools to diagnose and treat heart problems. This review highlights key studies using techniques like echocardiograms, MRI, CT scans, and nuclear imaging.

Artificial intelligence is playing a bigger role, helping doctors analyse images more accurately. Large studies are also providing more detailed information about heart diseases. For coronary artery disease, new imaging methods are helping doctors decide the best treatment, reducing the need for invasive procedures. In particular, CT scans are getting better at predicting plaque buildup and its risks. For valvular heart problems, imaging is crucial for planning minimally invasive treatments like transcatheter valve replacement and repair, which are now available for quite a wide range of diseases affecting the aortic, mitral, tricuspid and pulmonary valve. In heart failure and cardiomyopathies, advanced imaging helps doctors diagnose problems earlier and predict how patients will fare long term, offering more detailed information for prognostic and therapeutic decisions.

Graphical Abstract



The most recent advancements of cardiovascular imaging are represented, including both technological novelties for each modality (top row) and pathophysiological and clinical applications (bottom row). ACS, acute coronary syndrome; AI, artificial intelligence; CAD, coronary artery disease; CMR, cardiovascular magnetic resonance; CT, computed tomography; DCM, dilated cardiomyopathy; HCM, hypertrophic cardiomyopathy; LA, left atrium; LGE, late gadolinium enhancement; LV, left ventricle; MACE, major adverse cardiovascular event; MPI, myocardial perfusion imaging; MR, mitral regurgitation; MRI, magnetic resonance imaging; NDLVC, non-dilated left ventricular cardiomyopathy; PCI, percutaneous coronary intervention; PET, positron emission tomography; RV, right ventricle; SPECT, single photon emission computed tomography; TEER, transcatheter-edge-to-edge repair; TR, tricuspid regurgitation.

Keywords echocardiography • cardiovascular magnetic resonance • computed tomography • positron emission tomography • single photon emission tomography • multimodality imaging

Introduction

Cardiovascular imaging plays a pivotal role in diagnosing and managing a wide range of cardiac conditions. In recent years, rapid technological advancements have enhanced the capabilities across all imaging modalities. This review provides a comprehensive summary of the most impactful research in cardiovascular imaging published in 2024, highlighting key breakthroughs, emerging trends, and their implications for clinical practice. In the following sections, we will explore novel imaging technologies, and research on ischaemic heart disease (*Figure 1*), valvular heart disease (*Figure 2*), cardiomyopathies, and heart failure (HF) (*Figure 3*).

Technological innovations

Echocardiography

The left atrium (LA) and right ventricle (RV) gained recognition in the last decade, after demonstration of their strong prognostic role in many cardiac diseases. Three-dimensional (3D) echocardiography, a non-invasive and semiautomated method, can overcome some limitations of two-dimensional techniques, such as geometrical assumptions. However, reference values for 3D LA and RV parameters are lacking. From the large general population of the 5th Copenhagen City Heart Study, 979 individuals with no cardiovascular disease or risk factors were selected to determine updated reference values of 3D LA volume and function, including strain.[1] The median and limits of normality (2.5th and 97.5th percentiles) for volumes were—LA minimum volume index 10.2 (5.9–18.5) mL/m^2, and LA maximum volume index (LAVimax) 26.8 (16.5–40.1) mL/m^2. For functional parameters—LA reservoir strain 30.8% (18.4–44.2%), LA conduit strain 19.1% (6.8–32.0%), LA contractile strain 11.7% (4.3–22.2%), total LA emptying fraction (LAEF) 61.4% (47.8–71.0%), passive (conduit) LAEF 37.7% (17.4–53.9%), active (contractile) LAEF 37.4% (22.2–52.5%). The authors found reduction of LA strain indices and increase of dimensional parameters along with aging. Moreover, sex-specific differences were found for all parameters except active LAEF and LAVimax. Three-dimensional echocardiography was also applied to quantify the different longitudinal and non-longitudinal components of RV ejection fraction (RVEF) and systolic strain and to define their normal values in the World Alliance of Societies of Echocardiography (WASE) Study.[2] Similarly to LA analysis, aging was associated with reduction of all components of longitudinal shortening, except for radial contraction which was higher in elderly females. Also, some differences were found between Black, White, and Asian individuals. This study did not perform any direct comparison with cardiovascular magnetic resonance (CMR) imaging, which represents the gold-standard modality for the assessment of RV volumes and systolic function. While several previous comparative studies demonstrated a limited difference between 3D-echocardiography and CMR, with some volume underestimation by 3D-echocardiography,[3] further studies are needed to compare RV strain parameters.

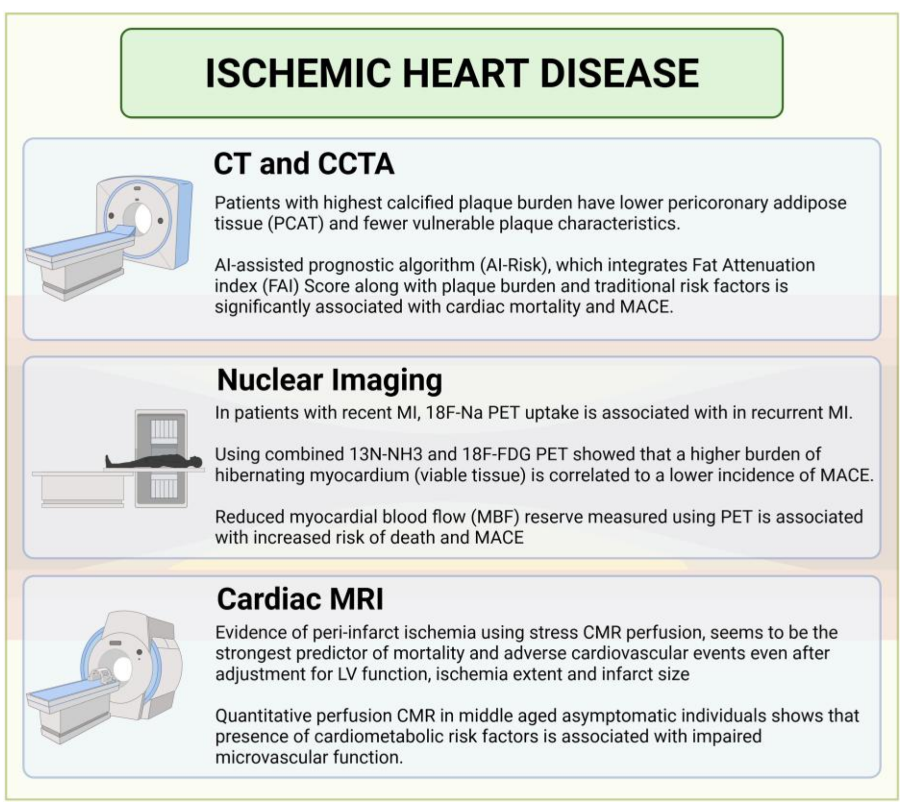


Figure 1 Cardiovascular imaging in ischaemic heart disease (IHD). The most important novelties of current imaging techniques in the clinical management of IHD are schematically indicated in the figure. AI, artificial intelligence; CCTA, coronary computed tomography angiography; CMR, cardiovascular magnetic resonance; CT, computed tomography; FAI, fat attenuation index; FDG, fluorodeoxyglucose; ICA, invasive coronary angiography; LV, left ventricle; MACE, major adverse cardiovascular events; MBF, myocardial blood flow; MI, myocardial infarction; MRI, magnetic resonance imaging; PCAT, pericoronary adipose tissue; PET, positron emission tomography.

