Cardiac Imaging in Heart Failure with Comorbidities

Chiew Wong, Sylvia Chen and Pupalan Iyngkaran*

Flinders University, NT Medical School, Darwin Australia

Abstract: Imaging modalities stand at the frontiers for progress in congestive heart failure (CHF) screening, risk stratification and monitoring. Advancements in echocardiography (ECHO) and Magnetic Resonance Imaging (MRI) have allowed for improved tissue characterizations, cardiac motion analysis, and cardiac performance analysis under stress. Common cardiac comorbidities such as hypertension, metabolic syndromes and chronic renal failure contribute to cardiac remodeling, sharing similar pathophysiological mechanisms starting with interstitial changes, structural changes and finally clinical CHF. These imaging techniques can potentially detect changes earlier. Such information could have clinical benefits for screening, planning preventive therapies and risk stratifying patients. Imaging reports have often focused on traditional measures without factoring these novel parameters. This review is aimed at providing a synopsis on how we can use this information to assess and monitor improvements for CHF with comorbidities.

Keywords: Congestive heart failure, comorbidity, echocardiography, imaging, MRI, review.

INTRODUCTION

Screening and risk stratification of congestive heart failure (CHF) are among the most established sciences for planning management pathways. Risk scores require information from clinical signs and symptoms, biomarkers, and imaging modalities. End-organ changes from causative comorbidities go through well defined stages, for example diabetes (DM), hypertension (HT) or chronic renal impairment (CRI) that leads to adverse cardiac remodeling (CR), would present with a history of poor control, subtle clinical symptoms and signs, and abnormal disease specific biomarkers before overt end organ damage [1-7]. Some of the earliest changes in tissues, e.g. endothelial dysfunction can be detected in peripheral blood vessels by techniques such as flow mediated dilatation and carotid intimal thickness. These techniques provide valuable information but are not readily available in all centers. Other investigations such electrocardiography (ECG) and brain natriuretic peptides (BNP) lack in sensitivity, specificity or reproducibility [6, 7].

Cardiac ultrasound or echocardiography (ECHO) and cardiac magnetic resonance imaging (CMR) can similarly characterize cardiac tissue with improved accuracy, adding information for risk scoring of CHF. The Framingham [8], Olmstead County [9], The Multi-Ethnic-Study of Atherosclerosis (MESA) [10], CARDIA [11], Dallas Heart [12], HyperGEN [13], Cardiovascular Health [14] and The Strong Heart Studies [15] have contributed to data that show early changes of diastolic dysfunction, left ventricular hypertrophy and regional myocardial deformation portend worse prognosis even in earliest stages [6, 8, 9, 14, 16-22]. The ability to monitor these processes, importantly, many of which are not unidirectional and thus can be delayed or reversed by treatments [6, 8, 9, 14, 16-22]. Furthermore it provides an additional avenue for clinicians to plan chronic disease care and alter the temporal profile for prevention and treatment closer to the evolution of the disease process. Accordingly some clinical and imaging guidelines have factored this in their guidelines. In this review we explore two imaging modalities that can characterize myocardial tissue and analyze myocardial mechanics providing additional information relevant for CHF care.

KEY PRINCIPLES

Pathophysiological Considerations in the Evolution of Heart Failure

All structures in the heart are subject to direct or indirect changes from comorbidities, such as the supporting connective tissues (CT), septum, valves, conduction system, blood vessels and the myocardium itself. Changes can manifest in tissue characteristics and mass, geometry, cardiac function and reserve. Cardiac remodeling (CR) is the term that best describes the pathophysiological process that alters molecules and genes within the cell and extracellular matrix that contributes to the clinical syndrome of CHF. There are 2 important processes affecting the anatomy and function that can be quantified [6, 23, 24]. Figure 1 highlights the evolution of this process with a clinical reference.
1. **Cardiac and vascular anatomy:** increased cross-links of collagen and laminin fibers leading to remodeling of the extracellular matrix or ‘cardiac fibrosis’, a stage in CR. Myocardial cells also undergo structural changes including increases in cross sectional area, best described as hypertrophy or dilatation, and best studied in the left ventricle.

2. **Cardiac and vascular function:** Contraction occurs in two quantifiable phases. In ventricular systole contraction longitudinally (base moves to apex), radially (wall thickening) and circumferentially (cavity size reduction) are coupled with rotation (base and apex moving in opposite directions) and twist where helical myocardial fibers are orientated right handed in the subendocardium to circumferential in midwall and left handed in subepicardium. Ventricular diastole is a passive energy dependent reversal of the previous process. Tissue displacement and the rate at which it occurs are quantifiable in direction and magnitude. CR increases diastolic wall stress.

3. **Echocardiographic Principles**

   When sound waves (ultrasound) interact with cardiac tissues the resulting effect can be described by four phenomena: reflection, scattering, refraction and attenuation. Thus far the novel technology allows us to exploit the first two factors. Doppler velocity and speckle tracking can measure strain, torsion or twist, surrogates for myocardial systolic mechanics. Diastolic function can be determined by spectral doppler at mitral valve and tissue doppler at the mitral annulus. Multiarray transducers can provide 3D echocardiographic images. These appear to have increased accuracy and reproducibility for quantifying volumes and function, as geometric assumptions are negated [24].

**CMR Principles**

Imaging of protons within hydrogen atoms can be done in any plane with unrestricted field of view, and without geometrical assumptions. Various MRI sequences can be used to obtain the desired information (Table 1) [25-29]. Spin echo with dark blood provides the highest resolution for static morphology and structure. Phase contrast sequences with myocardial tagging can map myocardial mechanics as contractility, strain or twist. CMR contrast techniques with gadolinium based contrast agents that remain in the extracellular space can identify regional fibrosis or scar. Tissue mapping techniques such as TI mapping can also identify interstitial fibrosis.

---

**Fig. (1).** Heart Failure and role of Imaging Technique. As disease progresses the risk of heart failure increases with gradual remodeling with interstitial deposition followed by structural changes. The advent of diastolic dysfunction which often precedes systolic dysfunction is perhaps the earliest stage of clinical CHF. In the at risk stages, structural changes are either undetectable in early in stage A or inferable later in stages A to B using novel MRI and echocardiographic techniques. When CHF has developed, these techniques can also be used to provide incremental information that point to a greater risk of an adverse outcome. Many of these areas are still evolving and could play important roles for clinical practice. Stages of HF: A – At high risk but without structural heart disease or symptoms; B – Structural heart disease but without symptoms; C – Structural heart disease with current or previous symptoms; D – Refractory HF requiring specialized intervention. Concepts adapted from Ref 6
Assessing Cardiac Remodeling

Echo and CMR could benefit ACC stage A and B patients by detecting subclinical components of geometry and deformation (function) of early HF (Fig. 1). Comorbidities such as diabetes [1, 31-33], hypertension [2, 34-36], obesity [21, 37-41] and renal impairment [3, 42-44] can all contribute to cardiac remodeling individually, together or idiosyncratically. Myocardial hypertrophy is an early feature of CR and warrants further discussion. Morphologically the left ventricle can be classified as having: normal geometry [normal left ventricular mass (LVM) and relative wall thickness (RWT)]; concentric remodeling (normal LVM, ↑ RWT); concentric hypertrophy (↑ LVM, normal RWT); or eccentric hypertrophy (↑LVM, normal RWT). Cardiac remodeling is defined by M-mode echo as LVM >115g/m² in men and >95g/m² in women or RWT >0.42. Subclinical alteration in systolic function is also a feature of CR, but has been less well studied and described. Risk scores are the easiest to use non-invasive surrogates. However, they are inconsistently used as they do not consistently assist daily clinical decisions [45, 46]. Examples include the Framingham, Health ABC and Atherosclerotic Risk In Communities (ARIC) HF risk scores, which predict 10-year risk of CHF [47-49]. Adding N-terminal pro-B-type natriuretic peptides (NT-proBNP) increases risk prediction [47]. Biomarkers and ECG on their

Novel imaging techniques are able to quantify structural (fibrosis, mass, shape) and functional changes with improved temporality. This added information could have benefit for monitoring and planning treatments. However, there remain limitations of these modalities in routine clinical practice. Echocardiographic imaging of the earliest changes is based on extrapolation of tissue-ultrasound interaction to infer subtle changes in LV structure or function, and is limited by patient characteristics. MRI is able to combine anatomical and functional data regardless of patient characteristics, in many aspects with less inference. Sensitivity, specificity and reproducibility are further areas that require attention in both these modalities. Abbreviations: cm – centimeter; d – degree; DENSE - displacement encoding with stimulated echoes; DF – diastolic function; FSE – fast spin echo; GBCA - Gadolinium based contrast agents; GRE – gradient echo; L – final length; L0 – original length; LGE = late gadolinium enhancement; LV – left ventricular; PSIR - phase sensitive inversion recovery s – second; SF – systolic function; SR = strain rate; V – velocity.

Concepts adapted from Ref 5.

