Chapter

State of the Art and New Advances: Cardiac MRI

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Abstract

Cardiac Magnetic Resonance Imaging (CMR) is an advanced imaging modality for better assessment of cardiac structure, function and tissue characterization. This is an essential imaging modality when indicated for assessment of a variety of cardiomyopathies, cardiac ischemia, myocardial viability, arrhythmias, cardiac masses, congenital heart disease, shunts, acute and constrictive pericardial diseases among others. CMR is sometimes referred to as the non-invasive biopsy given the significant information it provides. This chapter discusses the current state of the art of CMR with discussion about the indications, common sequences used, and the role of CMR in evaluation of ischemic and non-ischemic cardiac disease. This chapter also discusses new advances and the future of the field of CMR.

Keywords: CMR, ischemic cardiomyopathy, non-ischemic cardiomyopathy, cardiac masses, pericardial disease, arrhythmias, advances in CMR

1. Introduction

Imaging the heart using magnetic resonance imaging (MRI) started for diagnostic utilization in the 1980s and has since contributed to significant advances in the fields of adult and pediatric cardiology and cardiothoracic surgery. Cardiac MRI (CMR) provides precise visualization of myocardial structure, function, perfusion, viability, and tissue characterization offering a comprehensive evaluation that remains unparalleled by any other imaging technique. Compared to other cardiac imaging modalities such as transthoracic echocardiogram (TTE), transesophageal echocardiogram (TEE), cardiac catheterization, or cardiac computed tomographic angiography (CTA), CMR has the advantages of reliable, high quality imaging with advanced tissue characterization which is not limited by body habitus, does not have radiation, is noninvasive, and has been shown to be sufficient for disease characterization and subsequent treatment strategies [1] aiding in tailoring specific treatment options and enhancing patient outcomes. Over the years, CMR with a continuing addition of several new techniques, has proven to be critically important for cardiovascular disease characterization and subsequent management and outcomes. We discuss the indications for CMR, common CMR scanning sequences, current state of the art of CMR followed by advances in CMR.

2. Indications for CMR

CMR should be considered as part of the diagnostic imaging in patients with

- Acute and chronic coronary artery disease
- Evaluation of ischemia in patients with chest pain
- Non ischemic cardiomyopathy, especially when the etiology of non-ischemic cardiomyopathy is unclear, or for prognosis in patients after etiology of non-ischemic cardiomyopathy is identified
- Valvular heart disease
- Cardiac masses
- Pericardial disease
- Cardiac arrhythmias including brady arrhythmias, complete heart block, ventricular arrhythmias, and sudden cardiac death
- Congenital heart disease (CHD)—simple CHD like atrial septal defects or ventricular septal defects or complex CHD like Tetralogy of Fallot, transposition of great arteries, truncus arteriosus and single ventricle physiology for diagnosis and for serial follow up
- Aortic diseases including coarctation, aneurysm, dissection, and vasculitis
- Anomalous coronaries or anomalous pulmonary veins

3. Scanning protocol and sequences

A regular CMR uses cine images for function and morphology followed by delayed enhancement (DE) images after administration of contrast for scar evaluation. While the scan as described provides significant information, additional information can be obtained, using additional sequences as desired. The study and the sequences are usually tailored for the indication to meet the needs appropriately. Commonly used sequences in CMR scanning include:

1. Steady state Free Precession (SSFP) or cine imaging provides high quality still or moving images for evaluation of structure and function. Image acquisition must be coupled to an EKG to gather adequate data over successive heartbeats. The lack of limitations of body habitus along with the superior contrast resolution and improved differentiation between blood pool and muscle are the advantages with CMR (Video 1).

2. DE imaging for late gadolinium enhancement (LGE) is performed a few minutes after injecting Gadolinium for evaluation of scar or infiltration using phase contrast inversion recovery or PSIR sequences (**Figure 1**). DE Images are obtained

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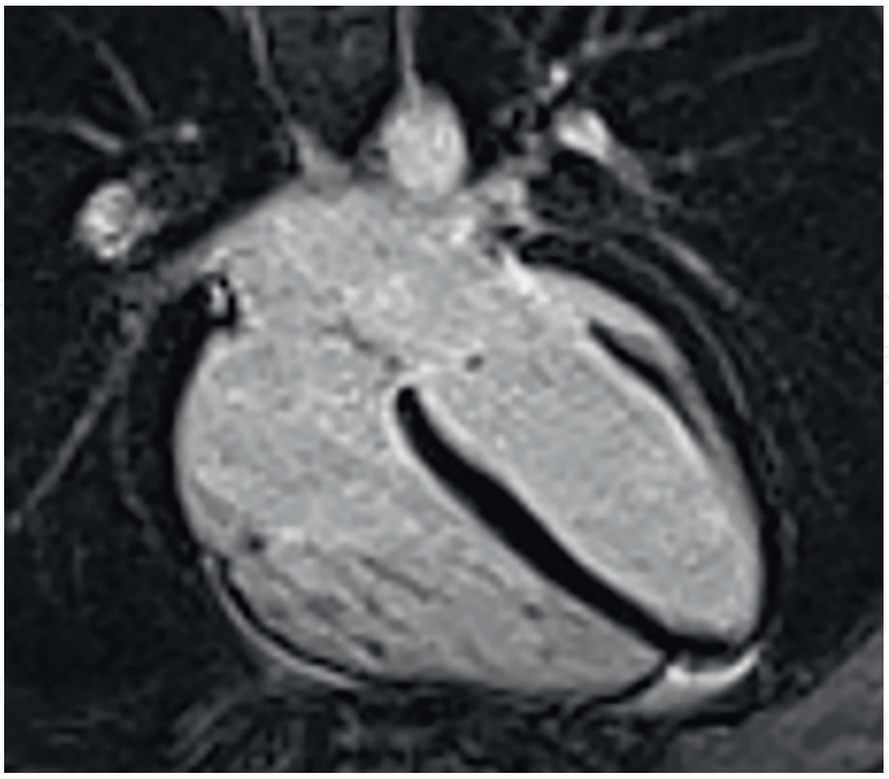

Figure 1.
Normal DE imaging with myocardium appearing uniformly black.

at a set time point post-contrast injection to evaluate how the contrast distributes into the extracellular space. LGE patterns on delayed enhancement imaging assist in the differentiation of ischemic and nonischemic cardiomyopathies. LGE in nonischemic cardiomyopathy is present in a noncoronary distribution and can have diffuse myocardial, mid myocardial or epicardial enhancement. Ischemic cardiomyopathy always has subendocardial involvement due to coronary blood flow pattern. Quantifying LGE and thereby assessing scar burden can provide prognostic and outcomes information. Studies have showed that presence of LGE in cardiomyopathy patients was associated with an increased risk of all-cause mortality, hospitalization for heart failure, and sudden cardiac death (SCD) [2].

3. Real time cine sequences are used in patients with arrhythmias for structure and function or routinely in patients being evaluated for constrictive pericarditis and ventricular interdependence and have a more continuous acquisition (Video 2)

4. T1 and T2 mapping and parametric imaging sequences for tissue characterization are excellent for assessing diffuse and localized myocardial inflammation, infiltration, edema, intracellular and extracellular volume, and fibrosis (**Figure 2**). Extracellular volume (ECV) is measured by analyzing T1 values pre- and post-contrast and has been found useful in identifying edema or fibrosis specific to cardiac diseases [3]. T1, T2 and ECV evaluation provides prognostic information in addition to aiding in the diagnosis.

5. T2* sequences for myocardial iron content can assist in the evaluation of myocardial iron content in diseases characterized by iron deposition.