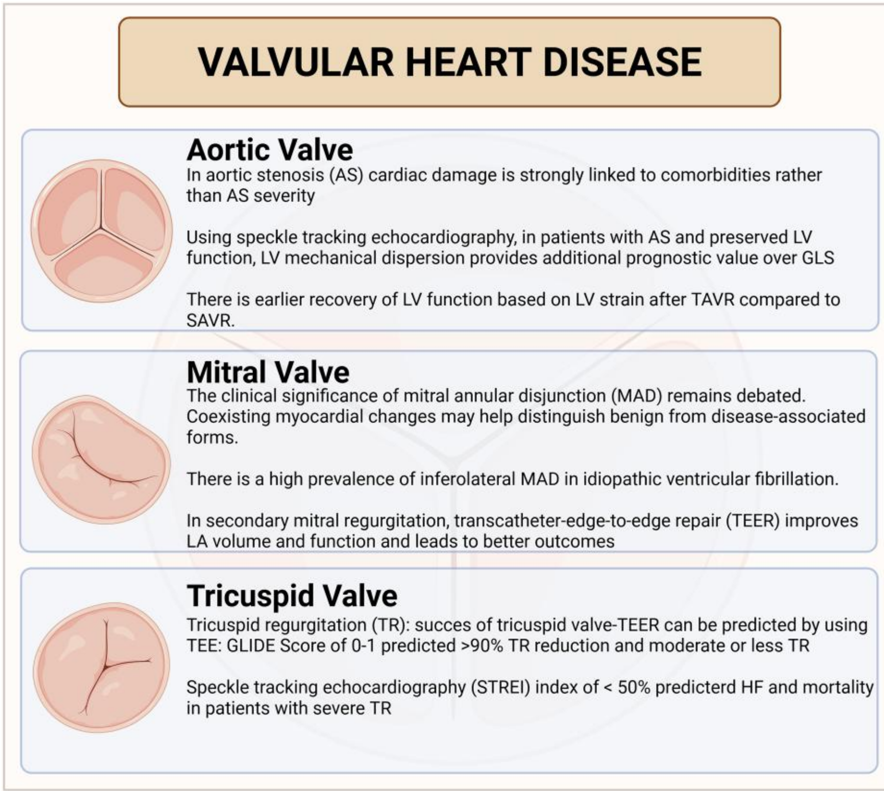


Figure 2 Cardiovascular imaging in valvular heart disease. The most important novelties of current imaging techniques in the clinical management of valvular heart are schematically indicated in the figure. AS, aortic stenosis; GLS, global longitudinal strain; LA, left atrium; LV, left ventricle; MAD, mitral annular disjunction; SAVR, surgical aortic valve replacement; STREI, speckle tracking echocardiography; TAVR, transcatheter aortic valve replacement; TEE, transoesophageal echocardiography; TEER, transcatheter-edge-to-edge repair; TR, tricuspid regurgitation.

Several recent studies investigated novel parameters of left atrioventricular coupling. The third wave of the Trondelag Health (HUNT3) study on 1348 healthy adults investigated whether the LA end-systolic volume to left ventricular (LV) end-diastolic volume (LA:LV) ratio could help discriminate between pathological and physiological LA enlargement.[4] The LA:LV volume ratio increased with higher age, mainly attributed to lower LV end diastolic volume with higher age. A higher LA:LV was associated with a higher burden of cardiovascular risk factors, with a decline in absolute VO2peak, with diastolic dysfunction and filling pressures.[4]

Another group assessed retrospectively the association between left atrioventricular coupling index (LACI—LA to LV volume at end-diastole) and LV diastolic function in 1158 patients with stable HF and optimal medical therapy.[5] Median LACI value was 0.29, increasing with age and more advanced HF symptoms. The prevalence of grade 3 LV diastolic dysfunction increase across LACI tertiles, with a cut-off of ≥0.26 to identify moderate to severe diastolic dysfunction, with an area under the curve (AUC) of 0.75. Moreover, on multivariable analysis, LACI was independently associated with all-cause mortality and/or HF hospitalization, showing incremental predictive value over the classical diastolic dysfunction grading system.[5]

In addition, LA and LV deformation, using LA–LV strain loops, was retrospectively assessed in 30 patients with transthyretin amyloid (ATTR) cardiomyopathy and in 20 patients with LV hypertrophy.[6] Significantly lower LA longitudinal peak strain and LA–LV strain slope values were detected in ATTR patients compared to LV hypertrophy patients, with similar AUC (0.72 and 0.71), and better that LV deformation alone. Therefore, LA deformation demonstrated an independent ability to differentiate ATTR from LV hypertrophy, potentially enabling quicker ATTR diagnosis and treatment initiation.

Artificial intelligence (AI) is progressively changing the way we analyse echocardiographic images, aiming to improve efficiency, reproducibility, and standardization.[7] A new AI software was applied to measure LV volumes and ejection fraction (LVEF) in comparison to manual evaluation by modality experts. The time taken to perform the measurements was reduced by a median of 5.3 min (77%). Moreover, AI agreement was superior in inter-observer and non-inferior in intra-observer settings.[8] Similar advantages were reported with the application of a fully-automated AI-guided analysis of LV global longitudinal strain (*Figure 4*), including automated view selection, classification, endocardial border tracing, and strain calculation from an entire echo exam.[9] By AI, a novel index for the estimation of LV filling pressures was created and then validated in a second WASE-derivate cohort.[10] The so-called left atrial strain index (LASi) is a continuous and dimensionless variable, calculated from the entirety of the left atrial strain time curve, and validated against invasive haemodynamic measurements. Left atrial strain index allowed the detection of elevated LV filling pressures using invasive measurements as a reference, at least as accurately as peak LA strain and current diastolic function guideline algorithm, with the advantage of no indeterminate classifications in patients with measurable LAS, allowing a better non-invasive characterization of filling pressures.[10]