Table 1. Novel Techniques and Clinical Correlates for the Left Ventricle.

| Echocardiography | Modality                  | Methodology                                      | Clinical Correlate/ Time | Notes                                      |
|------------------|---------------------------|-------------------------------------------------|--------------------------|--------------------------------------------|
|                  | Tissue Doppler Imaging    | Velocity (cm/s) with pulsed doppler              | DF                       | Pro:                                      |
|                  | Tissue Doppler Strain     | SR = (V₂ – V₁)/D (s⁻¹)                          | DF                       | Availability                          |
|                  | Speckle Tracking Strain   | [(L - L₀)/ L₀] x 100%                           | DF                       | Standardization                     |
|                  | Speckle Tracking motion   | Rotation – long axis circular motion (d)        | DF, SF                   | (Intermediate limitation)             |
|                  |                           | Twist – difference in rotation base and apex (d)|                         | Cost                                  |
|                  |                           | Torsion – gradient in rotation angle from base to apex (d/cm) |                         | Time                                  |
| Stress Testing   | Tissue Doppler Strain     |                                                  |                         | Reproducibility                     |
|                  | Speckle Tracking          |                                                  |                         | Sensitivity                          |
| 3D Echo          | Volume and surface rendered imaging |                                            | SF                      | Specificity                          |
| MRI              | Pulse Sequence CMR        | SE/FSE Dark Blood                               | Anatomy                  | Pro:                                   |
|                  |                           | T1 FSE                                           | Chamber, vasculature, pericardium, fat | Accuracy                          |
|                  |                           | T2 FSE                                           |                         | Reproducibility                     |
|                  |                           | Multi-Echo SE T2                                 |                         | Sensitivity                          |
| Cine CMR         | GSE or Cine steady state free precision (SFPP) |                                      | Motion and volumes     | Specificity                          |
|                  |                           | Bright Blood                                     |                          | Pro:                                   |
|                  | Modifiers                 | FSE Saturation recover T1 weighted imaging      | Improve image            | Accuracy                          |
|                  |                           | FSE Inversion recovery - T2 fat suppression     | Edema, ischemia, infection, infiltration | Reproducibility                     |
|                  |                           | GRE Myocardial grid or line tagging/ phase contrast / DENSE | Intramyocardial motion (T) | Sensitivity                          |
|                  |                           | GRE Phase Contrast                               | Flow velocity/vol       | Specificity                          |
| Contrast         | GBCA                      |                                                  | Blood Flow               | Cons:                                |
|                  | GBCA T1 - LGE PSIR        |                                                  | Fibrosis                 | Availability                        |
| Perfusion imaging| Adenosine                 |                                                  | Ischemia                 | Cost                                  |
|                  | Dobutamine                |                                                  |                          | Standardization                     |

Novel imaging techniques are able to quantify structural (fibrosis, mass, shape) and functional changes with improved temporality. This added information could have benefit for monitoring and planning treatments. However, there remain limitations of these modalities in routine clinical practice. Echocardiographic imaging of the earliest changes is based on extrapolation of tissue-ultrasound interaction to infer subtle changes in LV structure or function, and is limited by patient characteristics. MRI is able to combine anatomical and functional data regardless of patient characteristics, in many aspects with less inference. Sensitivity, specificity and reproducibility are further areas that require attention in both these modalities. Abbreviations: cm – centimeter; d – degree; DENSE - displacement encoding with stimulated echoes; DF – diastolic function; FSE – fast spin echo; GBCA - Gadolinium based contrast agents; GRE – gradient echo; L – final length; L₀ – original length; LGE = late gadolinium enhancement; LV – left ventricular; PSIR - phase sensitive inversion recovery s – second; SF – systolic function; SR = strain rate; V – velocity.

Concepts adapted from Ref 5.
own lack accuracy and reproducibility, while cardiac CT exposes individuals to unacceptable radiation [6, 50, 51].

**COMORBIDITY ASSESSMENT WITH ECHOCARDIOGRAPHY**

**Disease Specific Considerations**

There are no contraindications to echocardiography. In the majority of cases echocardiography provides qualitative and quantitative information with good sensitivity, specificity and reproducibility at rest and under stress. Operator and observer training contribute largely to any temporal variations. Client related factors such as chronic lung disease and obesity can interfere with optimal image quality.

**Cardiac Geometry with Echocardiography**

2DE is the gold standard for assessing and is also the only guideline-approved modality for monitoring volumes and mass, which also has prognostic correlates. In this assessment we have to make an assumption of the LV shape as ellipsoid. In addition the formula for mass requires a cubing of the linear measurements, with the potential to magnify errors. Many of the earlier studies used M-Mode to generate and report data [52-57]. This is one reason this important prognostic marker, is not used more readily in clinical decision-making. Armstrong et al. and Gjesdal et al. have presented the findings in chronological detail. Essentially the findings support good reproducibility and reliability when one method is used. M-Mode is however the least accurate. Large hypertensive trials and population studies have been the main source for data. Variations in ethnicity and sex can be standardized by body surface area [6, 54, 57]. Several points are worth considering: less standardization have been done for non-hypertensive comorbidities; and despite positive reproducibility, many clinicians use the geometric findings but not the LVM in routine clinical decisions.

3DE, with increased spatial resolution, provides greater accuracy than 2DE for volumes and LVM. The early studies showed comparable results with CMR, with better interobserver variability compared to 2DE [58-64]. Increasingly comparisons are being done with younger participants, obese subjects, dialysis, post myocardial infarction, dysssynchrony and with novel techniques such as 3D strain dispersion, with promising findings [65-71]. 3DE is limited by lower temporal resolution than 2DE. Acquisition still requires good windows and image quality. Patients need to comply with breath holds to acquire images over several heartbeats. Cardiac arrhythmias can be a problem. Finally post-processing is required. Thus 2DE remains the gold standard cardiac investigation for all cases where feasible. 3DE echo is likely to fill the space where MRI level accuracy and reproducibility are needed, such as volumes and LVM.

**Cardiac Function with Echocardiography**

Tissue Doppler imaging (TDI) assessing diastolic function, is now validated and in the guidelines. TDI and speckle tracking can be used to quantify myocardial strain and strain rate. The latter, that is angle independent, has also been increasingly used to assess torsion. Such subtle changes can be seen when the ventricular structure is altered, the connective tissues is fibrosed, wall stress is increased or a reduction in blood supply at rest or exercise. Many of the earlier studies went on to study these techniques in normal subjects and athletes [72-82], while validating the technique with other modalities including over time [83-87], which allowed factoring in guidelines [88]. Clinical correlations have highlighted predictive capacity for exercise capacity in HF [89], prognosis [90], valve assessment [91-93], chemotherapy cardiotoxicity [94] and ischemia evaluation [95-99]. The data suggest that, like TDI this technique is user friendly and can answer important clinical questions. The important points are addressing subclinical changes reproducibly. The data from oncology patients and valve assessment is an example where this technique can alter practice. What is needed are prospective studies where actual clinical decisions are made in comparison to CMR derived data.

Moving on, this point than becomes relevant in assessing and monitoring for cardiac changes from comorbidities. In obesity the multiethnic CARDIA study tracked 3,265 participants aged 18-30 years from the mid 1980’s. After 25 years the authors noted associations between impaired stress echocardiography (STE) systolic and diastolic parameters with duration of obesity. A comparison of STE at baseline was however not possible [100]. These changes appear to occur quite early [101]. In 172 diabetes followed for 3 years, baseline decrease in longitudinal systolic strain was associated with greater wall thickness and volumes that failed to decrease over time [102]. This appears to correlate with the severity of diabetes. Supporting this finding, in 1,065 type 1 diabetics decrease strain was largely noted in participants with albuminuria [103]. Furthermore in the Val- sartan trial of heart failure with preserved ejection fraction, in 219 subjects and 50 hypertensive and normal controls lower strain rates identified systolic impairments, not detected by routine 2DE [104]. Interestingly these studies appear to paint a picture consistent with the chronology and pathophysiology. Hypertensives appear to have changes later and starting with the basal segments with radial and circumferential segments altered later. As LVM and wall thickness correlates with strain impairment, this would imply that strain may not be as beneficial in HT, or alternatively the added information could point to other contributors to CR [105, 106]. Finally in CRI, where hypertension and diabetes are potential contributors, strain rate imaging similarly confirms the ability to detect subclinical systolic changes [107, 108]. A learning curve still exists for use in dynamic loading conditions [109].

**COMORBIDITY ASSESSMENT WITH CMR**

**Disease Specific Considerations**

Excluding the routine contraindications and patients preference CMR has no limitations for major comorbidities if safety guidelines are adhered [110]. Nephrogenic systemic fibrosis, a very rare but serious multisystem disease has been associated with the use of gadolinium contrast agents. The greatest risks are in renal impairment (glomerular filtration rate <30ml/min/1.73m²) and these patients are typically excluded from contrast administration unless the information obtained is likely to outweigh the risks [28]. We believe
however that in many patients with severe renal impairment, CR is usually advanced and other modalities can provide similar information.