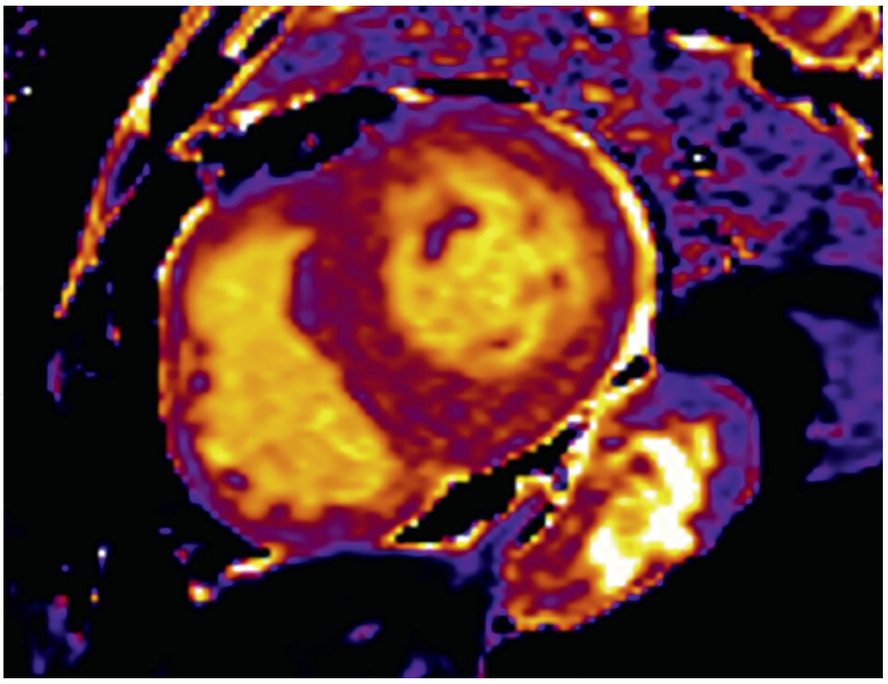

Figure 2.
T1 mapping sequence.

6. Perfusion CMR is a technique that uses contrast dynamics to visualize saturations of blood flow into the myocardium. Perfusion imaging is used for assessment of perfusion of myocardium and cardiac masses when present (Video 3).

7. Phase contrast velocity encoded sequences or flow sequences for hemodynamic assessment for assessment of flows, peak velocity, gradients and volumes.

8. Contrast-enhanced CMR angiography (MRA) for assessment of vascular structures. 3-Dimensional (3D) visualization and accurate assessment can be performed for aneurysms, dissections, vasculitis, or congenital heart disease (Video 4).

4. Current state of the art of CMR

CMR has extensive role in the evaluation of various ischemic and non-ischemic etiologies. A few of the common pathologies are discussed below.

4.1 Evaluation of ischemic heart disease

Coronary artery disease (CAD) is the leading cause of death in the United States. One person dies every 33 seconds from cardiovascular disease in the United States [4]. CMR has unique value in the evaluation of acute and chronic ischemic heart disease and in patients presenting with chest pain for the evaluation of ischemia.

4.1.1 Acute ischemic heart disease and CMR

CMR provides many insights in the evaluation of patients presenting with acute MI. While TTE is easily accessible, CMR is superior to TTE in the evaluation wall

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motion abnormalities and LV ejection fraction (EF) with high quality imaging in cine sequences. CMR provides additional information about edema and the area at risk of infarction which can be evaluated by T1, T2 mapping and assessment of ECV. Resting myocardial perfusion imaging in patients presenting with chest pain can show areas of decreased resting myocardial perfusion, denoting significant coronary stenosis (greater than 80% stenosis) in the coronary arteries supplying those territories [5] (Video 5). Early gadolinium imaging shows areas of thrombus (**Figure 3**) and microvascular obstruction (**Figure 4**). Microvascular obstruction signifies areas with extensive ischemia with associated capillary cell death in addition to myocardial cell death. Presence of microvascular ischemia portends a worse prognosis compared to patients who do not have microvascular ischemia [6] LGE on DE imaging

Figure 3.
Early gadolinium imaging with a right atrial thrombus as hypointense lesion.

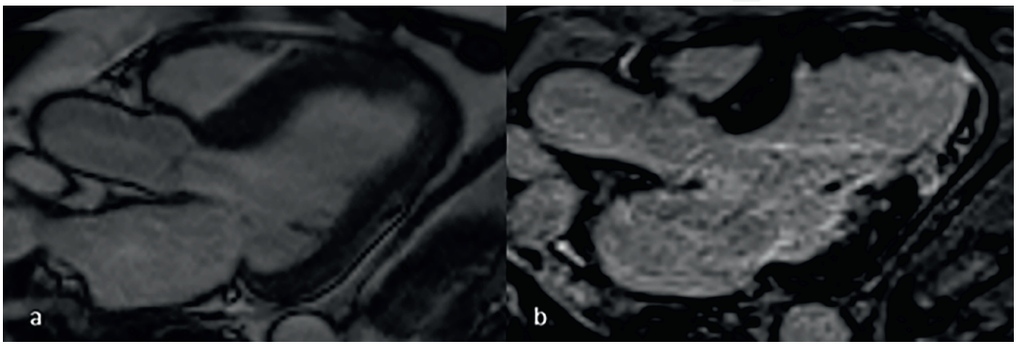

Figure 4.
Cine image (a) and DE imaging (b) in acute MI showing a significant dark zone of microvascular obstruction embedded within the infarcted area in the mid to apical inferolateral wall.

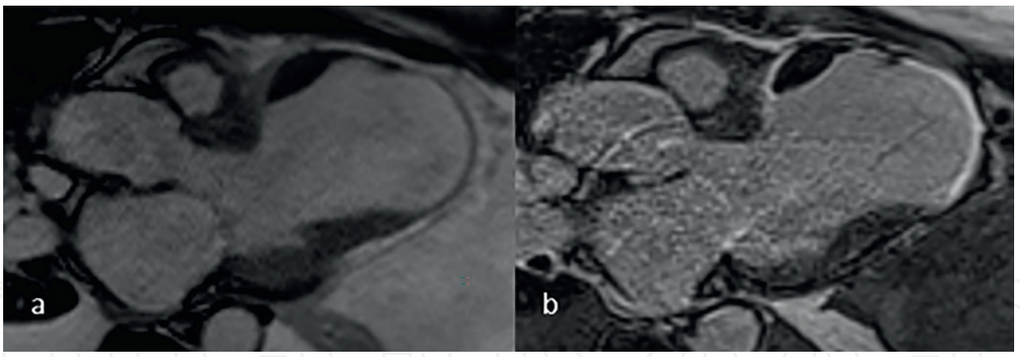

Figure 5.
Cine image (a) and DE imaging (b) in MI showing bright scar tissue in LAD territory, signifying lack of viable myocardium with superimposed thrombus in black.

shows areas of myocardial scar [7] (**Figure 5**). Ischemic scar always involves the sub endocardium as shown on pathology studies. Studies have shown that myocardium with less than 50% involvement of the myocardial thickness with scar have improvement in function with revascularization, suggestive of viable myocardium, while segments with more than 50% wall thickness involvement with scar do not have functional recovery [7]. Assessment of viable myocardium can have value in deciding revascularization strategies. CMR also plays an important role in the evaluation of complications of acute MI such as pseudoaneurysm (Video 6), thrombus, rupture of the septum, myocardial free wall rupture or papillary muscle rupture. Above findings, especially LV EF, microvascular obstruction and degree of scar have been shown to have prognostic valve.

4.1.2 Chronic ischemic heart disease and CMR

In patients with chronic CAD, CMR provides information about EF with cine imaging, thrombus evaluation with cine, early gadolinium enhancement, LGE imaging as described in the above section along with the detection and quantification of scar. Despite its widespread availability, TTE can be diagnostically limited in evaluation of intracardiac thrombus. Studies comparing TTE, TEE and CMR have clearly demonstrated the superiority of CMR in diagnosing thrombi [8]. CMR imaging provides tissue characterization of thrombus and can identify structural risk factors for LV thrombus such as infarct size/distribution and contractile dysfunction [9]. Presence of scar in myocardial infarcts can be most accurately detected by CMR compared to any other imaging study [10]. Transmural scar shows non-viable myocardium and identifies patients who are less likely to improve function [11]. Studies in patients with non-Q wave MI and unstable angina demonstrated the importance of subendocardial scar detected in CMR and its prognostic value [12]. Other studies have shown how these subendocardial scars can be easily missed on single-photon emission computed tomography (SPECT) imaging. Above findings, especially LV EF, and degree of scar have been shown to have prognostic valve.

4.1.3 Evaluation of ischemia in patients with chest pain and CMR

CMR provides valuable information in the evaluation of chest pain or ischemia with stress testing. Perfusion CMR, a technique that uses contrast dynamics to

visualize saturations of blood flow into the myocardium is used in stress perfusion CMR. In stress CMR, Gadolinium based contrast agent is paired with a vasodilator such as adenosine or Regadenoson and images are obtained continuously over several cardiac cycles to visualize the myocardial uptake and fade-out of contrast. In healthy myocardium, the contrast distributes homogenously. Defects in perfusion are typically detected as areas of low contrast resulting in minimal signal and therefore representing hypoperfusion and must last for four or more consecutive cardiac cycles [13]. Studies such as CE MARC showed the non-inferiority of Stress CMR compared to SPECT [14]. The GadaCad trial which compared Stress CMR to invasive coronary angiography or coronary CTA as the reference standard showed that stress CMR had sensitivities of 79% and 87% and specificities of 87% and 73% for single- and multi-vessel CAD, respectively. Studies such as SPINS showed the prognostic value of Stress CMR with patients with normal Stress CMR—patients with normal myocardial perfusion and normal LGE have 99.3% event free survival for a median 5.5 years [15].