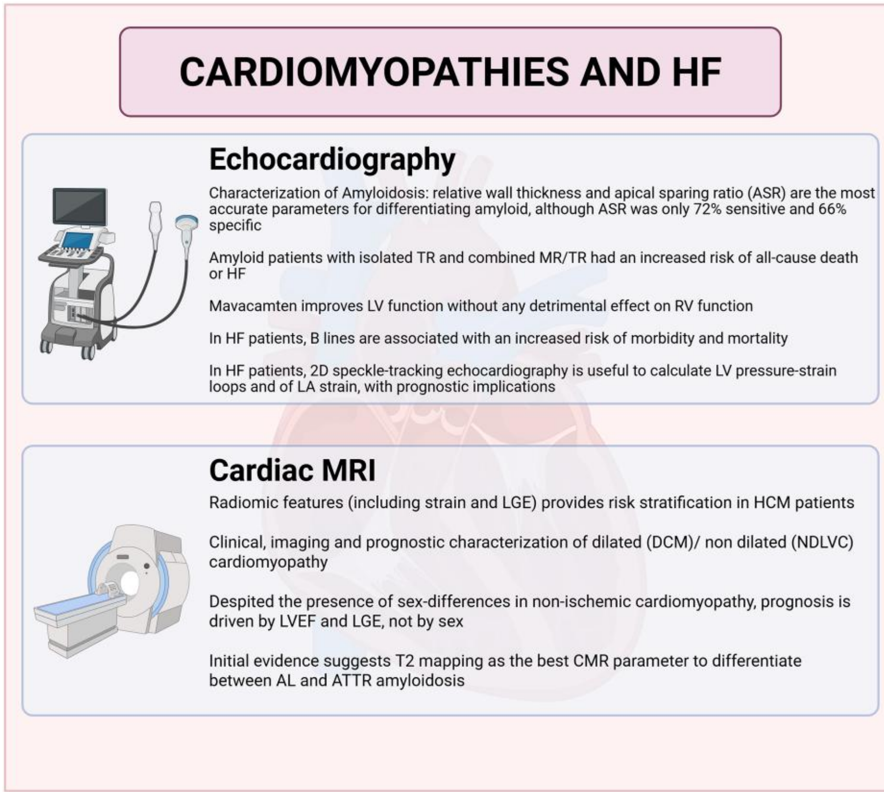


Figure 3 Cardiovascular imaging in cardiomyopathies and heart failure. The most important advantages and the most recent advancements of each technique are schematically indicated in the figure. AL, light chain amyloidosis; ASR, apical sparing ratio; ATTR, transthyretin amyloidosis; CMR, cardiovascular magnetic resonance; DCM, dilated cardiomyopathy; HCM, hypertrophic cardiomyopathy; HF, heart failure; LA, left atrium; LGE, late gadolinium enhancement; LV, left ventricle; LVEF, left ventricular ejection fraction; MR, mitral regurgitation; MRI, magnetic resonance imaging; NDLVC, non-dilated left ventricular cardiomyopathy; RV, right ventricle; SCD, sudden cardiac death; TR, tricuspid regurgitation.

Cardiovascular magnetic resonance

Recent advancements in CMR post-processing tools have enabled the measurement of intraventricular pressure gradients (IVPGs) from routine long-axis cine CMR images, providing insights into both systolic and diastolic LV function (*Figure 5*). In a prospective study by Konijnenberg *et al.*,[11] 307 patients post first ST-segment elevation myocardial infarction were followed for a median of 9.7 (5.9–12.5) years, revealing that LV-IVPGs were significantly associated with major adverse cardiovascular events (MACE): HF hospitalization in 34 patients, cardiovascular death in 15. Patients with larger infarcts, more microvascular injury, and impaired LV-IVPGs had a higher risk of MACE. Overall LV-IVPG was significantly associated with MACE, though LV-IVPG did not add prognostic value beyond LVEF and LV global longitudinal strain (GLS). A possible explanation might be related to the tight relationship of LV-IVPGs with both LVEF and LV GLS but also to the fact that patients suffering MACE had more pronounced systolic dysfunction, which was well detected by conventional LVEF and LV GLS, while LV-IVPG might be more useful to detect more subtle conditions.

Vascular inflammation plays a critical role in atherosclerotic plaque rupture and detecting active inflammation can guide treatment. By using molecular magnetic resonance with a gadolinium-based myeloperoxidase-selective probe, Nadel *et al.*[12] demonstrated that elevated myeloperoxidase activity in plaques could differentiate between high-risk and stable plaques, predicting future atherothrombosis.

In myocardial tissue characterization, normal T1 and T2 values are sex-dependent. Thomas *et al.*[13] found that following current guidelines could lead to misclassification in up to 36% of healthy females and 37% of males for T1, and 16% of females and 12% of males for T2. They propose that sex-specific reference ranges and per-scanner calibration should be incorporated into clinical practice to improve diagnostic accuracy.

Nuclear and CT

While recent guidelines have conferred a pivotal role of coronary computed tomography angiography (CCTA) on patients with suspected chronic coronary syndromes, manual analysis of CCTA images is still characterized by a relevant inter-individual variability. The CERTAIN (Changes in CAD Diagnosis, Imaging, Intervention and Medication with AI-QCT) study assessed the incremental impact of the AI-based 'atherosclerosis imaging-quantitative computed tomography' software (AI-QCT; Cleerly, Inc., Denver, CO, USA) on diagnostic certainty and downstream patient management.[14] Compared with conventional CCTA evaluation, AI-QCT analysis improved physicians' diagnostic confidence and patients' management, leading to a better assessment of atherosclerotic burden, lower need for downstream non-invasive and invasive testing by 37.1% ($P < 0.001$), and more frequent optimization of medical therapy (i.e. statin and aspirin initiation/increase).[14]

The EMERALD-II (Exploring the Mechanism of Plaque Rupture in Acute Coronary Syndrome Using Coronary Computed Tomography