CMR for Cardiac Geometry

CMR is the gold standard for ventricular geometry assessment [57, 111-113], with validation in an ex-vivo canine model [30]. Direct comparison with 2D echocardiography (2DE) has shown superior accuracy and reproducibility [114-116]. Accurate and reproducible imaging of chamber size, wall thickness and mass are among the most important surrogates in ACC stage A/B HF risk prediction [6, 7]. The Multi-Ethnic-Study of Atherosclerosis (MESA) study, with 4,309 participants provides much of the data on CMR and LVM [117]. In a review by Armstrong et al., four studies from MESA and a fifth with 2194 participants referred for known or suspected coronary artery disease, showed correlations with development of HF and adverse clinical outcomes with follow-up from 2.5 to 5.8 years [57, 118-122]. Higher systolic blood pressures were associated with increased LVM and volume [41], while participants diagnosed with diabetes had 1.5 fold increased risk of LVH, increased LVM, lower stroke volumes and ejection fractions [41, 123, 124].

Similarly in the Dallas Heart Study with 2, 548 healthy participants increasing cystatin C levels correlated with higher LVM [117]. In a review by Armstrong et al., four studies from MESA and a fifth with 2194 participants referred for known or suspected coronary artery disease, showed correlations with development of HF and adverse clinical outcomes with follow-up from 2.5 to 5.8 years [57, 118-122]. Higher systolic blood pressures were associated with increased LVM and volume [41], while participants diagnosed with diabetes had 1.5 fold increased risk of LVH, increased LVM, lower stroke volumes and ejection fractions [41, 123, 124].

CMR for Cardiac Fibrosis

CMR is the gold standard for imaging myocardial fibrosis. With accurate measures of relaxation properties of tissues, changes in content of various components can be estimated and monitored over time to determine fluctuations between inflammation or fibrosis from many groups [133-147]. Myocardial fibrosis is a significant cause and consequence for HF. We are now learning that the pattern and degree of fibrosis are important factors. In ischemic cardiomyopathies LGE-CMR can assess viability or reversibility of injured myocardium following acute or chronic infarcts [148-152], without stressing patients [28, 153, 154], the transmural extent (even small subendocardial infarcts) [144] and localize no reflow segments [28, 155]. Combining T2-weighted imaging high signal from edema differentiates acute from chronic injury and size of ischemic zone following reperfusion [28, 156-159]. In non-ischemic cardiomyopathies LGE-CMR and more recently T1 mapping, can identify the foci of regional or diffuse scarring [133, 134]. These patterns vary with different etiologies for HF. The differences in the techniques are the tissue characterization with or without contrast replacement in the scar. T1 mapping has the added advantage of detecting diffuse interstitial fibrosis, thus severity, where LGE is less sensitive [133, 160].

In hypertensives and diabetics with preclinical HF, CMR detected fibrosis predicts the risk of diastolic dysfunction [138,139, 161] and future HF [162-164]. When comparing to a younger cohort with mean duration diabetes 4.7 years, aortic distensibility and diabetes duration correlated with diastolic dysfunction, which was significantly associated with lower peak systolic strain. In regards to prognosis, one study of 187 diabetic subjects showed one in three patients had LGE-CMR evidence of a silent prior myocardial infarction (MI). The subsequent 17 months of follow-up revealed there were four and seven fold increased risk of cardiovascular event and all-cause mortality, similarly noted in a larger study with 300 patients [165, 166], and even in those with just impaired fasting glucose [33, 167]. This highlights again that across the spectrum of the comorbid disease serial CMR can predict and monitor progression with therapies as early as ACC stage 1, or recommend those who require more aggressive treatment [168, 169]. There have also been benefits reported for predicting clinical response to resynchronization therapies [141, 142, 145-147] and electrophysiological procedures [140, 146].

Tissue mapping may also allow for prediction of which comorbid condition is contributing greater to the disease burden. The premise here is that disease duration, severity or poor control should show signs specific to that disease with a temporal profile. For example diabetic cardiomyopathy may be associated with cardiac steatosis, which precedes fibrous deposition [33, 164, 170]. Hypertensives would show cardiac geometrical changes earlier [6, 34-36]. CRI could show a combination as both the previous etiologies contribute and with areas of increased calcification. The prevalence and distribution of fibrosis has been well summarized by Mewton et al., describing: in diabetics, a nonspecific or ischemic pattern; in hypertensives, patchy, nonspecific or ischemic pattern; and CRI, ischemic pattern, diffuse and mid wall focal [160]. In time we should gain better insights into the temporal profiles of tissue changes and how this correlates with more advanced risk such as sudden cardiac death.

CMR Functional Imaging

Myocardial tagging has been used to show impairment in myocardial mechanics with carotid intimal thickness and higher calcium scores in asymptomatic participants [171-174]. Phase contrast imaging and myocardial tissue tagging can provide diastolic measurements that match or better 2DE: In the former similar parameters as Doppler echocardiography are used; in the latter diastolic torsion and strain recovery rates are extended with diastolic dysfunction [175, 176]. Stress Myocardial Perfusion Imaging by CMR provides greater accuracy than SPECT and is among the strongest predictors of major cardiovascular outcomes [177-184]. For real world clinical use three issues stand out: firstly, myocardial tagging requires extensive user involvement and are laborious and time consuming - the ability of new software to “feature track” myocardial MRI images without the
need for dedicated tracking sequences may address some of these issues; secondly, standardizations of values need further study; finally, sensitivity and specificity issues with any one modality. Increasingly combinations of parameters are being used to provide incremental benefits and negate this point. Specifically for comorbidities, studies have explored such combinations [185-190].

Among diabetics and obese subjects: in a study of 19 diabetics, 30 pre-diabetics and 16 controls who underwent comprehensive CMR, LVM and LV torsion, were increased while myocardial perfusion reserve (MPR) was decreased. There was significant correlation between MPR and early diastolic strain rate and LV torsion [191]; Ernande et al, showed in 37 diabetics without known heart disease circumferential, radial and longitudinal strain were decreased compared with 23 age matched controls, reproducibly between operators [192]; in obese subjects with poor echocardiographic windows, longitudinal systolic strain, and peak radial and longitudinal diastolic strain were lower in the 59 obese compared to 40 controls [193]. Among hypertensives, CMR offer good correlations for LVM, LVH and MPR which provide prognostic information [194]. There is less data on TI mapping and LGE in HDD [195, 196]. Nearly half of hypertensives with LVH have detectable fibrosis which correlates with diastolic abnormalities [197, 198]. Available data also suggests that the benefits in screening can be increased by recognizing aortopathy and atrial myopathies in HDD [199]. In the MESA study with 1184 participants peak systolic circumferential strain was inversely correlated with diastolic BP [200]. Small vessel ischemia can be a feature of LVH and HHD and is detected accurately by CMR [201-204]. CMR can similarly detail CR in CRI. As there are other determinants of LVH beyond hypertension including calcium-phosphate balance, this method can inform the adequacy for RRT [205-213]. Impairment in strain rates from all fibers, which go onto correlates with outcomes, is noted in early CRI and hemodialysis [210, 211]. Edwards et al, has summarized all the findings and associations with CRI and CMR and proposes strong arguments for increased use across all stages [208].

NOVEL IMAGING AND CLINICAL TRIALS

Clinical trials in HF can cost billions, and take and average of 7 years. Only 3 in 10 drugs recuperate investment costs and there is a high attrition rate for novel drugs. Innovations of heart failure therapeutics for many areas are lacking and the impetus for this is likely to decline, as the business case remains uncompetitive. It is thus vital that measures to reduce cost are explored. Imaging with novel techniques can reduce follow-up times. Presently surrogate endpoints for HF outcomes are unreliable or lacking [214]. Novel surrogates of CR will take time to secure a front line role in clinical trials. Routine electrocardiography and echocardiography will also remain a modality for the majority of information. An important area where CMR and 3DE should be used with the current evidence is the assessment of LVH and LVM [215, 216], and to guide protocol driven clinical decisions [217]. CMR is able to accurately obtain and reproduce these values that are also independent of loading conditions tested in all comorbidities mentioned in the review, thus potentially leading to reduced sample sizes [218-221].

LGE and strain rate imaging are also important parameters that will require more studies to understand the incidences, chronology and reversibility with therapies for the various comorbidities. Health systems should invest in researching novel imaging devices and techniques to deliver improvements in detection, initiating preventive therapies and/or improving clinical trial conduct.

CONCLUSION

Cardiac remodeling occurs chronologically in all the common comorbid contributors to CHF. In many of these cases cardiac fibrosis and hypertrophy can be identified early and accurately with echo and CMR. These tools are however not used frequently enough for this indication. There are still research translational gaps in the more novel non-invasive tools. However their promise for a ‘one stop shop’ from screening and risk stratification, to diagnosis, to monitoring and planning long term cardiovascular care will more than likely advance. It is important that knowledge of these techniques be disseminated to general practitioners, and specialists such that the experience can be built within health clusters. On the research front there are important gaps that need to be addressed. Feasibility of use particularly of acquisition times and offline processing in busy clinical units are areas manufactures need to factor. Clinician scientists need to generate data for normal values that can be standardized for clinical use for each modality and across modalities and factors these into guidelines. Cardiologists should increasingly factor these advancements for their patients.