When compared to SPECT, stress CMR has several technical advantages. CMR has a larger field of view, superior spatial resolution, and better tissue differentiation. It is not limited by attenuation artifacts or contamination of the myocardium by other signal sources such as gut uptake as can be the case with SPECT. Stress CMR can also identify subendocardial ischemia, making it less susceptible to balanced ischemia than SPECT, where multivessel ischemia may be present but falsely appear normal on perfusion images [16]. Additionally, stress CMR does not expose patients to ionizing radiation, making it advantageous for younger patients and those who require multiple scans over time.

4.2 Evaluation of non-ischemic heart disease (NICM)

The present classification system for cardiomyopathies, established by the American Heart Association distinguishes between primary ones that solely impact the heart and secondary ones that are part of a larger systemic disease affecting multiple organs. CMR has a distinct advantage in evaluation of these cardiomyopathies by providing insights into tissue composition and characteristics beyond structural imaging.

4.2.1 Primary cardiomyopathies

4.2.1.1 Hypertrophic cardiomyopathy (HCM)

HCM is a genetic cardiomyopathy, characterized by myocardial hypertrophy and disarray with an estimated prevalence of 1 in 500. CMR excels in identifying location and degree of hypertrophy, accurate maximal wall thickness, systolic anterior motion of the mitral valve and LV outflow tract obstruction, LV crypts, aneurysms and morphological variations involving the mitral valve apparatus and papillary muscles (Video 7). The classic scar pattern in HCM involves LGE at right ventricular (RV) insertion points [17] (**Figure 6**). A comprehensive multicenter study involving nearly 1300 patients diagnosed with HCM revealed that the extent of LGE can effectively identify individuals who are at an elevated risk of sudden death who would need to be considered for implantable cardioverter-defibrillator (ICD) placement. Extensive LGE, encompassing 15% or more of the LV mass, indicates a twofold higher risk of sudden death compared to the absence of LGE [18].

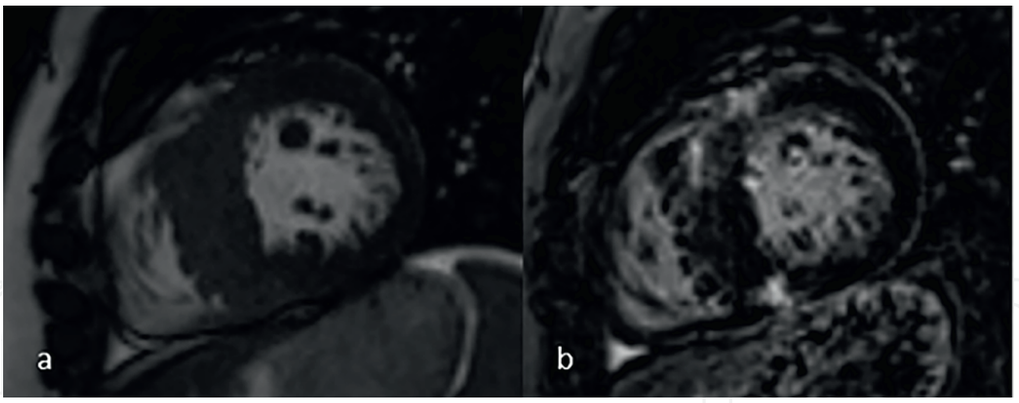

Figure 6.
Short axis cine (a) and DE (b) showing septal hypertrophy with LGE at RV insertion points in HCM.

4.2.1.2 Arrhythmogenic right ventricular cardiomyopathy (ARVC)

ARVC, the most prominent form of heritable arrhythmogenic cardiomyopathy (ACM), is a genetic disorder that is characterized by the loss of myocytes and the replacement of myocardial tissue with fibrofatty deposits, primarily affecting the RV. ARVC is associated with the occurrence of ventricular arrhythmias and an elevated risk of SCD and heart failure. Given the limitations of TTE in the visualization of the RV, CMR is the preferred diagnostic test for this lethal cardiomyopathy. CMR offers a comprehensive assessment of RV for enlargement of the RV outflow tract, dilation of the RV, fibrofatty replacement of the myocardium, as well as global or regional systolic dysfunction (Video 8). According to the 2010 Task Force Criteria, qualitative CMR identification of increased RV end-diastolic volumes, RV akinesia, dyskinesia, or dyssynchronous RV contraction is necessary to fulfill major or minor diagnostic criteria.

In the coming years, the analysis of tissue deformation and strain using CMR holds the potential to offer valuable diagnostic and prognostic insights. Strain imaging has shown promise in distinguishing individuals with ARVC and borderline ARVC from healthy volunteers, as well as differentiating it from other conditions like right ventricular outflow-tract ventricular tachycardia (RVOT-ventricular tachycardia) and Brugada syndrome. Impaired strain in both the LV and RV is indicative of ARVC. Emerging techniques, such as water and fat separation and high-resolution 3D LGE imaging hold potential for enhancing the identification of ARVC [19].

4.2.1.3 Left ventricular non-compaction (LVNC)

LVNC refers to a structural configuration of the LV wall that is distinguished by prominent trabeculae within the LV, a thin layer of compacted myocardium, and deep recesses between the trabeculae. CMR cine images offer superior contrast resolution and improved differentiation between blood and muscle, enabling clearer visualization of ventricular trabeculation (**Figure 7**). Various CMR criteria have been proposed, with the criterion introduced by Petersen et al. being the most utilized. According to this criterion, a ratio of trabecular to compact myocardial thicknesses greater than 2.3 at end-diastole in long-axis views is consistent with noncompaction cardiomyopathy [20]. With the help of LGE in LVNC, regions of LGE in the trabecular and subendocardial layers can be observed, indicating the presence of

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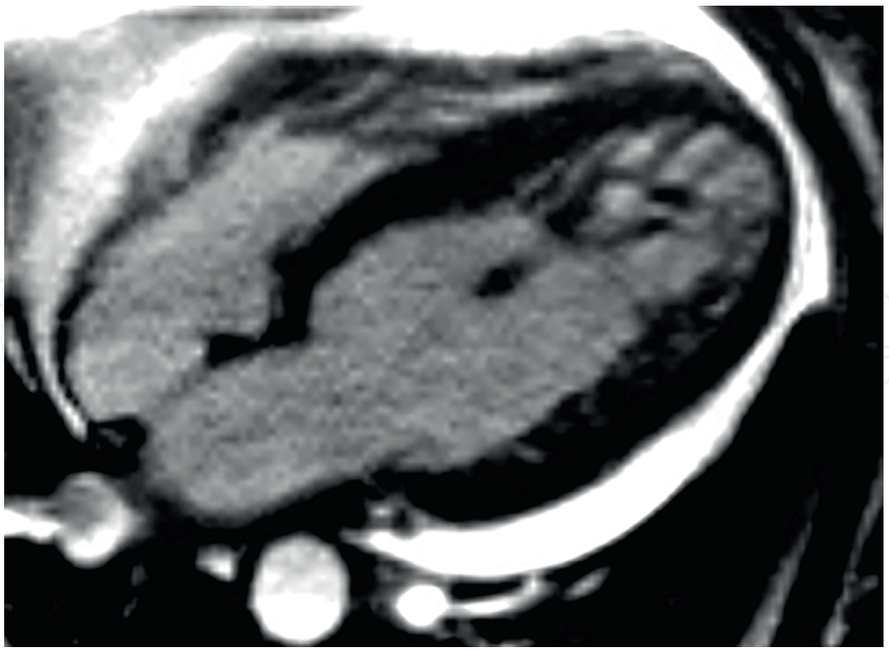

Figure 7.
Four chamber cine images with non-compacted myocardium in the mid to apical segments.