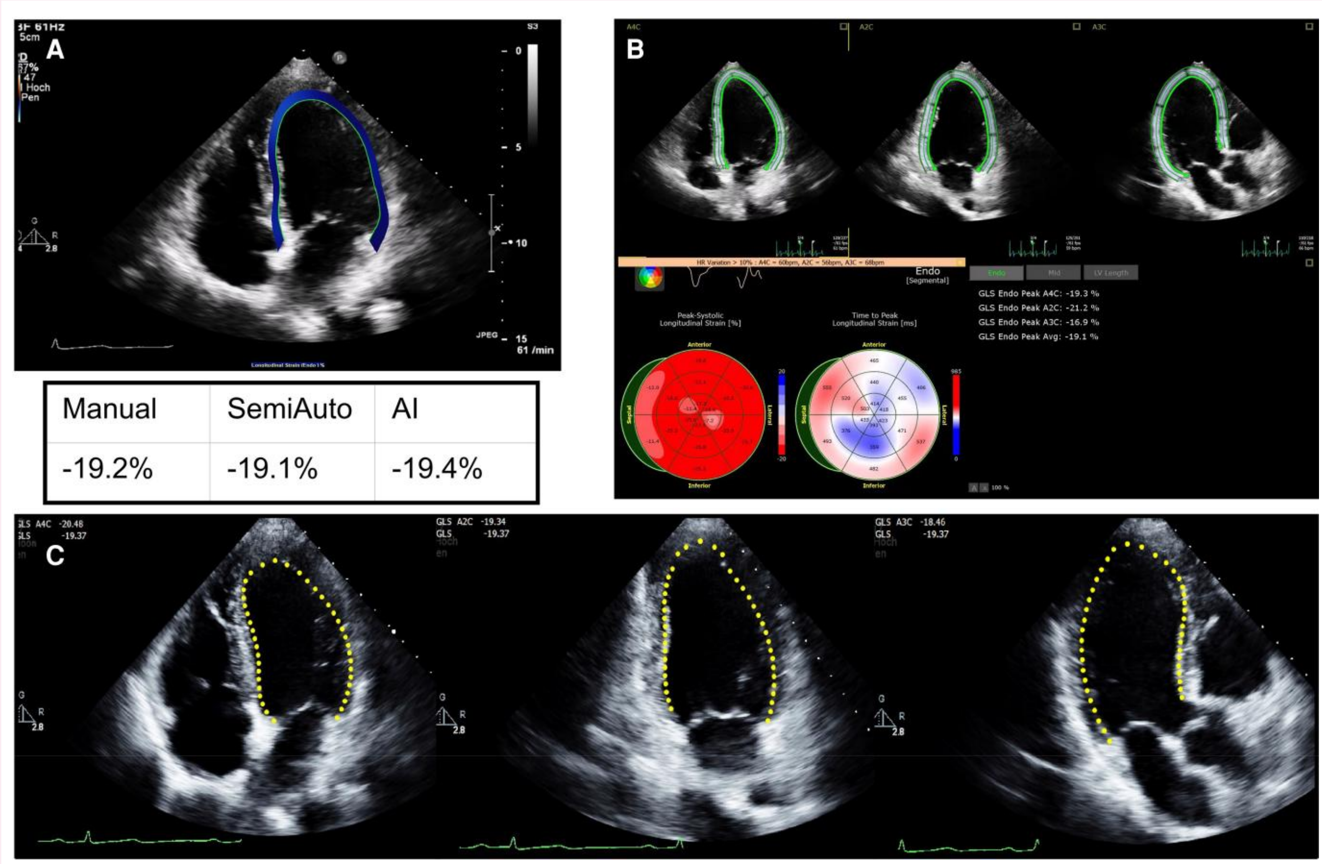


Figure 4 Example of left ventricular global longitudinal strain calculation in a 47-year-old person by using a manual method (*A*), a semi-automated method (*B*), and a fully automated artificial intelligence (AI) method (*C*). Reproduced from Sveric KM *et al.*[9]

Angiography and Computational Fluid Dynamics II) study investigated the additive value of AI–enabled quantitative coronary plaque and haemodynamic analysis (AI-QCPHA) to provide a lesion-level risk prediction model for acute coronary syndrome (ACS).[15] In a total of 351 patients who underwent coronary CCTA 1 month to 3 years before the ACS, the characteristics of culprit vs. non-culprit lesions were assessed. The best AI-QCPHA features were fractional flow reserve across the lesion, plaque burden, total plaque volume, low-attenuation plaque volume, and averaged percent total myocardial blood flow. The addition of AI-QCPHA features showed higher predictability for ACS than the reference model (AUC: 0.84 vs. 0.78; $P < 0.001$).[15]

Another recent study on 39 CT datasets showed that a fully automatic deep learning approach for calculation of cardiac function parameters using CT datasets outperformed other manual and semiautomated methods, in terms of speed and reliability[16] (*Figure 6*).

Some recent studies assessed the cost-effectiveness of novel CT imaging techniques, which at first sight appear very expensive. A first study assessed the cost-effectiveness of ultrahigh-resolution photon-counting detector coronary CT angiography over conventional energy-integrating detector CT: photon counting CT resulted in 19% reduction of functional follow-up tests, 6% reduction in coronary invasive angiographies and 9% reduction in major procedure-related complications.[17] Over a 10-year expected life expectancy, photon-counting CT led to an average cost saving of nearly 800 pounds per patient and an overall cost difference of nearly 12 million pounds.[17] A second study assessed the lifetime cost-effectiveness of integrating a novel AI-enhanced image analysis algorithm (AI-Risk) that stratifies the risk of cardiac events by quantifying coronary inflammation, combined with the extent of coronary artery plaque and clinical risk factors, by analysing images from routine CCTA: AI-Risk stratification led to treatment initiation or intensification in 39% of patients beyond the current clinical guideline recommendations, potentially leading to fewer cardiac events and increased cost-effectiveness.[18]

The prognostic role of myocardial ischaemia/viability burden in patients with ischaemic heart disease has been largely investigated. By using combined 13N-ammonia and 18F-fluorodeoxyglucose positron emission tomography/computed tomography (PET/CT), Kovacs B. *et al.*[19] demonstrated that a higher burden of hibernating myocardium (>7% of the LV myocardium) was associated with a lower incidence of MACE (hazard ratio 0.29, 95% confidence interval 0.1–0.8, $P = 0.016$). Those patients also showed a more favourable LVEF improvement over a median 5.4-year follow-up, likely due to the beneficial effect of optimized HF therapy, independently of early revascularization.