DISCLOSURES

All co-authors have won independent and governmental research funding. None pose a conflict of interest for this review.

ABBREVIATIONS AND SYNONYMS

2DE = two dimensional echocardiography
ACH = All Cause Hospitalization
ACM = All Cause Mortality
AHF = Acute Heart Failure
CDMP = Chronic Disease Management Programs
CHF = Congestive Heart Failure
CM = cardiomyopathy
CMR = cardiac magnetic resonance
CRI = chronic renal insufficiency
CRT = cardiac resynchronization therapy
CT = connective tissues
DENSE = displacement encoding with simulated echoes
DM = diabetes mellitus
ECG = electrocardiography
ECHO = echocardiography
EF = ejection fraction
CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

ACKNOWLEDGEMENTS

Declared none.

REFERENCES

[1] Miki T, Yuda S, Kouzu H, Miura T. Diabetic cardiomyopathy: pathophysiology and clinical features. Heart Fail Rev 2013; 18: 149-66.
[2] Drazner MH. The Progression of Hypertensive Heart Disease. Circulation 2011; 123: 327-34.
[3] Schiffrin EL, Lipman ML, Mann JFE. Chronic Kidney Disease Effects on the Cardiovascular System. Circulation 2007; 116: 85-97.
[4] Dale Abel A, Litwin SE, Sweeney G. Cardiac Remodeling in Obesity. Physiol Rev 2008; 88(2): 389-419.
[5] Herzog CA, Asinger RW, Berger AK, et al. Cardiovascular disease in chronic kidney disease. A clinical update from Kidney Disease: Improving Global Outcomes (KDIGO). Kidney Int 2011; 80(6): 572-86.
[6] Gjesdal O, Blumeke DA, Lima JA. Cardiac remodeling at the population level - risk factors, screening, and outcomes. Nat Rev Cardiol 2011; 8(12): 673-85.
[7] Cohn JN, Ferrari R, Sharpe N. Cardiac remodeling – clinical concepts and clinical implications: a consensus paper from an international forum on cardiac remodeling. J Am Coll Cardiol 2000; 35: 569-82.
[8] Gjesdal O, Blumeke DA, Lima JA. Cardiac remodeling at the population level - risk factors, screening, and outcomes. Nat Rev Cardiol 2011; 8(12): 673-85.
[9] Gjesdal O, Blumeke DA, Lima JA. Cardiac remodeling – clinical concepts and clinical implications: a consensus paper from an international forum on cardiac remodeling. J Am Coll Cardiol 2000; 35: 569-82.
[10] Levy D, Garrison RJ, Savage DD, Kannel WB, Castelli WP. Prognostic Implications of Echocardiographically Determined Left Ventricular Mass in the Framingham Heart Study. N Engl J Med 1990; 322: 1561-6.
[11] Owan TE, Barger JD, Barlow JS, et al. ACRIN 6665: A Randomized Trial of Vasodilators to Improve Left Ventricular Function in Heart Failure Patients With Reduced Ejection Fraction. Am J Cardiol 2006; 98(11): 1566-71.
[12] Gardin JM, Arnold A, Gottlieber JS, et al. Left ventricular mass in the elderly. The Cardiovascular Health Study. Hypertension 1997; 29(5): 1095-103.
[13] Park SJ, Yoon SJ, Lee KH, et al. Incremental Prognostic Value of Assessing Left Ventricular Myocardial Mechanics in Patients With Chronic Systolic Heart Failure. J Am Coll Cardiol 2013; 62: 2074-81.
[14] Haider AW, Larson MG, Benjamin EJ, Levy D. Increased left ventricular mass and hypertrophy are associated with increased risk for sudden cardiac death. J Am Coll Cardiol 1998; 32: 1454-9.
[15] Cohn JN. Pharmacotherapy: inhibiting LV remodeling—the need for a targeted approach. Nat Rev Cardiol 2011; 8(5): 248-9.
[16] Gjesdal O, Blumeke DA, Lima JA. Cardiac remodeling at the population level - risk factors, screening, and outcomes. Nat Rev Cardiol 2011; 8(12): 673-85.
[17] Gjesdal O, Blumeke DA, Lima JA. Cardiac remodeling – clinical concepts and clinical implications: a consensus paper from an international forum on cardiac remodeling. J Am Coll Cardiol 2000; 35: 569-82.
[18] Gjesdal O, Blumeke DA, Lima JA. Cardiac remodeling – clinical concepts and clinical implications: a consensus paper from an international forum on cardiac remodeling. J Am Coll Cardiol 2000; 35: 569-82.
[19] Gjesdal O, Blumeke DA, Lima JA. Cardiac remodeling – clinical concepts and clinical implications: a consensus paper from an international forum on cardiac remodeling. J Am Coll Cardiol 2000; 35: 569-82.
[20] Gjesdal O, Blumeke DA, Lima JA. Cardiac remodeling – clinical concepts and clinical implications: a consensus paper from an international forum on cardiac remodeling. J Am Coll Cardiol 2000; 35: 569-82.
[29] Wang H, Amini AA. Cardiac Motion and Deformation Recovery From MRI: A Review IEEE Trans Med Imaging 2012; 31(2): 487-503.

[30] Childs H, Ma L, Ma M, et al. Comparison of long and short axis quantification of left ventricular volume parameters by cardiovascular magnetic resonance, with ex vivo validation. J Cardiovasc Magn Reson 2011; 13: 40.

[31] Bauter C, Lemblan N, Mc Fadden EP, Van Belle E, Millaire A, Groopo T. Influence of diabetes mellitus on heart failure risk and outcome. Cardiovasc Diabetol 2003; 2: 1.

[32] Devereux RB, Roman MJ, Parancias M, et al. Impact of Diabetes on Cardiac Structure and Function - The Strong Heart Study. Circulation 2000; 101: 2271-6.

[33] Shah RV, Abbasi SA, Kwong RY. Role of cardiac MRI in diabetes. Curr Cardiol Rep 2014; 16(2): 449.

[34] Nadruz W. Myocardial remodeling in hypertension. J Hum Hypertens 2015; 29: 1-6.

[35] Maceira AM, Mohiaddin RH. Cardiovascular magnetic resonance in systemic hypertension. J Cardiovasc Magn Reson 2012; 14: 28.

[36] Papari P, Konstantinou K, Sutaria N, et al. Comprehensive cardiovascular MRI in hypertension: a UK single centre experience. J Cardiovasc Magn Reson 2014; 16(Suppl 1): P236.

[37] Aurigemma GP, de Simone G, Fitzgibbons TP. Cardiac Remodeling in Obesity. Circ Cardiovasc Imaging 2013; 6: 142-52.

[38] Patel DA, Lavie CJ, Artham SM, Milani RV, Cardenas GA, Ventura HO. Effects of left ventricular geometry and obesity on mortality in women with normal ejection fraction. Am J Cardiol 2014; 113(5): 877-80.

[39] Chinali M, de Simone G, Roman MJ, et al. Impact of obesity on cardiac geometry and function in a population of adolescents: The Strong Heart Study. J Am Coll Cardiol 2006; 47(11): 2267-73.

[40] Lieb W, Xanthakis V, Sullivan LM, et al. Longitudinal tracking of left ventricular mass over the adult life course: clinical correlates of short- and long-term change in the framingham offspring study. Circulation 2009; 119: 3085-92.

[41] Heckbert SR, Post W, Pearson GD, et al. Traditional cardiovascular risk factors in relation to left ventricular mass, volume, and systolic function by cardiac magnetic resonance imaging: the Multi-ethnic Study of Atherosclerosis. J Am Coll Cardiol 2006; 48: 2285-92.

[42] Rebic D, Rašić S. Cardiovascular Remodeling In Chronic Kidney Disease. EMJ Neph 2014; 1: 113-9.

[43] Gansevoort RT, Correa-Rotter R, Hemmelgarn BR, et al. Chronic kidney disease and cardiovascular risk: epidemiology, mechanisms, and prevention. Lancet 2013; 382(9899): 339-52.

[44] McIntyre CW, John SG, Jefferies HJ. Advances in the cardiovascular assessment of patients with chronic kidney disease. NDT Plus 2008; 6: 383-91.

[45] Howlett JG. Should we perform a heart failure risk score? Circ Heart Fail 2013; 6: 4-5.

[46] Aaronson KD, Cowger J. Heart Failure Prognostic Models Why Bother? Circ Heart Fail 2012; 5: 6-9.

[47] Agarwal SK, Chambless LE, Ballantyne CM, et al. Prediction of incident heart failure in general practice: the Atherosclerosis Risk in Communities (ARIC) Study. Circ Heart Fail 2012; 5(4): 422-9.

[48] Kannel WB, D’Agostino RB, Silbershatz H, Belanger AJ, Wilson PW, Levy D. Prediction of risk of heart failure. Arch Intern Med 1999; 159(11): 1197-204.