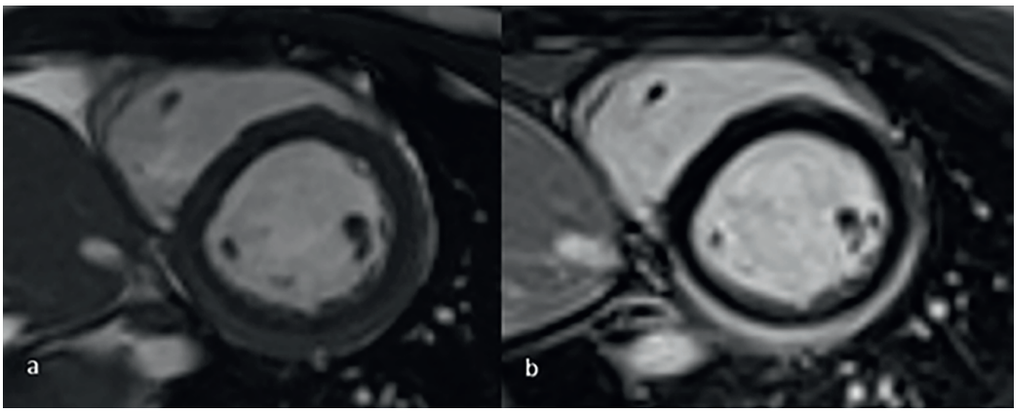

Figure 8.
Short axis cine (a) and DE (b) imaging showing the inferolateral epicardial scar in myocarditis.

subendocardial and trabecular fibrosis as well as fibroelastosis. These fibrotic areas serve as the substrate for potentially life-threatening arrhythmias, which are the primary cause of sudden death in affected patients [21].

4.2.1.4 Myocarditis

Myocarditis is an inflammatory condition of the myocardium, which can arise due to various causes, including a broad spectrum of infectious and noninfectious etiologies [22]. CMR detects several cardinal features of myocarditis such as inflammation, edema, necrosis, and contractile dysfunction (**Figure 6**) [23]. Cine images assist with assessment of wall motion abnormalities, T1 and T2 mapping with assessment for ECV and myocardial edema and DE imaging with assessment for focal scars. DE is typically observed in a mid-myocardial or sub-epicardial pattern primarily affecting the basal to mid inferolateral and inferior segments [24] (**Figure 8**). The Lake Louise

Criteria aid in the decision making by using CMR to detect myocarditis with high specificity and positive predictive value [3].

4.2.2 Secondary cardiomyopathies

4.2.2.1 Cardiac amyloidosis

Amyloidosis is a rare medical condition that arises due to the accumulation of insoluble proteinaceous material in the extracellular matrix. The likelihood of amyloidosis affecting the heart varies depending on the specific type, with primary/AL type having the highest incidence of cardiac involvement, affecting up to 50% of patients, followed by familial/ATTR type affecting 10–50% of patients, while the incidence is less than 5% for secondary/AA type [25]. CMR can detect key features of cardiac amyloid and can serve to rule in or rule out a diagnosis of cardiac amyloidosis [26]. The presence of the abnormal protein in the myocardium affects its T1 relaxation, making it challenging to null the myocardium and resulting in increased T1 values, which can be quantified using mapping techniques. ECV calculates the extracellular expansion due to amyloid and represents the closest, non-invasive quantification of cardiac amyloid burden. DE imaging shows a global subendocardial or transmural patchy enhancement (**Figure 9**). The presence and the degree of enhancement have been shown to have prognostic value in addition to the prognostic value provided by T1 and ECV values [28, 29].

4.2.2.2 Sarcoidosis

Sarcoidosis is a destructive granulomatous disease of the myocardium, which can lead to several cardiac pathologies including heart failure, heart blocks, ventricular arrythmias, and SCD. Diagnosing cardiac sarcoidosis is a challenge as symptoms often mimic other cardiac conditions. Autopsy studies have shown that isolated cardiac sarcoidosis can occur, and cardiac arrhythmias can be the first presentation [29]. Currently, the best imaging modalities for detecting sarcoid inflammation are cardiac positron emission tomography (CPET) and CMR [30]. CPET is useful for detecting active areas of inflammation and can provide good insight into disease burden. CMR on the other hand can show active areas of inflammation using T1 and T2 mapping in addition to detecting areas of involved myocardium and scar tissue left

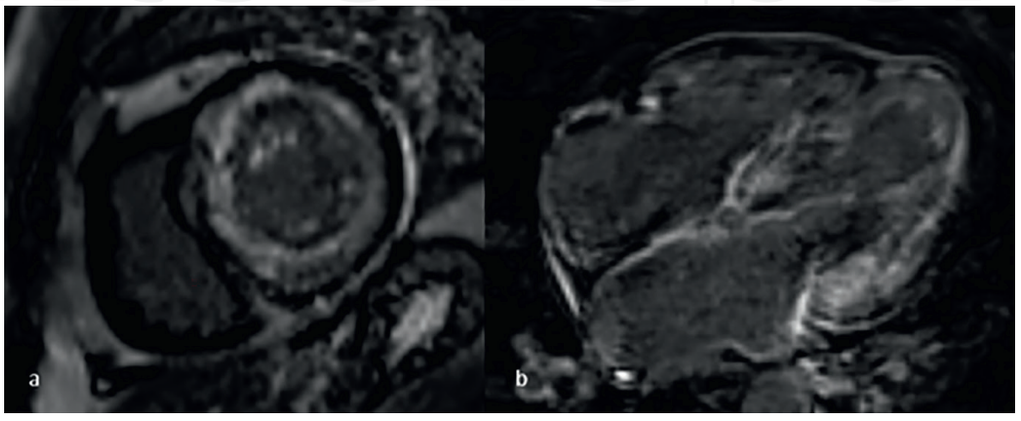

Figure 9.
Global subendocardial (a) and diffuse (b) enhancement in amyloidosis.

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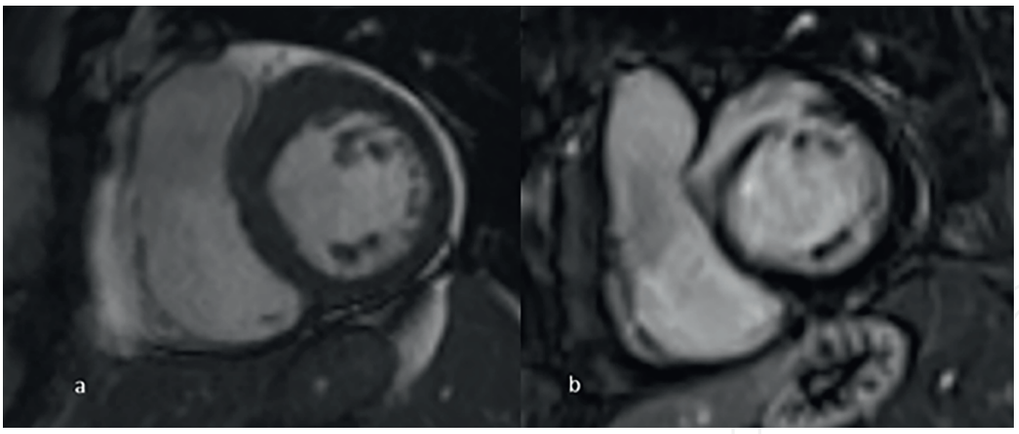

Figure 10.
Short axis cine (a) and DE (b) imaging showing epicardial and septal scar in sarcoidosis.

over from active disease with DE imaging (**Figure 10**). The societal recommendation for imaging cardiac sarcoidosis involves obtaining cine, LGE, resting perfusion and T2-weighted sequences [31]. Regional wall motion abnormalities with cine imaging, focal perfusion abnormalities during perfusion imaging, signs of inflammation and edema during the acute phase of the disease on T1-weighted images [25], epicardial, midmyocardial DE and RV involvement with wall motion abnormalities and scarring have all been reported. Scar tissue serves as the epicenter for developing arrythmias. CMR locates and quantifies scar tissue burden and can aid in predicting risk for fatal arrythmias and patients that need treatment with an ICD [32].

4.2.2.3 Fabry cardiomyopathy

Fabry disease (FD) is a lysosomal storage disorder that presents with a range of cardiac manifestations such as ventricular hypertrophy and fibrosis, valve thickening or regurgitation, heart failure, angina, dysrhythmias, cardiac conduction abnormalities, and SCD [33]. CMR has contributed significantly to our understanding of the underlying processes that lead to inflammation and fibrosis as a response to the accumulation of glycosphingolipids [34]. Earlier in the disease when the characteristic feature is fatty changes, decrease in native T1 time occurs [35]. This finding has the potential to identify individuals with early cardiac involvement and has been demonstrated to be predictive of disease progression [34]. As the disease progresses, the fatty changes are replaced with fibrosis, which leads to increase in T1 values along with patchy enhancement which is typically seen in the basal inferolateral wall [33] (**Figure 11**). These changes can occur concurrently with fatty changes in the septum and fibrosis in the inferolateral wall with rate of disease progression varying in different segments. These changes can also happen prior to the detection of LV hypertrophy, leading to early diagnosis.