Another study investigated whether PET-based myocardial flow reserve (MFR) provides additive prognostic value than conventional single photon emission tomography (SPECT) myocardial perfusion imaging in patients with cardiometabolic disease and without known coronary artery disease (CAD).[20] Eventhough myocardial perfusion defects >5% of total myocardium were infrequent (PET: 21% and SPECT: 11%), suggesting a low prevalence of obstructive CAD, impaired MFR on PET (<2.0) was common (62%). At long-term follow-up, PET-MFR had a higher predictability of adverse events than SPECT, with normal PET identifying low-risk (0.9%/year MACE) patients while those with

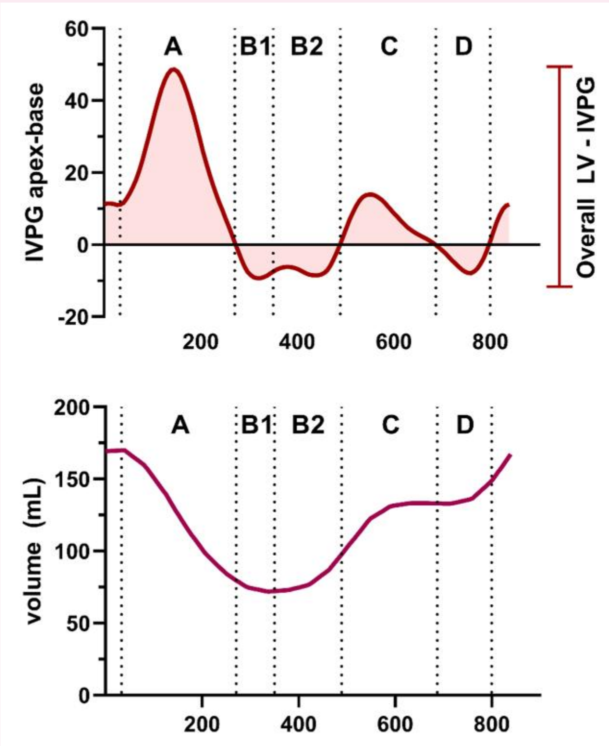


Figure 5 Apex-to-base LV-IVPG time curve analysis. Demonstration of the apex-to-base LV-IVPGs (dimensionless, y-axis) during one cardiac cycle (in ms, x-axis), with corresponding volume curve below (in mL on y-axis and ms on x-axis). In this time curve, five distinct phases can be distinguished. First, the positive vector 'A' represents the systolic ejection phase. Second, the negative vector 'B' represents the systolic-diastolic transition, including the end-systolic LV contraction slow down phase and aortic valve closure 'B1', followed by the opening of the mitral valve and diastolic suction 'B2'. Fourth, the positive vector 'C' represents the passive filling phase. Fifth, the negative vector 'D' represents the left atrial contraction in late diastole. The area under the curve represents the overall apex-to-base LV-IVPG. LV-IVPG, left ventricular intraventricular pressure gradients. Reproduced from Konijnenberg LSF *et al.*[11]

normal pharmacologic SPECT remained at moderate-risk (1.6%/year, $P < 0.001$ compared to normal PET).[20]

Ischaemic heart disease

Management of symptomatic patients with suspected obstructive CAD relies on estimating the pretest probability to guide further testing. New models, including the coronary artery calcium score–weighted clinical likelihood and risk factor–weighted clinical likelihood appear to offer improved patient-specific risk assessment. A recent study validated these models against invasive coronary angiography with fractional flow reserve in 4371 patients with stable chest pain.[21] It showed that both models identified more patients with very low clinical likelihood (≤5%) of obstructive CAD compared to the basic pretest probability model, while maintaining a low prevalence of haemodynamically obstructive CAD (<5% across all models). Furthermore, both models demonstrated superior calibration and discrimination in predicting haemodynamically obstructive CAD compared to the basic pretest probability model, suggesting that clinical likelihood models may offer a more precise and clinically advantageous approach to risk stratification than the traditional pretest probability model.[21]

The randomized POST-PCI (Pragmatic Trial Comparing Symptom-Oriented vs. Routine Stress Testing in High-Risk Patients Undergoing Percutaneous Coronary Intervention) study addressed surveillance strategies for high-risk diabetic patients after percutaneous coronary intervention (PCI).[22] In this trial, 1706 patients who had undergone PCI were randomized to either follow-up functional testing—including exercise electrocardiography, nuclear stress testing, or stress echocardiography—at 1 year or standard care alone. Among the study population, 38.7% patients had diabetes, with diabetic patients exhibiting a 52% greater risk of primary composite events than non-diabetic patients. However, in both diabetic and non-diabetic groups, routine surveillance functional testing 1-year post-PCI did not reduce major ischaemic cardiovascular events or mortality within 2 years but increased invasive coronary angiography and repeated revascularization. The study concluded that high-risk diabetic patients did not gain incremental benefit from routine stress testing after PCI over standard care alone.[22]

Recent studies have also examined various aspects of atherosclerosis, ranging from its presence in ancient populations to its relationship with vascular inflammation and plaque vulnerability in modern patients. Atherosclerosis has been considered as a disease of modern times. However, a CT study of 237 adult mummies from around the world suggested that atherosclerosis is widespread across human populations, with 37.6% of the mummies showing calcifications, at similar rates in both men and women.[23] The aorta was the most involved vascular bed (22%), followed by the ilio-femoral (21%), the popliteal-tibial (16%), the carotid (14%), and the coronary arteries (0.4%). Another study compared optical coherence tomography results in ACS patients aged under and over 35 years.[24] The results showed that older ACS patients had significantly higher frequencies of thin-cap fibroatheroma, microchannels, macrophages, and intimal thickness, whereas younger patients had notably thicker fibrous caps.

CCTA-derived pericoronary adipose tissue (PCAT) attenuation is a vascular inflammatory biomarker, which prognostic potential has been recently extensively studied. Research investigating the relationship between calcified plaque burden, vascular inflammation, and plaque vulnerability in CAD patients found that those in the highest calcified plaque burden tertile had lower PCAT attenuation and fewer vulnerable plaque characteristics.[25] Factors such as older age, statin use, and lower PCAT attenuation were independently associated with higher calcified plaque burden, suggesting that greater calcified plaque burden may indicate more stable plaques with less inflammatory activity.[25]

In another retrospective study of 483 patients with an intermediate pretest likelihood of obstructive CAD, PCAT attenuation was not associated with MACEs over a median follow-up of 9.5 years.[26] However, findings from the longitudinal multi-centre ORFAN (Oxford Risk Factors And Non-invasive imaging) study,[27] including 40 091 patients undergoing clinically indicated CCTA, an elevated fat attenuation index score across all three coronary arteries was strongly associated with increased risk for cardiac mortality and MACE, when comparing patients in the top vs. bottom quartile for each artery. A newly developed AI-assisted prognostic algorithm (AI-Risk), which integrates fat attenuation index score from each coronary artery along with coronary atherosclerotic plaque burden and traditional risk factors, was significantly associated with cardiac mortality and MACE, and performed well on internal and external validation testing.[27]

Several studies have explored the prognostic value of 18F-sodium fluoride PET-derived assessment of coronary atherosclerotic plaque activity in individual coronary arteries and its association with myocardial infarction (MI) risk. In a secondary analysis of an international multicentre study of patients with recent MI and multivessel CAD, Wang