[49] Butler J, Kalogeropoulos A, Georgiopoulou V, et al. Incident heart failure prediction in the elderly: The health abc heart failure score. Circ Heart Fail 2008; 1: 125-33.

[50] Gaggin HK, Januzzi Jr JL. Biomarkers and diagnostics in heart failure. Biochim Biophys Acta 2013; 1832(12): 2442-50.

[51] Ellims AH, Taylor AJ, Mariani JA, et al. Evaluating the utility of circulating biomarkers of collagen synthesis in hypertrophic cardiomyopathy. Circ Heart Fail 2014; 7(2): 271-8.

[52] Cheng S, Xanthakis V, Sullivan LM, et al. Correlates of Echocardiographic Indices of Cardiac Remodeling Over the Adult Life Course - Longitudinal Observations From the Framingham Heart Study. Circulation 2010; 122: 570-8.

[53] Perdrix L, Mansencal N, Cochetxeu B, et al. How to calculate left ventricular mass in routine practice? An echocardiographic versus cardiac magnetic resonance study. Arch Cardiovasc Dis 2011; 104: 343-51.

[54] Foppa M, Duncan BB, Rohde LEP. Echocardiography-based left ventricular mass estimation. How should we define hypertrophy? Cardiovasc Ultrasound 2005; 3: 17.

[55] Reddy HK, Koshy SK, Wasson S, et al. Echocardiography predicts adverse cardiac remodelling in heart failure. Exp Clin Cardiol 2008; 9(2): 112-6.

[56] Djurdjaj KS, Enriquez-Sarano M, Rossi A, Bailey KR, Seward JB. Echocardiographic Assessment of Left Ventricular Remodeling: Are Left Ventricular Volumes Suitable Tools? J Am Coll Cardiol 1997; 30(6): 1534-41.

[57] Armstrong AC, Gidding S, Gjesdal O, Wu C, Bluemke DA, Lima JA. LV mass assessed by echocardiography and CMR, cardiovascular outcomes, and medical practice. JACC Cardiovasc Imaging 2012; 5(8): 837-48.

[58] Mor-Avi V, Sugeng L, Lang RM. Real-Time 3-Dimensional Echocardiography An Integral Component of the Routine Echocardiographic Examination in Adult Patients? Circulation 2009; 119: 314-29.

[59] Hung J, Lang R, Flachskampf F, et al. 3D Echocardiography: A Review of the Current Status and Future Directions. J Am Soc Echocardiogr 2007; 20: 213-33.

[60] Marwick TH. Application of 3D echocardiography to everyday practice – Development of normal ranges is step 1. JACC Cardiovasc Imaging 2012; 5(12): 1198-200.

[61] Shimada YJ, Shiota T. Meta-analysis of accuracy of left ventricular mass measurement by three-dimensional echocardiography. Am J Cardiol 2012; 110: 445–52.

[62] Mor-Avi V, Sugeng L, Weineit L, et al. Fast measurement of left ventricular mass with real-time threedimensional echocardiography: comparison with magnetic resonance imaging. Circulation 2004; 110: 1814–8.

[63] Jenkins C, Bricknell K, Hanekom L, Marwick TH. Reproducibility and accuracy of echocardiographic measurements of left ventricular parameters using real-time three dimensional echocardiography. J Am Coll Cardiol 2004; 44: 878-86.

[64] Laser KT, Houben BA, Korperich H, et al. Calculation of pediatric left ventricular mass: validation and reference values using real-time three-dimensional echocardiography. J Am Soc Echocardiogr 2015; 28(3): 275-83.

[65] Krenning BJ, Voormolen MM, Geleijnse ML, et al. Three-dimensional echocardiographic analysis of left ventricular function during hemodialysis. Nephron Clin Pract 2007; 107: e43–9.

[66] Pacileo G, Castaldi B, Di Salvo G, et al. Assessment of left-ventricular mass and remodeling in obese adolescents: M-mode, 2D or 3D echocardiography? J Cardiovasc Med (Hagerstown) 2012; 14(2): 134–9.

[67] De Castro S, Faletra F, Di Angelantonio E, et al. Tomographic Left Ventricular Volumetric Emptying Analysis by Real-Time 3-Dimensional Echocardiography - Influence of Left Ventricular Dysfunction With and Without Electrical Dysynchrony. Circ Cardiovasc Imaging 2008; 1: 41-9.

[68] Upton R, Levett E, Gamble J, et al. Abstract 12183: Strain Dispersion is an Early Subclinical Manifestation of Diabetic Cardiomyopathy Assessed by 3D Echocardiography. Circulation 2014; 130: A12183.

[69] Jenni S, Park CM, Baker MD, et al. Rapid reductions in left ventricular mass following a community based 12-week prevention programme are partially predicted by changes in fat depots. Eur Heart J 2011; 32: 225.

[70] Vieira MLC, Oliveira WA, Cordovil A, et al. 3D Echo Pilot Study of Geometric Left Ventricular Changes after Acute Myocardial Infarction. Arq Bras Cardiol 2013; 101(1): 43-51.

[71] Uematsu M. Speckle Tracking Echocardiography - Quo Vadis? Curr J 2015; 79(4): 735-41.

[72] Opdahl A, Hellesøe T, Skulstad H, Smiseth OA. Strain, strain rate, torsion, and twist: echocardiographic evaluation. Curr Cardiol Rep 2015; 17(3): 568.

[73] Sita S, Tomasoni L, Turiel M. Speckle tracking echocardiography: A new approach to myocardial function. World J Cardiol 2010; 2(1): 1-5.

[74] Blessberger H, Binder T. Two dimensional speckle tracking echocardiography: basic principles. Heart 2010; 96: 716-22.
Cardiac Imaging in Heart Failure with Comorbidities

[76] Pavlopoulos H, Nihoyannopoulos P. Strain and strain rate deformation parameters: from tissue Doppler to 2D speckle tracking. Int J Cardiovasc Imaging 2008; 24(5): 479-91.

[77] Onishi T, Saha SK, Delgado-Montero A, et al. Global Longitudinal Strain and Global Circumferential Strain by Speckle-Tracking Echocardiography and Feature-Tracking Cardiac Magnetic Resonance Imaging: Comparison with Left Ventricular Ejection Fraction. J Am Soc Echocardiogr 2015; 28(5): 587-96.

[78] Demirilli S, Sam CT, Ernis E, et al. Long-Term Cardiac Remodeling in Elite Athletes: Assessment by Tissue Doppler and Speckle Tracking Echocardiography. Echocardiography 2015; 32(9): 1367-73.

[79] Caselli S, Montesanti D, Autore C, et al. Patterns of left ventricular longitudinal strain and strain rate in athletic. J Am Soc Echocardiogr 2015; 28(2): 245-53.

[80] Demirilli S, Sam CT, Ernis E, et al. Long-Term Cardiac Remodeling in Elite Athletes: Assessment by Tissue Doppler and Speckle Tracking Echocardiography. Echocardiography 2014 Dec 3.

[81] Kaku K, Takeuchi M, Tsang W, et al. Age-related normal range of left ventricular strain and torsion using three-dimensional speckle-tracking echocardiography. J Am Soc Echocardiogr 2014; 27(1): 55-64.

[82] Tsang W, Kenny C, Adhya S, et al. Interinstitutional measurements of left ventricular volumes, speckle-tracking strain, and dysynchrony using three-dimensional echocardiography. J Am Soc Echocardiogr 2013; 26(11): 1253-7.

[83] Cheng S, Larson MG, McCabe EL, et al. Reproducibility of speckle-tracking-based strain measures of left ventricular function in a community-based study. J Am Soc Echocardiogr 2013; 26(11): 1258-66.

[84] Crendal E, Dutheli F, Naughton G, McDonald T, Obert P. Increased myocardial dysfunction, dyssynchrony, and epicardial fat across the lifespan in healthy males. BMC Cardiovasc Disord 2014; 14: 95.

[85] Cheng S, Larson MG, McCabe EL, et al. Age- and sex-based reference limits and clinical correlates of myocardial strain and synchrony: the Framingham Heart Study. Circ Cardiovasc Imaging 2013; 6(5): 602-9.

[86] Marwick TH, Leano RL, Brown J, et al. Myocardial strain measurement with 2-dimensional speckle-tracking echocardiography: definition of normal range. JACC Cardiovasc Imaging 2009; 2(1): 80-4.

[87] Amundsen BH, Helle-Valle T, Edvarden T, et al. Noninvasive myocardial strain measurement by speckle tracking echocardiography: validation against sonomicrometry and tagged magnetic resonance imaging. J Am Coll Cardiol 2006; 47(4): 789-93.

[88] Voigt JU, Pedrizzetti G, Lysyansky P, et al. Definitions for a Common Standard for 2D Speckle Tracking Echocardiography: Consensus Document of the EACVI/ASE/Industry Task Force to Standardize Deformation Imaging. J Am Soc Echocardiogr 2015; 28(2): 183-93.