4.2.2.4 Endomyocardial fibrosis (EMF)

EMF is a type of restrictive cardiomyopathy, and although no exact cause has been fully understood, various factors have been described that contribute to an inflammatory response, leading to damage in the endomyocardial layers and the subsequent formation of fibrosis [36]. On CMR cine images shows apical

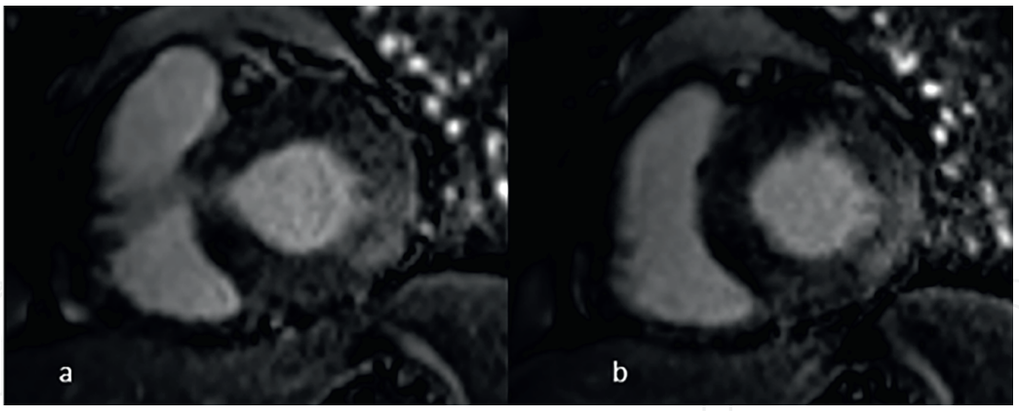

Figure 11.
Short axis basal (a) and mid-level (b) DE imaging showing inferolateral patchy enhancement in Fabry cardiomyopathy.

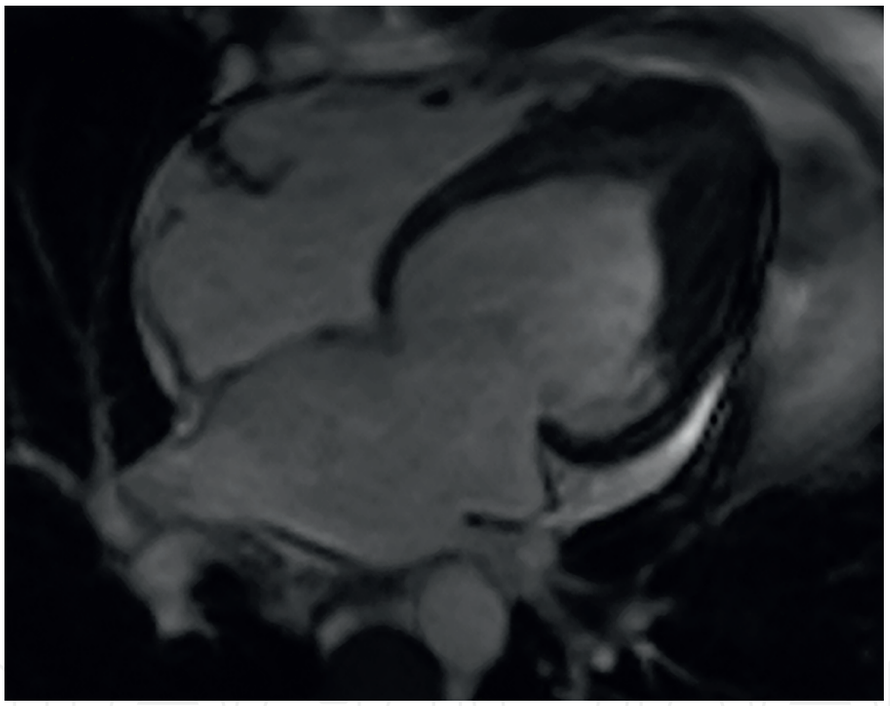

Figure 12.
Cine imaging in endomyocardial fibrosis showing apical hypertrophy.

hypertrophic pattern, (**Figure 12**) however LGE serves as a dependable noninvasive approach for diagnosing EMF. The characteristic DE pattern observed in EMF is subendocardial, not limited to a specific coronary distribution with overlying thrombus. It primarily affects the apical walls of the LV and may extend continuously to the inflow tract. At the ventricular apex, a distinct imaging feature known as a "double V" sign can be observed. This sign exhibits a three-layered appearance comprising normal myocardium, enhanced endomyocardium and a layer of thrombus (**Figure 13**). CMR findings also have prognostic value. An increased deposition of apical fibrous tissue, indexed to body surface area (BSA) (>19 mL/m^2), has been directly associated with worse New York Heart Association (NYHA) functional class and elevated mortality rates [37].

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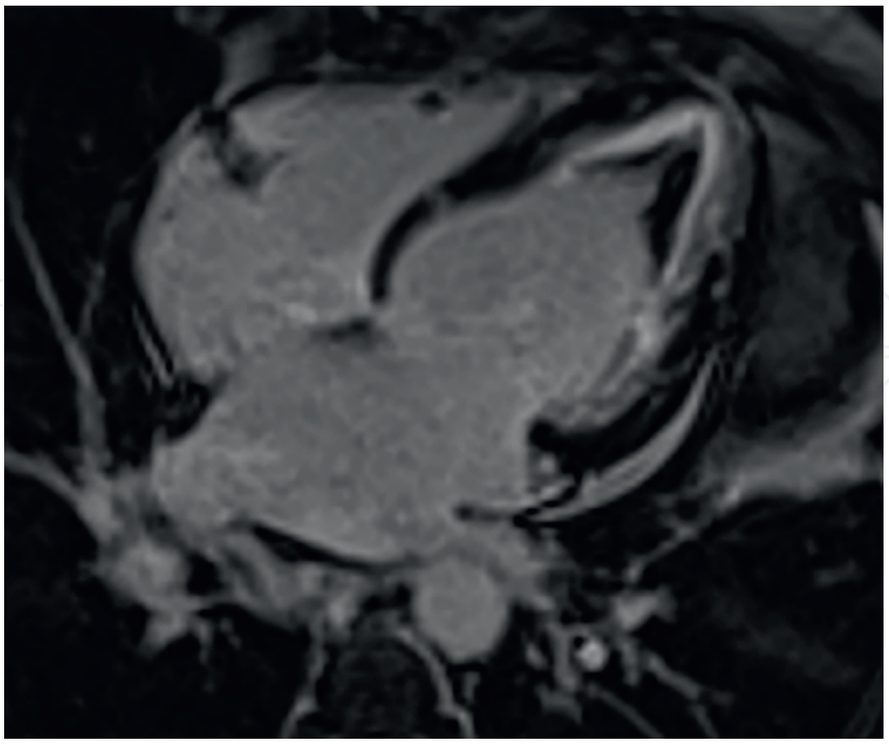

Figure 13.
DE imaging in endomyocardial fibrosis showing apical to mid ventricular scar with superimposed thrombus.

4.3 Valvular heart disease

Over the last two decades CMR has emerged as a non-invasive and radiation-free alternative that can be used in individuals with valvular heart disease. CMR can provide images of valve anatomy and enables the quantitative evaluation of stenosis and regurgitation. Cine imaging assists with assessment the valvular structures in motion along with visualization of flows. Phase-contrast velocity encoded sequences help with quantification of peak velocities and regurgitant fractions. CMR can also detect the consequences of valvular lesions, such as changes in systolic function and the effects of ventricular volume or pressure overload [38]. Time-resolved 3D phase-contrast MRI, also known as 4D flow MRI, is a newer sequence, that possesses impressive capabilities in measuring blood flow velocities within a volume, noninvasively and in vivo, across the three primary directions, enabling the dynamic assessment of blood flow in both the heart and major vessels [38].