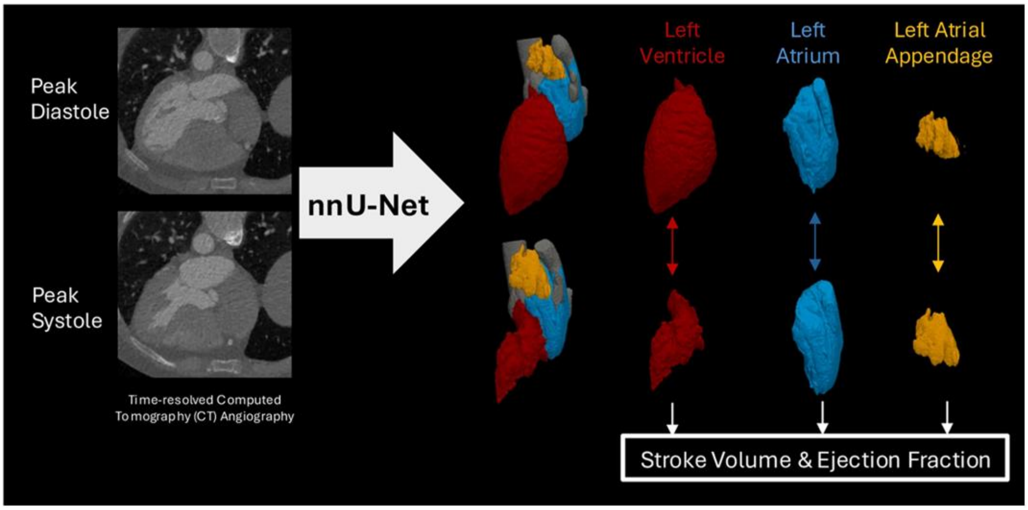


Figure 6 Accurate fully automated assessment of left ventricle, left atrium, and left atrial appendage function from computed tomography using deep learning (U-Net is a convolutional neural network commonly used for medical image segmentation). Reproduced from Jollans L *et al.*[16]

et al.[28] demonstrated that MI occurred more frequently in vessels exhibiting increased coronary atherosclerotic plaque activity compared to those without increased activity. Furthermore, increased coronary atherosclerotic plaque activity across multiple coronary arteries was associated with a higher patient-level risk of cardiac death or MI as well as a greater likelihood of first and total MI.[28] Additional analysis of sex differences in the predictive value of 18F-sodium fluoride PET imaging revealed that while men exhibited more severe and extensive CAD, there was no sex-related difference in coronary microcalcification activity.[29] Moreover, coronary microcalcification activity was associated with an increased risk of future MI, independently of sex.[29]

Emerging research has also explored novel imaging biomarkers for predicting adverse cardiovascular outcomes in ischaemic heart disease. Analysis of the expanded SPINS (Stress CMR Perfusion Imaging in the United States) cohort identified peri-infarct ischaemia—defined as ischaemic segments adjacent to infarcted regions—as the strongest predictor of mortality and adverse cardiovascular events, with a more than 6-fold increase in primary event rates even after adjustment for clinical factors, LV function, ischaemia extent, and infarct size.[30]

Coronary artery calcium scoring (CACS) has been shown to provide incremental prognostic information beyond traditional risk factors for MACE in asymptomatic patients; however, its utility in symptomatic patients referred for invasive coronary angiography has been less well understood. A sub-analysis of the DISCHARGE (Diagnostic Imaging Strategies for Patients With Stable Chest Pain and Intermediate Risk of Coronary Artery Disease) trial demonstrated a strong correlation between CACS and the prevalence of obstructive CAD on CCTA.[31] The prevalence of obstructive CAD increased from 4.1% (95% CI: 2.8, 5.8) in patients with a CACS of 0% to 76.1% (95% CI: 70.3, 81.2) in those with a CACS of 400 or higher. Furthermore, patients with a CACS of 0 had a significantly lower MACE risk, as did those with a CACS between 1 and 399, compared with those with a CACS of 400 or higher.[31]

Recent studies have investigated the relationship between metabolic risk factors, coronary microvascular dysfunction and long-term cardiovascular outcomes. A quantitative perfusion CMR study in middle-aged asymptomatic individuals without known cardiovascular disease found that cardiometabolic risk factors, including metabolic syndrome components, diastolic blood pressure, diabetes, and elevated fasting plasma glucose, were associated with impaired coronary microvascular function, as indicated by an inverse relationship between myocardial perfusion reserve and these risk factors.[32] Another study assessed the prognostic value of high fasting plasma glucose and MBF reserve measured by PET in predicting long-term outcomes in patients with stable chest pain or dyspnoea.[33] Over a median follow-up of 10.9 years, age, high fasting plasma glucose, and depressed MBF reserve were independent predictors of death, with only high fasting plasma glucose and reduced MBF reserve significantly associated with increased long-term risk of death and MACE.[33]

Valvular heart disease

Aortic valve

Recent studies provide insights into parameters that may refine risk and the underlying mechanism of myocardial damage that is often associated with aortic stenosis (AS).

Staging classifications for AS integrate extra-aortic valve parameters of myocardial damage. However, it is unclear whether myocardial damage results from altered aortic valve haemodynamic or reflects coexisting comorbidities. A cohort study of 9611 patients from the Mayo Clinic with mild AS demonstrated that myocardial damage prevalence was strongly linked to comorbidities, such as hypertension and ischaemic heart disease, rather than AS severity.[34]

Thellier *et al.*[35] used speckle-tracking echocardiography to assess LV mechanical dyssynchrony (by LV mechanical dispersion). In a cohort of 364 patients with severe AS and preserved LVEF, an LV mechanical dispersion threshold of 68 ms was found to predict mortality in patients with severe asymptomatic AS, providing additional prognostic value over LV GLS.

Another study compared LV and RV systolic function in patients with severe, symptomatic AS who underwent surgical aortic valve replacement (SAVR—from the Placement of Aortic Transcatheter Valves [PARTNER 2A] trial, randomized cohort) or transcatheter aortic valve replacement (TAVR—from the PARTNER 2 SAPIEN 3 registry).[36] Although LVEF improved at 1 year in both groups, there was earlier recovery of LV systolic function in the TAVR cohort based on LV longitudinal strain. Furthermore, RV–pulmonary artery (PA) coupling and tricuspid annular plane systolic excursion (TAPSE) remained stable after TAVR but deteriorated in SAVR patients and predicted cardiac mortality at 5 years.

Mitral valve

The clinical significance of mitral annular disjunction (MAD) remains debated. Figliozzi *et al.*[37] examined MAD in 441 patients undergoing CMR to define the threshold between normal variation and pathology. They found that while MAD can be present in healthy individuals, its extent and coexisting myocardial changes may help distinguish benign from disease-associated forms. In another analysis, Verheul *et al.*[38] report a high prevalence of inferolateral MAD in idiopathic ventricular fibrillation. Prospective studies in unselected cohorts are needed to clarify the prognostic significance of MAD.