[89] Hasselberg NE, Haugaa KH, Sarvari SI, et al. Age-related normal range of myocardial myocardial strain measurement by speckle-tracking echocardiography: validation against sonomicrometry and tagged magnetic resonance imaging. J Am Coll Cardiol 2006; 47(4): 789-93.

[90] Wang J, Fang F, Wai-Kwok Yip G, et al. Left ventricular long-axis performance during exercise is an important prognosticator in patients with heart failure and preserved ejection fraction. Int J Cardiol 2015; 187: 131-5.

[91] Hofmann R, Aitoki E, Friedman Z, Becker M, Frick M. Myocardial deformation imaging by two-dimensional speckle-tracking echocardiography in comparison to late gadolinium enhancement cardiac magnetic resonance for analysis of myocardial fibrosis in severe aortic stenosis. Am J Cardiol 2014; 114(7): 1083-8.

[92] Singh A, Steadman CD, McCann GP. Advances in the understanding of the pathophysiology and management of aortic stenosis: role of novel imaging techniques. Can J Cardiol 2014; 30(9): 994-1003.

[93] Carasso S, Mutlak D, Lessick J, Reisner SA, Rakowski H, Agmon Y. Symptoms in Severe Aortic Stenosis are Associated with Decreased Compensatory Circumferential Myocardial Mechanics. J Am Soc Echocardiogr 2015; 28(2): 218-25.

[94] Thavendiranathan P, Poulin F, Lim KD, Planam JC, Woo A, Marwick TH. Use of myocardial strain imaging by echocardiography for the early detection of cardiotoxicity in patients during and after cancer chemotherapy: a systematic review. J Am Coll Cardiol 2014; 63(25 Pt A): 2751-68.

[95] Asanuma T, Nakatani S. Myocardial ischaemia and post-systolic shortening. Heart 2015; 101(7): 509-16.

[96] Carasso S, Agmon Y, Roguin A, et al. Left ventricular function and functional recovery early and late after myocardial infarction: a prospective pilot study comparing two-dimensional strain, conventional echocardiography, and radionuclide myocardial perfusion imaging. J Am Soc Echocardiogr 2013; 26(11): 1245-44.

[97] Hwang HJ, Lee HM, Yang IH, et al. The value of assessing myocardial deformation at recovery after dobutamine stress echocardiography. J Cardiovasc Ultrasound 2014; 22(3): 127-33.

[98] Nagy AI, Sahlén A, Manours A, et al. Combination of contrast-enhanced wall motion analysis and myocardial deformation imaging during dobutamine stress echocardiography. Eur Heart J Cardiovasc Imaging 2015; 16(1): 88-95.

[99] Yamada A, Luis SA, Sathianathan D, et al. Reproducibility of regional and global longitudinal strains derived from two-dimensional speckle-tracking and doppler tissue imaging between expert and novice readers during quantitative dobutamine stress echocardiography. J Am Soc Echocardiogr 2014; 27(8): 880-7.

[100] Kishi S, Armstrong AC, Gidding SS, et al. Association of obesity in early adulthood and middle age with incipient left ventricular dysfunction and structural remodeling: the CARDIA study (Coronary Artery Risk Development in Young Adults). JACC Heart Fail 2014; 2(5): 500-8.

[101] Monte IP, Mangiafico S, Buccheri S, et al. Early changes of left ventricular geometry and deformational analysis in obese subjects without cardiovascular risk factors: a three-dimensional and speckle tracking echocardiographic study. Int J Cardiovasc Imaging 2014; 30(6): 1037-47.

[102] Earnande L, Bergerot C, Girend N, et al. Longitudinal myocardial strain alteration is associated with left ventricular remodeling in asymptomatic patients with type 2 diabetes mellitus. J Am Soc Echocardiogr 2014; 27(5): 479-88.

[103] Jensen MT, Sogaard P, Andersen HU, et al. Global Longitudinal Strain Is Not Impaired in Type 1 Diabetes Patients Without Albuminuria: The Thousand & 1 Study. JACC Cardiovasc Imaging 2015; 8(4): 400-10.

[104] Kragger-Krainer E, Shah AM, Gupta DK, et al. Impaired systolic function by strain imaging in heart failure with preserved ejection fraction. J Am Coll Cardiol 2014; 63(5): 447-56.

[105] Narayanan A, Aurigemma GP, Chinali M, Hill JC, Meyer TE, Tighe DA. Cardiac mechanics in mild hypertensive heart disease: a speckle-strain imaging study. Circ Cardiovasc Imaging 2009; 2(5): 382-90.

[106] Kosmal W, Plaksej R, Strotmann JM, et al. Progression of left ventricular functional abnormalities in hypertensive patients with heart failure: an ultrasonic two-dimensional speckle tracking study. J Am Soc Echocardiogr 2008; 21(12): 1309-17.

[107] Panoulas VF, Sulemane S, Konstantinou K, et al. Early detection of subclinical left ventricular myocardial dysfunction in patients with chronic kidney disease. Eur Heart J Cardiovasc Imaging 2015; 16(5): 539-48.

[108] Krishnasamy R, Isbel NM, Hawley CM, et al. The association between left ventricular global longitudinal strain, renal impairment and all-cause mortality. Nephrol Dial Transplant 2014; 29(6): 1218-25.

[109] Kovácová A, Topolayi M, Celeng C, et al. Impact of hemodialysis, left ventricular mass and FGF-23 on myocardial mechanics in end-stage renal disease: a three-dimensional speckle tracking study. Int J Cardiovasc Imaging 2014; 30(7): 1317-31.

[110] Kramer CM, Barkhausen J, Flamm SD, Kim RJ, Nagel E, Society for Cardiovascular Magnetic Resonance and Board of Trustees Task Force on Standardized Protocols. Standardized cardiovascular magnetic resonance (CMR) protocols 2013 update. J Cardiovasc Magn Reson 2013; 15: 91.

[111] Dias ND, Ho TR, Murry KM, McKendeigh F, Connelly P, Glassman AH, et al. Improved Late gadolinium enhancement cardiac magnetic resonance imaging with bi-dimensional speckle tracking: Clinical utility and reproducibility. JACC Cardiovasc Imaging 2013; 6(1): 100-101.

[112] Gidding SS. Controversies in the assessment of left ventricular mass. Hypertension 2010; 56: 26-8.

[113] Myerson SG, Bellenger NG, Pennell DJ. Assessment of left ventricular mass by cardiovascular magnetic resonance. Hypertension 2002; 39(3): 750-5.

[114] Alfikih K, Bloomer T, Bainbridge S, et al. A comparison of left ventricular mass between two-dimensional echocardiography, us-
ing fundamental and tissue harmonic imaging, and cardiac MRI in patients with hypertension. Eur J Radiol 2004; 52(2): 103-8.

[115] Missoui CG, Forbat SM, Singer DR, Markandu ND, Underwood R, MacGregor GA. Echocardiography overestimates left ventricular mass: a comparative study with magnetic resonance imaging in patients with hypertension. J Hypertens 1996; 14: 1005-10.

[116] Bottini PB, Carr AA, Prisant LM, Flickinger FW, Allison JD, Gottdiener JS. Magnetic resonance imaging compared to echocardiography to assess left ventricular mass in the hypertensive patient. Am J Hypertens 1995; 8: 221-8.

[117] Rodríguez CJ, Díez-Roux AV, Moran A, et al. Left ventricular mass and ventricular remodeling among Hispanic subgroups compared with non-Hispanic blacks and whites. MESA (Multi-ethnic Study of Atherosclerosis) J Am Coll Cardiol 2010; 55: 234-42.

[118] Brumbauck LC, Kronmull R, Heckbert SR, et al. Body size adjustment for left ventricular mass by cardiovascular magnetic resonance and their impact on left ventricular hypertrophy classification. Int J Cardiovasc Imaging 2010; 26: 429-46.

[119] Chirinos JA, Segers P, De Buyzere ML, et al. Left ventricular mass: allometric scaling, normative values, effect of obesity, and prognostic performance. Hypertension 2010; 56(1): 91-8.

[120] Blueken DA, Kronmal RA, Lima JA, et al. The relationship of left ventricular mass and geometry to incident cardiovascular events: the MESA (Multi-Ethnic Study of Atherosclerosis) study. J Am Coll Cardiol 2008; 52: 2148-55.

[121] Jain A, McClelland RL, Polak JF, et al. Cardiovascular imaging for assessing cardiovascular risk in asymptomatic men versus women: the multi-ethnic study of atherosclerosis (MESA). Circ Cardiovasc Imaging 2011; 4(1): 8-15.

[122] Krittayaphong R, Boonyasirinant T, Saiviroonporn P, et al. Prognostic significance of left ventricular mass by magnetic resonance imaging study in patients with known or suspected coronary artery disease. J Hypertens 2009; 27(11): 2249-56.

[123] Eguchi K, Boden-Albala B, Jin Z, et al. Association between diabetes mellitus and left ventricular hypertrophy in a multiethnic population. Am J Cardiol 2008; 101(12): 1787-91.