4.4 Cardiac masses

Either of primary or secondary origin, cardiac masses can have various tissue compositions such as myxomas, rhabdomyomas, fibromas, angiosarcomas, and metastasis from extra-cardiac cancers. The characterization of cardiac masses is based on size, location, interaction with surrounding structures and mobility [39]. The first level of diagnostics remains to be an TTE as it is widely available, convenient, and of relatively minimal cost but has its own limitations. CMR can provide a multiplanar approach to assess the mass relative to surrounding intra- and extra-cardiac structures, tissue characterization, perfusion to assess for vascularity

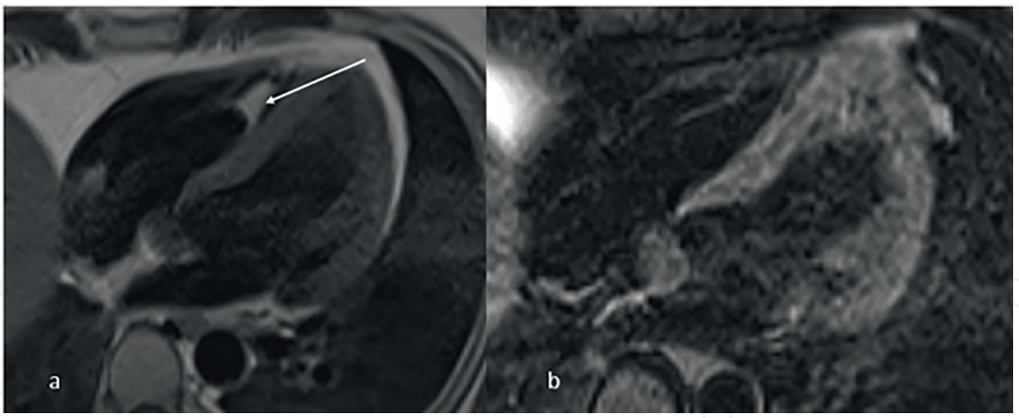

Figure 14.
T2 Stir image without (a) and with (b) fat saturation, showing a fatty mass in the right ventricular apex, likely lipoma.

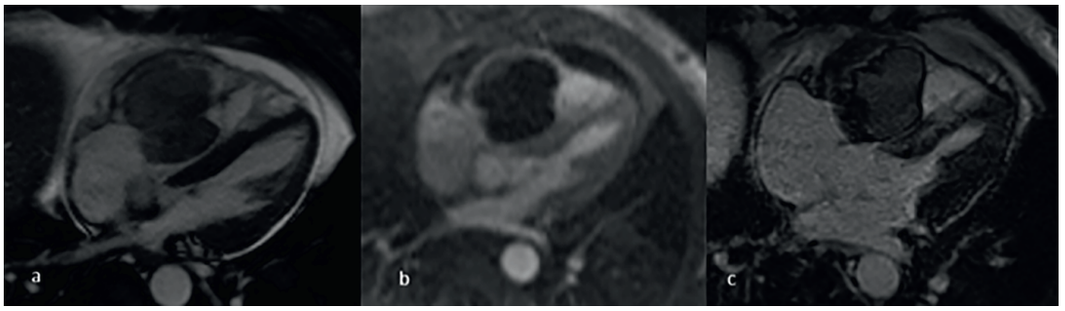

Figure 15.
Four-chamber cine (a), perfusion (b) and DE (c) imaging in a large RV mass showing a large mass, which has partial perfusion, and a partial "etched appearance" on DE imaging consistent with a tumor with a large thrombus burden.

and enhancement. CMR enables the evaluation of various characteristics including morphology, dimensions, location, extension, homogeneity, presence of infiltration in the surrounding tissues, and signal characteristics that aid in histopathological characterization. These signal characteristics encompass fatty infiltration, necrosis, hemorrhage, calcification, vascularity, among others. To achieve a comprehensive assessment, several imaging sequences are employed, such as double-inversion recovery fast spin-echo with triple inversion recovery to assess the amount of fat within the mass, (**Figure 14**) pre-contrast T2-weighted imaging, resting first-pass perfusion sequences, early gadolinium imaging, and late gadolinium DE imaging (**Figure 15**) [40]. CMR is considered a non-invasive biopsy in the assessment of cardiac masses.

4.5 Pericardial evaluation

CMR is a highly beneficial tool for evaluating and tracking various pericardial conditions, such as pericarditis, pericardial effusion, and constrictive pericarditis. Cine sequences evaluate function and effusion, free-breathing real time sequence assess ventricular interdependence in constriction, T2-STIR identifies edema, DE sequence detects LGE that indicates inflammation or fibrosis (**Figure 16**), and other T1- and T2-weighted and perfusion imaging techniques are used for tissue characterization of pericardial effusion and masses [41]. DE sequence plays a crucial role

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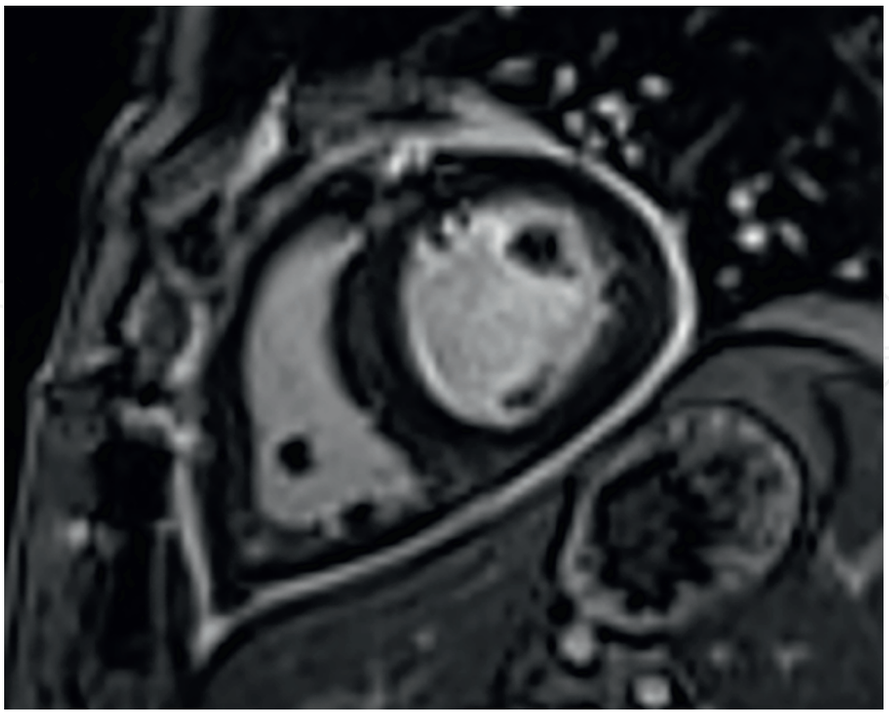

Figure 16.
Short axis DE imaging showing diffuse circumferential pericardial enhancement, consistent with acute pericarditis.

in diagnosing pericardial inflammation and monitoring the effectiveness of anti-inflammatory treatments [42]. The degree of pericardial LGE observed in the initial MRI is significantly linked to recurring episodes of pericarditis and the need for intensified therapy. Recent research has introduced quantitative methods for measuring pericardial LGE, which may have potential clinical applications in the future [43]. Differentiating between active pericarditis and chronic inflammation leading to constrictive pericarditis is of utmost importance, as the treatment modalities are completely different (anti-inflammatory drugs vs. pericardiectomy).

4.6 Arrhythmias and application in electrophysiology

CMR is widely used in electrophysiology (EP) for primary prevention of SCD and for secondary prevention in both brady and tachy arrhythmias. ICDs are used for primary prevention of SCD in patients with ischemic and NICM. A proportion of these patients do not have any lethal arrhythmias after implantation, prompting the need for better risk stratification of these patients. Scar quantification by DE imaging has been shown to have prognostic value in identifying patients more likely to benefit from ICD implantation for primary prevention. Further studies are underway to identify percent of scar and features of scar which denote increased arrhythmogenic substrate. CMR adds significantly to the management of patients presenting with bradyarrhythmia and heart block. Identification of scar involving the myocardium, predominantly the basal septum has been seen with cardiac sarcoidosis in addition to other etiologies.

Patients presenting with arrhythmias causing SCD from a variety of etiologies benefit from a CMR to identify and understand myocardial characteristics and abnormalities. In patients with arrhythmias, mapping techniques, such as T1/T2,

can identify edema, necrosis, and scarring contributing to arrhythmias [44] which is further enhanced by identification of LGE in DE imaging. Further characterization of these lesions and anatomical geometry with CMR also allows for stratifying patients most suitable for ablation [45], along with identifying focus of arrhythmia to assist with ablation procedures. These maps can be used alone or integrated with electro-anatomic mapping to identify potential arrhythmogenic targets for ablation [46]. Post-ablation CMR images can also be used to determine prognostic factors contributing to the recurrence of arrhythmia.