Advancements in imaging techniques have enabled extraction of novel biomarkers for quantification of mitral regurgitation (MR), which require validation prior to integration into clinical care. Fiore *et al.*[39] establish cut-off values for 3D vena contracta area in MR grading and demonstrate its superior accuracy over conventional bidimensional methods. Berg-Hansen *et al.*[40] highlight sex-specific MR remodelling, showing that women have smaller LA volumes but greater stiffness than men, suggesting differences in MR adaptation and progression. A personalized approach is needed for optimal intervention timing.

Imaging is essential for assessing cardiac remodelling and functional outcomes following valve interventions. The COAPT (Cardiovascular Outcomes Assessment of the MitraClip Percutaneous Therapy for HF Patients with Functional Mitral Regurgitation) trial investigated LA improvement in HF patients with secondary MR who underwent transcatheter edge-to-edge repair (TEER).[41] The study found that TEER led to favourable LA remodelling, including reductions in LA volume and improved function, compared to medical therapy alone. These changes were associated with better clinical outcomes, suggesting that LA improvement may be a key mechanism in the benefits of TEER for HF patients with secondary MR.

Tricuspid valve

Two important papers were dedicated to patients with tricuspid regurgitation (TR). In the first study, procedural transoesophageal echocardiography was used to determine the best predictors of procedural success of tricuspid valve-TEER (T-TEER).[42] The five best predictors (septal-lateral coaptation gap, chordal structure density, en face TR jet morphology, TR jet location, and image quality) were incorporated in the GLIDE (Gap, Location, Image quality, density, en-face TR morphology) score. A score 0–1 predicted >90% TR reduction and moderate or less TR. External validation confirmed it as being an effective tool for predicting successful T-TEER.

Another study proposed the STREI (speckle-tracking echocardiography) index in severe TR, integrating right atrium (RA) and RV strain, for prediction of a composite of HF hospital admission and all-cause mortality, up to 2 years.[43] An index <50% demonstrated the highest accuracy. STREI stratification with four risk groups combining RV free wall longitudinal strain (>−20%) and reservoir RA strain (<10%) as binary variables demonstrated a better predictive performance, compared with each parameter separately, reflecting a broader effect of TR on right heart chambers.

Cardiomyopathies

Cardiomyopathies encompass a heterogeneous group of myocardial disorders, where the advancements in cardiovascular imaging are providing major diagnostic and prognostic contributions.

In patients with hypertrophic cardiomyopathy (HCM) some recent studies have confirmed that the burden and heterogeneity of late gadolinium enhancement (LGE) are associated with worse outcomes, and radiomics analysis has improved the predictive accuracy of sudden cardiac death (SCD) models by incorporating myocardial texture and shape features into risk assessment.[44,45] In a study on 1229 HCM patients, LV myocardial radiomic features were calculated from LGE images.[44] During a 4-year follow-up, sudden death events occurred in 30 (2.4%) patients. Risk prediction using radiomics resulted in higher c-statistics than the European Society of Cardiology risk score (0.69 vs. 0.57; $P = 0.02$) and the American College of Cardiology/American Heart Association algorithm (0.69 vs. 0.67; $P = 0.75$). In particular, LGE heterogeneity was a major component of radiomic analysis and a significant predictor of SCD risk. In another study on HCM 758 patients, a machine learning prognostic model integrating 14 CMR imaging features (including strain and LGE) and 23 clinical variables was developed.[45] MACEs included a composite of arrhythmic events, SCD, HF, and atrial fibrillation-related stroke. The model outperformed the European risk score. In particular, LGE extent, global radial strain and global circumferential strain were non-linearly correlated with MACEs.

Recent pharmacological advances, particularly with mavacamten, have further transformed HCM management. By reducing LV outflow tract obstruction, this myosin inhibitor has been shown to improve LV systolic function, as assessed by LV GLS, and clinical outcomes, offering a pharmacologic alternative to surgical septal myectomy.[46] Both free wall and 4-chamber RV-GLS remained unchanged, suggesting that mavacamten had no detrimental impact on RV systolic function

Dilated cardiomyopathy (DCM) is defined by LV dilation and systolic dysfunction, while non-dilated left ventricular cardiomyopathy (NDLVC) includes patients with either LV systolic dysfunction or LV fibrofatty replacement, in the absence of LV dilation. The integration of genetic and imaging findings allows for better diagnostic and prognostic assessment of patients affected by these two cardiomyopathies. Recently, a large multicentre study provided a thorough clinical, genetic and imaging characterization of 235 NDLVC patients and 227 DCM patients.[47] In comparison to DCM, NDLVC had a higher prevalence of pathogenic or likely pathogenic variants of arrhythmogenic genes (40% vs. 23%), higher LVEF (51% vs. 36%), and higher prevalence of free-wall LGE (27% vs. 14%). Conversely, DCM showed higher prevalence of pathogenic or likely pathogenic variants of non-arrhythmogenic genes (23% vs. 12% and septal LGE (45% vs. 32%). Septal LGE, LV dilatation, age, advanced New York Heart Association class, frequent and recurrent ventricular arrhythmias were independent predictors of SCD or major ventricular arrhythmias. Myocardial tissue heterogeneity has also been recently investigated with a novel LGE-derived parameter, i.e. LGE-dispersion mapping. In a study on 510 DCM patients (45% with LGE, with a median extent 12% of LV mass), LGE-dispersion mapping resulted an independent predictor of malignant ventricular arrhythmias during a 3.3-year follow-up.[48] Its prognostic value was confirmed in the subgroups of patients with LVEF ≤ 35% and >35%. Other studies investigated the incremental diagnostic and prognostic role of T1 and extracellular volume (ECV) mapping in DCM: in a recent metanalysis including 12 observational studies on 4025 DCM patients, both native T1 mapping and ECV were associated with increased risk of HF and arrhythmic-related events.[49]

Sex-based differences in cardiomyopathy phenotypes have garnered attention in recent research. A large study on 747 patients [531 (71%) males] with non-ischaemic cardiomyopathies demonstrated that women presented with greater concentric remodelling, less severe bi-ventricular systolic dysfunction, and a lower burden of replacement fibrosis, but a similar prognosis compared to men.[50] After Z-score correction for chamber volumes and function compared to 157 sex-matched healthy volunteers, women showed significantly higher LVEF, LV mass and RVEF compared to men, despite similar chamber volumes and a lower prevalence of mid-wall LGE (22% vs. 34%). Over a median follow-up of 4.7 years, 173 patients (23%) experienced the composite outcome (all-cause mortality, HF admission, or ventricular arrhythmia), with equal distribution in males and females. Left ventricular volumes and ejection fraction and LGE were significant independent predictors of the outcome, while sex was not.[50] These findings highlight sex-specific differences in disease expression and suggest the potential need for tailored therapeutic approaches.