[124] Vela galeti RS, Gona P, Chuang ML, et al. Relations of insulin resistance and glycemic abnormalities to cardiovascular magnetic resonance measures of cardiac structure and function: the Framingham Heart Study. Circ Cardiovasc Imaging 2010; 3(3): 257-63.

[125] Patel PC, Ayers CR, Murphy SA, et al. Association of cystatin C with left ventricular structure and function: the Dallas Heart Study. Circ Heart Fail 2009; 2(2): 98-104.

[126] Vogel-Clausen J, Finn JP, Gomes AS, et al. Left ventricular papillary muscle mass: relationship to left ventricular mass and volumes by magnetic resonance imaging. J Comput Assist Tomogr 2006; 30: 426-32.

[127] Barkhausen J, Ruehm SG, Goyen M, et al. Evaluation of left ventricular function: true fast imaging with steady-state precession versus fast low-angle shot cine MR imaging: feasibility study. Radiology 2001; 219: 264-9.

[128] Plein S, Bloomer TN, Ridgway JP, Jones TR, Bainbridge GJ, Sivananthan MU. Steady-state free precession magnetic resonance imaging of the heart: comparison with segmented k-space gradient-echo imaging. J Magn Reson Imaging 2001; 14: 230-6.

[129] Moon JC, Loree CE, Francis JM, Smith GC, Pennell DJ. Breathhold FLASH and FISP cardiovascular MR imaging: left ventricular volume differences and reproducibility. Radiology 2002; 223: 789-97.

[130] Steen H, Nasir K, Flynn E, et al. Is magnetic resonance imaging the ‘reference standard’ for cardiac functional assessment? Factors influencing measurement of left ventricular mass and volumes. Clin Res Cardiol 2007; 96: 743-51.

[131] Gandy SJ, Waugh SA, Nicholas RS, Simpson HJ, Milne W, Houston JG. Comparison of the reproducibility of quantitative cardiac left ventricular assessments in healthy volunteers using different MRI scanners: a multicenter simulation. J Magn Reson Imaging 2008; 28: 359-65.

[132] Gandy SJ, Waugh SA, Nicholas RS, Rajendra N, Martin P, Houston JG. MRI comparison of quantitative left ventricular structure, function and measurement reproducibility in patient cohorts with a range of clinically distinct cardiac conditions. Int J Cardiovasc Imaging 2008; 24: 627-32.

[133] Aminale-Venkatesh B, Lima JAC. Cardiac MRI: a central prognostic tool in myocardial fibrosis. Nat Rev Cardiol 2015; 12: 18-29.

[134] Dass S, Suttie JJ, Piechnik SK, et al. Myocardial tissue characterization using magnetic resonance noncontrast T1 mapping in hypertrophic and dilated cardiomyopathy. Circ Cardiovasc Imaging 2012; 5: 726-33.

[135] Sibley CT, Noureldin RA, Gai N, et al. T1 mapping in cardiomyopathy: review of clinical utility. Radiology 2012; 265: 724-32.

[136] Iles LM, Ellims AH, Llewellyn H, et al. Histological validation of cardiac magnetic resonance analysis of regional and diffuse interstitial myocardial fibrosis. Eur Heart J Cardiovasc Imaging 2015; 16(1): 14-22.

[137] Ellims AH, Iles LM, Ling LH, et al. A comprehensive evaluation of myocardial fibrosis in hypertrophic cardiomyopathy with cardiac magnetic resonance imaging: linking genotype with fibrotic phenotype. Eur Heart J Cardiovasc Imaging 2014; 15(10): 1108-16.

[138] Ellims AH, Iles LM, Ling LH, Hare JL, Kaye DM, Taylor AJ. Diffuse myocardial fibrosis in hypertrophic cardiomyopathy can be identified by cardiovascular magnetic resonance, and is associated with left ventricular diastolic dysfunction. J Cardiovasc Magn Reson 2012; 14: 76.

[139] Ellims AH, Shaw JA, Stub D, et al. Diffuse myocardial fibrosis evaluated by post-contrast T1 mapping correlates with left ventricular stiffness. Am J Cardiol 2014; 63(11): 1112-8.

[140] Ling LH, Kalman JM, Ellims AH, et al. Diffuse ventricular fibrosis is a late outcome of myocardial-mediated cardiomyopathy after successful ablation. Circ Arrhythm Electrophysiol 2013; 6(4): 697-704.

[141] Ellims AH, Pfluger H, Elskim M, Butler MJ, Hare JL, Taylor AJ. Utility of cardiac magnetic resonance imaging, echocardiography and electrocardiography for the prediction of clinical response and long-term survival following cardiac resynchronisation therapy. Int J Cardiovasc Imaging 2013; 29(6): 1303-11.

[142] Taylor AJ, Elskim M, Broughton A, et al. Combined dysynchrony and scar imaging with cardiac magnetic resonance imaging predicts clinical response and long-term prognosis following cardiac resynchronisation therapy. Europace 2010; 12(5): 708-13.

[143] McLean AJ, McKenzie SC, Taylor AJ. Cardiac magnetic resonance imaging predicts recovery of left ventricular function in acute onset cardiomyopathy. Heart Lung Circ 2012; 21(1): 30-5.

[144] Iles L, Pfluger H, Phrommittinkul A, et al. Evaluation of diffuse myocardial fibrosis in heart failure with cardiac magnetic resonance contrast-enhanced T1 mapping. J Am Coll Cardiol 2008; 52(19): 1574-80.

[145] Iles L, Pfluger H, Lefkovits L, et al. Myocardial fibrosis predicts appropriate device therapy in patients with implantable cardioverter-defibrillators for primary prevention of sudden cardiac death. J Am Coll Cardiol 2011; 57(7): 821-8.

[146] McLean AJ, Schlach MP, Taylor AJ, et al. Reverse Cardiac Remodelling Following Renal Denervation - Atrial Electrophysiology and Gene Expression Associated with Blood Pressure Lowering. Heart Rhythm 2015; pii: S1547-5271(15)00138-1.

[147] Taylor AJ, Ellims A, Lew PJ, Murphy B, Sally P, Younie S. Impact of cardiac magnetic resonance imaging on cardiac device and surgical therapy: a prospective study. Int J Cardiovasc Imaging 2013; 29(4): 855-64.

[148] Wagner A, Mahtholdt H, Thomson L, et al. Effects of time, dose, and inversion time for acute myocardial infarct size measurements based on magnetic resonance imaging-delayed contrast enhancement. J Am Coll Cardiol 2006; 47: 2027-33.

[149] Kim RJ, Fieno DS, Parrish TB, et al. Relationship of MRI delayed contrast enhancement to irreversible injury, infarct age, and contractile function. Circulation 1999; 100: 1992-2002.

[150] Phrommittinkul A, Abdel-Aty H, Schulz-Menger J, Friedrich MG, Taylor AJ. Acute oedema in the evaluation of microvascular perfusion and myocardial salvage in reperfused myocardial infarction with cardiac magnetic resonance imaging. Eur J Radiol 2010; 74(3): e12-7.

[151] Beek AM, Kuhl HP, Bondarenko O, et al. Delayed contrast enhanced magnetic resonance imaging for the prediction of regional functional improvement after acute myocardial infarction. J Am Coll Cardiol 2003; 42: 895-901.

[152] Selvanayagam JB, Kardos A, Francis JM, et al. Value of delayed enhancement cardiovascular magnetic resonance imaging in predicting myocardial viability after surgical revascularization. Circulation 2004; 110: 1535-41.
Cardiac Imaging in Heart Failure with Comorbidities

Khan JN, Wilmot EG, Leggate M, Imaging 2014; 15(11): 1263-9.

Ng AC, Auger D, Delgado V, Enhanced TI mapping and subclinical myocardial dysfunction in diabetes mellitus. Circulation 2010; 122: 2538-44.

Ambale Venkatesh B, Volpe GJ, Donekal S, Assessment of left ventricular diastolic function by cardiac magnetic resonance and echo. Circ Cardiovasc Imaging 2009; 2: 437-43.

Friedrich MG, Abdel-Aty H, Taylor A, Schulz-Menger J, Messroghli D, Dietz R. The salvaged area at risk in reperfused acute myocardial infarction as visualized by cardiovascular magnetic resonance. J Am Coll Cardiol 2008; 52: 181-9.

Ng AC, Technology of cardiovascular magnetic resonance. J Am Coll Cardiol 2009; 5: 1194–201.

Cury RC, Shash K, Nagurney JT, Cardiac magnetic resonance with T2-weighted imaging detects comparison between angiography, electrophysiography, and cardiovascular magnetic resonance measures of microvascular injury. J Am Coll Cardiol 2008; 52: 1581-7.

Abdel-Aty H, Cocker M, Meek C, Tyberg JV, Friedrich MG. Edema as a very early marker for acute myocardial ischemia: a cardiovascular magnetic resonance study. J Am Coll Cardiol 2009; 53: 1194–201.