Real-time CMR ablations have also been studied as an alternative to current ablation procedures utilizing radiation and iodinated contrast [47]; however, clinical implementation is limited by a lack of CMR-compatible devices and catheters required for these procedures.

4.7 Congenital heart disease (CHD)

In CHD, CMR can aid in diagnostics as well as post-intervention follow up. CMR provides unrestricted evaluation of intracardiac and vascular structures pertinent to the altered anatomy present in CHD to assist with diagnosis. Assessment of LV and RV size and function by cine, shunt quantification and Qp/Qs calculations by flow hemodynamics assist in assessing the severity of congenital heart defect guiding medical and surgical management accordingly (**Figure 17**). The utilization of contrast enhanced MRA is highly advantageous in visualizing and defining vascular structures, which often exhibit abnormalities in cases of CHD [48]. CMR is considered the imaging modality of choice in the serial follow in CHD.

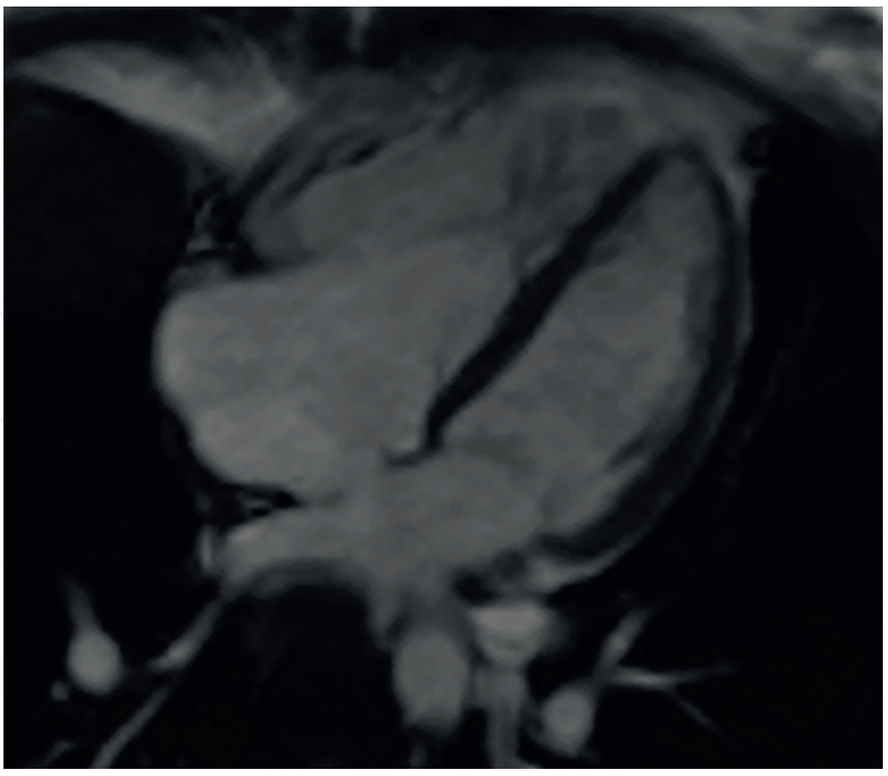

Figure 17.
Four chamber cine showing defect in the atrial septum with dilated right atrium and ventricle in a patient with atrial septal defect.

5. Advances in CMR

Advances are being made in CMR in the scanning part and in post processing. This section discusses technologic developments and advances in CMR with a focus on improvements in data acquisition, and reconstruction, new technologies and new clinical applications of CMR, MR guided cardiac procedures, and the role of artificial intelligence and machine learning in further advancing the field.

5.1 Advances in data acquisition techniques

5.1.1 Faster scanning

One of the limitations for the widespread use of CMR has been the time needed for scanning and for post processing. Considerable efforts are underway to decrease these times with a focus on improving the speed and efficiency of image acquisition, resolution, and reconstruction. Parallel imaging (PI) is used currently to decrease acquisition times. PI reduces redundant phase coiling data and processing steps [49]. PI, however, has known limitations due to under-sampling, such as lowering the signal-to-noise ratio and thus contributing to image degradation [50]. A novel method has since been developed called compressed sensing (CS) that utilizes similar under-sampling from PI with the addition of a noise-reduction algorithm [51]. CS results in faster data acquisition times without compromising image quality [51]. Current research is directed at further optimizing these systems to improve image quality and reduce artifacts, such as combing CS and PI [52] and designing algorithms to separate cardiac and respiration motion artifacts [53]. In addition to developments with CS, there is an interest in implementing artificial intelligence (AI) to improve data acquisition and processing performance further. The use of deep learning (DL) has been shown to accurately reconstruct cardiac MRI images at a faster rate compared to the methods described previously [54].

5.1.2 Respiratory and cardiac gating

Respiratory and cardiac gating techniques are well-established with CMR to reduce the physiologic motion of both systems and synchronize data acquisition throughout the cardiorespiratory cycle. These gating methods rely on ECGs, and image accuracy can be affected by arrhythmia and fluctuations in cardiac rhythm even in healthy subjects [55]. Novel techniques have been developed, such as non-ECG gated protocols, and have been found to improve spatial resolution and reduce cardiac motion artifacts without relying on ECG synchronization [56]. The same techniques have been implemented to reduce respiratory motion artifacts [57].

5.1.3 Whole heart spatial coverage

One of the limitations of current CMR imaging protocols is the use of 2D mapping slices. This method limits image acquisition to focal areas of tissue due to the thicker slices that can only cover a portion of the heart and require multiple breath holds impractical for certain patient populations. Newer mapping techniques have now emerged that provide a comprehensive analysis and image of the entire heart to better detect fibrosis and edema that may have been missed on older scanning

modalities. This developing image acquisition technique provides whole heart spatial coverage with 3-dimensional (3D) data from one scan. The quicker scan times and improvements in motion artifacts have allowed for whole heart spatial coverage with 3D analysis to emerge as an effective alternative to more invasive diagnostic imaging techniques. While the image quality is currently a limitation, further efforts are in progress with potential in this area.

5.1.4 Cardiac mapping

Myocardial mapping and CMR fingerprinting continue to expand. Data acquisition speed and accuracy improvements have expanded the clinical utility of T1 and T2 mapping. CMR fingerprinting has recently been developed to efficiently produce T1 and T2 maps from a single scan and single breath hold [58]. Additional uses have included measuring fat fraction to further characterize ischemic scars to better prognosticate cardiomyopathies [59]. Future progression is focused on applying fingerprinting to more advanced imaging sequences in 3-dimensional (3D) and 4-dimensional (4D) data sets.

5.2 Stress testing

While stress testing is commonly used, the predominant form of stress is chemical. The difficulty with treadmill stress is the expense involved with MRI compatible treadmills along with the need to lay the patient down quickly on the MRI scanning table in the same position as images obtained prior to stress. Another limitation is excess motion whether whole body or during respiration with exercise. A novel stress testing technique is supine MRI-compatible exercise ergometer. With a better safety profile than pharmacological stressors, physical stress on the heart visualized via CMR can provide insight into tissue function and characteristics specific to ischemia [60]. For post processing of stress perfusion sequences, currently most centers use visual estimation for stress perfusion. Current quantitative perfusion post processing software is tedious and time consuming. Advances are being made in stress testing with faster post processing software for quantitative perfusion.

5.3 Artifact reduction

Artifact reduction has become important to obtain CMR images in patients with pacemakers (PM) and ICDs. Despite developments in manufacturing MRI-compatible PM and ICDs, there remains difficulty in acquiring accurate CMR images of the myocardium due to the obscuring metal artifacts from these devices [61]. Inversion recovery sequences in LGE imaging have since been modified by adjusting the bandwidth and rate of pulsed radio frequencies to eliminate hyperintense artifacts [62]. These efforts have further expanded compatible patient populations who may benefit from CMR.

5.4 4-dimensional (4D) acquisition

Four-dimensional (4D) data acquisition especially for flow analysis is an emerging advanced imaging sequence in CMR. The data from 4D image reconstruction provides 3D dynamic values over time, which can be useful in patients with complex anatomy and differing flow gradients [57]. While clinical application of 4D image acquisition

is limited by a lack of ubiquitous hardware and software, there is vast potential in developing imaging protocols to better diagnose and monitor valvular pathologies and CHD.