Cardiac amyloidosis is an infiltrative cardiomyopathy where cardiac imaging plays a pivotal diagnostic and prognostic role. Cardiovascular magnetic resonance is currently very accurate in detecting cardiac amyloidosis, but performance in differentiating transthyretin (ATTR) from immunoglobulin light chain (AL) forms is still matter of debate. In a small study on 53 amyloid patient (20 AL, 33 ATTR) and 22 controls with non-amyloid LV hypertrophy, ECV was confirmed as the single best parameter to detect cardiac amyloidosis (AUC 0.97, cut-off: >30%).[51] Moreover, T2 mapping was the best single parameter to differentiate between AL and ATTR amyloidosis (AUC: 0.86, cut-off: >61 ms), particularly when combined with a subendocardial LGE pattern (AUC: 0.96).[51] Other recent studies performed an echocardiographic characterization of amyloidosis. A large study on 544 amyloid patients showed that relative wall thickness and apical sparing ratio were the most accurate parameters for differentiating amyloid from 200 control patients (AUC 0.77 and 0.74, respectively), but apical sparing ratio was only 72% sensitive and 66% specific, being present also in 32% of control patients.[52] Another study on 538 amyloid patients showed 112 (21%) had isolated moderate and/or severe MR, 66 (12%) isolated moderate and/or severe tricuspid regurgitation, 120 (22%) combined mitral and tricuspid regurgitation.[53] Patients with isolated TR and combined MR/TR had an increased risk of all-cause death or worsening HF events, independently from other clinical and imaging factors, with tricuspid regurgitation carrying the highest risk.

Heart failure

Within the field of HF, adequate risk stratification of patients with HF with reduced ejection fraction (HFrEF) remains challenging. Abou Kamar *et al.*[54] studied the association between circulating proteins and echocardiographic parameters in patients with HFrEF. Circulating proteins reflecting different biological mechanisms were overrepresented in the different pathological processes. He *et al.*[55] hypothesized that patients with HF with preserved ejection fraction (HFpEF) and normal natriuretic peptide levels may represent a separate HFpEF subtype with adverse prognosis. Eventhough more extensive research is warranted, occurrence of atrial fibrillation, haemoglobin level and specifically early-diastolic global longitudinal strain rate were associated with occurrence of the primary endpoints (death, HF hospitalization, or stroke).

The prognostic implication of lung ultrasound in HF was investigated by Rastogi *et al.*[56] They showed that an increased number of B lines in patients with HF was associated with an increased risk of morbidity and mortality, irrespective of the clinical characteristics. Right ventricular dysfunction is of prognostic significance in all subtypes of HF. However, RV function cannot be interpreted without considering its interaction with the pulmonary circulation. Fauvel *et al.*[57] investigated whether the non-invasive assessment of TAPSE over systolic pulmonary artery pressure ratio (TAPSE/sPAP) is of prognostic value for patients hospitalized with acute HF. It was concluded that TAPSE/sPAP <0.40 mm/mmHg determined during an acute HF episode is independently associated with in-hospital MACEs. Another study assessed the usefulness of internal jugular vein distensibility by ultrasound as a non-invasive tool to assess right atrial pressure. Jugular vein distensibility was calculated as the Valsalva-to-rest ratio of the vein diameter in a calibration cohort ($n = 100$) and a validation cohort ($n = 101$) of HF patients who underwent pulmonary artery catheterization: a distensibility threshold of 1.6 identified patients with RA pressure ≤7 vs. >7 mmHg (AUC 0.74 in the calibration cohort, AUC 0.82 in the validation cohort) and was associated with worse prognosis.[58]

There has been an increasing number of studies which incorporate non-invasive LV pressure-strain loop among their bidimensional speckle-tracking echocardiography assessments. This method allows for quantifying myocardial work by incorporating LV pressure in measurements of myocardial deformation. Olsen *et al.*[59] have shown that hypertension modifies the association between LV myocardial work indices as measured by pressure-strain loop and HF outcomes. Saffi *et al.*[60] evaluated the potential role of global constructive work for predicting ventricular arrythmias. In patients with guideline recommended cardiac resynchronization therapy, during a median follow-up of 18 months, they showed that a below-median global constructive work (<1473 mmHg%) was associated with a 5-fold increase in the risk of ventricular arrhythmias.[60]

Several recent studies investigated LA strain with speckle-tracking echocardiography. As an example, Barki *et al.*[61] measured LA mechanics in patients with acute decompensated HF. In their longitudinal study with repeated measures, they showed better prognosis in patients with better LA strain. In another prospective study of patients with HFrEF undergoing cardiac transplantation, Mandoli *et al.*[62] showed a strong correlation of reduced global peak LA longitudinal strain with the invasively assessed LV filling pressure and degree of LV fibrosis assessed from myocardial biopsy samples obtained from the explanted heart of each patient immediately after transplantation.

Learning points

Recent progress in cardiovascular imaging is establishing new standards in cardiology for early detection, prognosis, and personalized treatment of heart diseases, driven by technological innovations and a deeper understanding of disease mechanisms. The integration of advanced imaging, genetic testing, and AI algorithms offers unprecedented opportunities for personalized care. Future research should focus on refining these tools and expanding access to ensure that the benefits of precision medicine are realized across diverse patient populations (Graphical Abstract).

Lead author biography

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Acknowledgements

This review was written by members of the Research and Innovation Committee (A.B., A.T.T., S.E.M., S.B.-J., G.E.M., E.L., A.A.R., Z.R.E., R.L., G.P., and D.N.), of the Heart Imagers of Tomorrow (HIT)

Committee (C.L., G.E.M., S.M., A.A.) and of the Web and Communication Committee (SME) of the European Association of Cardiovascular Imaging (EACVI). We would like to thank Dr Veronique Brassart for her invaluable help. Figures were drawn by using BioRender (https://www.biorender.com).

Funding

This research received no specific funding. A.A. was supported by a Grant by the Hellenic Foundation for Research and Innovation (HFRI), grant number 00468. C.L. received salary support from the Vancouver Coastal Health Research Institute and the Heart & Stroke Foundation. E.L acknowledges the support of a Wellcome Trust Clinical Career Development Fellowship (grant number: 221690/Z/20/Z). Z.R.E acknowledges the support of the National Institute for Health Research Barts Biomedical Research Centre (NIHR203330).

Conflict of interest: G.P. received honorarium as speaker/consultant and institutional research grant from GE Healthcare, Bracco, Heartflow, Novartis, Alexion, Menarini. All other authors have nothing to disclose.

Data availability

No new data were generated or analysed in support of this research.

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