Friedrich MG, Abdel-Aty H, Taylor A, Schulz-Menger J, Messroghli D, Dietz R. The salvaged area at risk in reperfused acute myocardial infarction as visualized by cardiovascular magnetic resonance. J Am Coll Cardiol 2008; 52: 181-9.

Abdel-Aty H, Cocker M, Meek C, Tyberg JV, Friedrich MG. Edema as a very early marker for acute myocardial ischemia: a cardiovascular magnetic resonance study. J Am Coll Cardiol 2009; 53: 1194–201.

Cury RC, Shash K, Nagurney JT, Cardiac magnetic resonance with T2-weighted imaging detects comparison between angiography, electrophysiography, and cardiovascular magnetic resonance measures of microvascular injury. J Am Coll Cardiol 2008; 52: 1581-7.

Friedrich MG, Abdel-Aty H, Taylor A, Schulz-Menger J, Messroghli D, Dietz R. The salvaged area at risk in reperfused acute myocardial infarction as visualized by cardiovascular magnetic resonance. J Am Coll Cardiol 2008; 52: 181-9.
Individuals The Multi-Ethnic Study of Atherosclerosis. Circulation 2012; 126: 2481-90.

[91] Larghat AM, Swoboda PP, Biglands JD, Kearney MT, Greenwood JP, Plein S. The microvascular effects of insulin resistance and diabetes on cardiac structure, function, and perfusion: a cardiovasculardbasic magnetic resonance study. Eur Heart J Cardiovasc Imaging 2014; 15: 1368-76.

[92] Emane L, Thibault H, Bergerot C, et al. Systolic Myocardial Dysfunction in Patients with Type 2 Diabetes Mellitus: Identification at MR Imaging with Cine Displacement Encoding with Stimulated Echoes. Radiology 2012; 265(2): 402-9.

[93] Rider OJ, Ajufo E, Ali MK, et al. Myocardial tissue phase mapping reveals impaired myocardial tissue velocities in obesity. Int J Cardiovasc Imaging 2015; 31(2): 339-47.

[94] Schiacci G, Verdecchia P, Porcellati C, Cuccurullo O, Cosco C, Perticone F. Continuous relation between left ventricular mass and cardiovascular risk in essential hypertension. Hypertension 2000; 35(2): 580-6.

[95] Janardhanan R, Kramer CM. Imaging in hypertensive heart disease. Expert Rev Cardiovasc Ther 2011; 9(2): 199-209.

[96] Raman SV. The hypertensive heart. An integrated understanding informed by imaging. J Am Coll Cardiol 2010; 55(2): 91-96.

[97] Rudolph A, Abdel-Aty H, Bohl S, et al. Noninvasive detection of fibrosis applying contrast enhanced cardiac magnetic resonance in different forms of left ventricular hypertrophy relation to remodeling. J Am Coll Cardiol 2009; 53(3): 284-91.

[98] Moreo A, Ambrosio G, De Chiara B, et al. Influence of myocardial fibrosis on left ventricular diastolic function: noninvasive assessment by cardiac magnetic resonance and echo. Circ Cardiovasc Imaging 2009; 2(6): 437-43.

[99] Ahmed MI, Desai RV, Gaddam KK, et al. Relation of Torsion and Myocardial Strains to LV Ejection Fraction in Hypertension. J Am Coll Cardiol Img 2012; 5(3): 273-81.

[100] Rosen BD, Saad MF, Shea S, et al. Hypertension and smoking are associated with reduced regional left ventricular function in asymptomatic: individuals the Multi-Ethnic Study of Atherosclerosis. J Am Coll Cardiol 2006; 47(6): 1150-8.

[101] Marcus ML, Koyanagi S, Harrison DG, Doty DB, Hirtzka LF, Eastham CL. Abnormalities in the coronary circulation that occur as a consequence of cardiac hypertrophy. Am J Med 1983; 75(3A): 62-6.

[102] Picano E, Palinkas A, Amyot R. Diagnosis of myocardial ischemia in hypertensive patients. J Hypertens 2001; 19(7): 1177-83.

[103] Murphy BP, Stanton T, Dunn FG. Hypertension and myocardial ischemia. Med Clin North Am 2009; 93(3): 681-95.

[104] Pilz G, Klos M, Ali E, et al. Angiographic correlations of patients with small vessel disease diagnosed by adenosine-stress cardiac magnetic resonance imaging. J Cardiovasc Magn Reson 2008; 10(1): 8.

[105] Chiu DYY, Abidin N, Sinha S, Kaltra PA. Cardiac imaging in patients with chronic kidney disease. Nat Rev Nephrol 2015; 11(4): 207-20.

[106] Karohl C, Raggi P. Cardiovascular Imaging in patients with chronic kidney disease. Blood Purif 2011; 31: 130-7.

[107] Edwards NC, Moody WE, Chue CD, Ferro CJ, Townend JN, Steeds RP. Defining the Natural History of Uremic Cardiomyopathy in Chronic Kidney Disease - The Role of Cardiovascular Magnetic Resonance. J Am Coll Cardiol Img 2014; 7(7): 703-14.

[108] Edwards NC, Ferro CJ, Townend JN, Steeds RP. Aortic distensibility and arterial-ventricular coupling in early chronic kidney disease: a pattern resembling heart failure with preserved ejection fraction. Heart 2008; 94: 1038-43.

[109] Patel RK, Oliver S, Mark PB, et al. Determinants of left ventricular mass and hypertrophy in hemodialysis patients assessed by cardiac magnetic resonance imaging. Clin J Am Soc Nephrol 2009; 4: 1477-83.

[110] Chue CD, Edwards NC, Moody WE, Steeds RP, Townend JN, Ferro CJ. Serum phosphorus is associated with left ventricular mass in patients with chronic kidney disease: a cardiac magnetic resonance study. Heart 2012; 98: 219-24.

[111] Edwards NC. Impaired circumferential and longitudinal myocardial deformation in early stage chronic kidney disease: the earliest features of uremic cardiomyopathy. J Cardiovasc Magn Reson 2013; 15: 153.

[112] Wang H, Liu J, Yao XD, et al. Multidirectional myocardial systolic function in hemodialysis patients with preserved left ventricular ejection fraction and different left ventricular geometry. Nephrol Dial Transplant 2012; 27: 4422-9.

[113] Iyngkaran P, Liew D, Stewart S, et al. Post Marketing Surveillance in Heart Failure - What is done and what is needed? Curr Cardiol Rev 2015; epub ahead of print.

[114] Marwick TH, Neubauer S, Petersen SE. Use of Cardiac Magnetic Resonance and Echocardiography in Population-Based Studies Why, Where, and When? Circ Cardiovasc Imaging 2013; 6: 590-6.

[115] Liu S, Han J, Nacif MS, et al. Diffuse myocardial fibrosis evaluation using cardiac magnetic resonance T1 mapping: sample size considerations for clinical trials. J Cardiovasc Magn Reson 2012; 14: 90.

[116] Abbasi SA, Ertel A, Shah RV, et al. Impact of cardiovascular magnetic resonance on management and clinical decision-making in heart failure patients. J Cardiovasc Magn Reson 2013; 15: 89.

[117] Reichek N, Devereux RB, Rocha RA, et al. Magnetic resonance imaging left ventricular mass reduction with fixed-dose angiotensin-converting enzyme inhibitor-based regimens in patients with high-risk hypertension. Hypertension 2009; 54(4): 731-7.

[118] Grothues F, Smith GC, Moon JC, et al. Comparison of interstudy reproducibility of cardiovascular magnetic resonance with two-dimensional echocardiography in normal subjects and in patients with heart failure or left ventricular hypertrophy. Am J Cardiol 2002; 90(1): 29-34.

[119] Pitt B, Reichek N, Willenbrock R, et al. Effects of eplerenone, enalapril, and eplerenone/enalapril in patients with essential hypertension and left ventricular hypertrophy: the 4E-left ventricular hypertrophy study. Circulation 2003; 108(15): 1831-8.

[120] Simpson HJ, Gandy SJ, Houston JG, Rajendra NS, Davies JI, Struthers AD. Left ventricular hypertrophy: reduction of blood pressure already in the normal range further regresses left ventricular mass. Heart 2010; 96: 148-52.

[121] Edwards NC, Steeds RP, Stewart PM, Ferro CJ, Townend JN. Effect of spironolactone on left ventricular mass and aortic stiffness in early-stage chronic kidney disease: a randomized controlled trial. J Am Coll Cardiol 2009; 54: 505-12.
Minerva Access is the Institutional Repository of The University of Melbourne

Author/s:
Wong, C; Chen, S; Iyngkaran, P

Title:
Cardiac Imaging in Heart Failure with Comorbidities.

Date:
2017

Citation:
Wong, C., Chen, S. & Iyngkaran, P. (2017). Cardiac Imaging in Heart Failure with Comorbidities. Curr Cardiol Rev, 13 (1), pp.63-75. https://doi.org/10.2174/1573403x12666160803100928.

Persistent Link:
http://hdl.handle.net/11343/260064

File Description:
Published version

License:
CC BY-NC