5.5 Myocardial strain

While myocardial strain is being done by TTE currently, the use of CMR strain has significant potential (**Figure 18**). Myocardial strain assesses myocardial deformation and can serve as a precursor to myocardial dysfunction and cardiomyopathy [63] and has also been shown to predict cardiac mortality [64]. CMR is emerging as a diagnostic modality in determining myocardial strain due to several developing techniques. Displacement encoding with stimulated echocardiography (DENSE) is an acquisition method that measures myocardial tissue displacement to estimate strain. Feature tracking (FT) is another post-processing algorithm that calculates myocardial deformation [65]. Both DENSE and FT have been utilized to measure cardiac strain. However, a lack of inter-vendor standardization and clinical validity for cardiac strain remain salient limitations [65]. A new and developing technique called fast strain-encoded CMR (fast-SENC) is another imaging technique that can determine cardiac contractility with comparable results to FT and DENSE [66]. The clinical implication

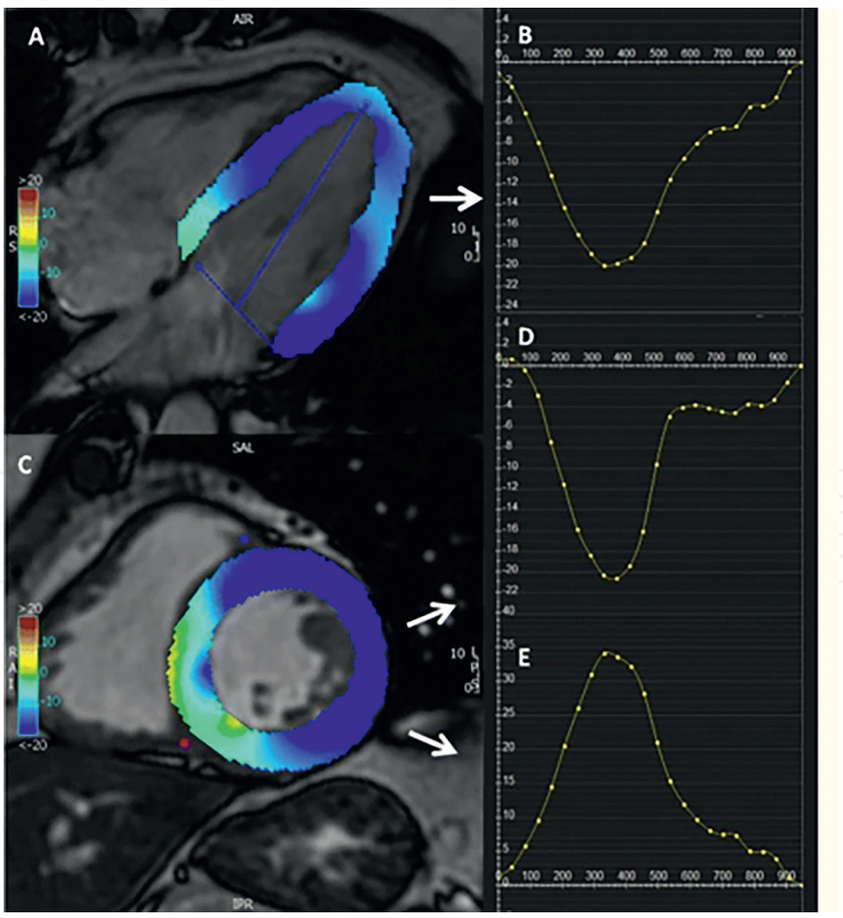

Figure 18.
Example of colored strain analysis with a feature-tracking software (Circle CVI42®). From long-axis four-chamber SSFP cine image (a), longitudinal strain curve is derived (b) and short-axis SSFP image (c) is used for calculation of circumferential (d) and radial strain curves (e). Reproduced with permission from Scatteia et al. [82].

is evaluating subclinical cardiomyopathies and adjusting treatment plans to prevent or monitor disease progression.

5.6 Diffusion-weighted CMR

Clinical utility and advances in diffusion-weighted imaging (DWI) of the heart is evolving. A subcategory of cardiac DWI with clinical potential is diffusion tensor imaging (DTI). DTI allows for 3-dimensional visualization and diffusion parameters of the cardiomyocyte microstructure without the need for exogenous contrast [67]. This modality measures water diffusion gradients within myocytes that are reconstructed to provide information about myofibers' orientation, rotation, and torsion [32]. One limitation of DWI and DTI in the heart is the signal loss inherent with cardiac motion which prevents the identification of true signal loss due to diffusion compared to signal loss due to cardiac motion. Recent advances have augmented pre-existing algorithms to account for this motion discrepancy [68] and improvements in the DTI data acquisition process reduce the total imaging time [69]. While the clinical utility of DTI information continues to expand, multiple studies have investigated how the cardiac microstructure data is affected by various pathologies. Parameters such as myocyte fiber orientation, fractional anisotropy, mean diffusivity gradients, tractographic propagation angle, and helical angle are all novel approaches to better characterizing infarcted tissue [70].

5.7 CMR guided interventions

CMR-guided interventions are continuously developing. Procedures like percutaneous coronary intervention used for obstructive CAD can cause acute kidney injury from the iodinated contrast used, leading to an increase in all-cause mortality [71]. Additionally, fluoroscopy exposes patients and staff to ionized radiation, increasing the risk of future malignancy [72]. While fluoroscopic X-ray remains the gold standard for these procedures, there is growing interest in using cardiac MRI as a procedural aid to reduce the need for fluoroscopy. Transarterial valve replacements and stenting procedures using CMR have been utilized in animal studies, however, the feasibility of implementing these techniques in human subjects remains a challenge and is still experimental at this stage. Other interventional cardiac procedures have also utilized CMR to reduce their fluoroscopic footprint such as EP.

5.8 Artificial intelligence and machine learning

Artificial intelligence (AI) is quickly becoming one of the fastest-growing fields within CMR. Briefly, AI is the method of developing intelligent algorithms that can perform tasks and solve complex problems [73]. Machine learning (ML) is a subset of AI that continually improves pattern recognition and makes data inferences with the more data it processes [74]. Although the clinical applications of AI and ML are still being developed and validated, implementing these resources will drastically change the future of CMR. Most notably, AI will significantly contribute to data acquisition and reconstruction acceleration, expand CMR metrics for further diagnostic and therapeutic effects, and increase the accessibility of CMR [74]. The current ML systems that have been developed expand on CS data acquisition models to further reconstruct under-sampled data. These models learn from CMR data sets by further exploiting redundancies of the temporospatial relationships of tissue, thus resulting

in quicker processing times and equivocal imaging resolution [74]. There have been numerous examples of ML-generated systems significantly accelerating processing times in CMR angiography [74], whole heart 3D LGE reconstruction [75], reduction of respiratory motion artifact [76], and T1 and T2 mapping [77]. Intracardiac volume measurements have also been generated from ML systems and have been used to risk stratify patients with severe AS [78]. There are instances where ML has been found to be more accurate in measuring certain parameters, such as ventricular volume, compared to human analyses [79]. Newer approaches are using ML to identify ischemic scars without utilizing LGE CMR and subjecting patients to contrast [80]. The clinical use of ML continues to expand within all fields of CMR in identifying fibrosis and scar with and without LGE, 3D and 4D flow reconstruction, and mapping techniques.

Several limitations exist regarding ML in CMR, given the field's novelty. For one, ML requires a fully sampled learning database to make inferences on testing samples, which is not widely available. Evidence suggests variations in image reconstruction based on certain parameters from the learning database, such as signal-to-noise ratios [81]. Additional improvements in central and graphical processing units are required to run these systems and models. Despite these restrictions, the use of AI and ML in CMR continues to improve and may have significant implications in imaging accessibility by providing automated analyses of cardiac disease.

6. Conclusion

CMR is an excellent and comprehensive imaging modality, providing information about myocardial structure, function, tissue characterization, edema, infiltration, inflammation, scar, myocardial perfusion, congenital heart disease, shunts, flow quantification in addition to viability and any other cardiac abnormalities like masses. Currently being limited by the time involved in acquiring the scan and in the post processing of these scans, as seen above, there are a lot of advances and research happening in all areas. The clinical and research uses of CMR continue to grow and it continues to offer valuable insight into a variety of cardiac pathologies.

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