Cardiac Magnetic Resonance Imaging and Computed Tomography: State of the Art in Clinical Practice

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ABSTRACT

Recent technological innovations in CT and MR imaging of the heart have vastly expanded the clinical utility of these modalities allowing them to complement and in some ways surpass the capabilities of more traditional methods. Cardiac MR (CMR) has an unrivaled ability to assess contractile function, characterize tissue, and detect minute areas of scar. In turn, CMR can reliably risk stratify ischemic heart disease and has emerged as a non-invasive gold standard technique for imaging non-ischemic cardiomyopathies.[1] Cardiac CT (CCT) by comparison reveals cardiac structure and, in particular, coronary anatomy with remarkable sub-millimeter detail. For the first time, coronary stenoses can be directly and reliably visualized non-invasively. Owing to its very high negative predictive value for the detection of significant coronary obstruction, CCT can accurately exclude coronary disease as a cause of chest pain in low- to intermediate-risk populations. This article describes these modalities and their recent clinical advances.

KEYWORDS: Cardiac CT (CCT), Cardiac MR (CMR)

INTRODUCTION

This article briefly reviews the methodologies of CCT and CMR, their specific roles in the diagnosis of cardiac pathophysiology, and their utility in outcomes assessment and prognosis with various disease states.

Cardiac MR: The Basics

Magnetic resonance imaging is based on the absorption and subsequent emission of radiofrequency (RF) energy by water protons in various tissues of the body while immersed in a strong magnetic field. The RF emission is tissue dependent and leads to the unparalleled ability of MRI to distinguish subtle regional tissue differences within a single organ of the body, for example scar or edema within myocardium (Figures 1 and 2). With intravenous gadolinium-based contrast agents, MRI can further distinguish tissues based on their blood flow and blood volume differences. Using ECG-gating for stop-action imaging and novel acquisition methods, MRI can readily demonstrate regional myocardial differences in tissue perfusion and in the same examination detect areas of acute myocyte necrosis or scar – sometimes 1 cm^3 or less. Myocardial fibrosis is a common endpoint of many cardiomyopathies, but the geographic patterns of fibrosis vary between disease states. As will be seen, with CMR these patterns commonly point towards a limited differential diagnosis, or in some cases the specific diagnosis. In the setting of ischemic heart disease, scar delineation has important prognostic utility. It has been shown that CMR with contrast accurately predicts viability – that is whether or not underperfused tissue will recover function after revascularization – and is probably the best method for determining this.[2] Moreover, the presence of even a small amount of scar,

Figure 1. Short axis (a) bright-blood and (b) post-contrast CMR images from a patient with occlusion of the right coronary artery. A small (bright) inferior scar is demonstrated (arrows) consistent with an infarction. LV/RV: Left/Right ventricle.

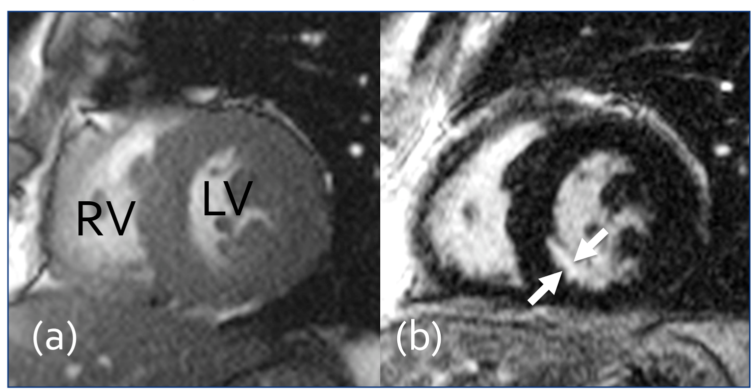
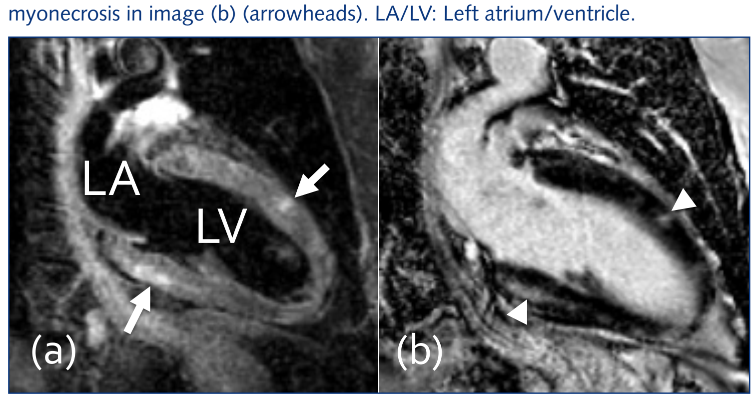


Figure 2. Vertical long axis (a) dark blood and (b) post-contrast CMR images from a patient with acute myocarditis. Bright areas of myocardial edema in image (a) (arrows) overlap spatially with areas of acute myonecrosis in image (b) (arrowheads). LA/LV: Left atrium/ventricle.



much smaller than can be detected with nuclear methods, confers a substantial increase in the risk of major adverse cardiovascular events compared with no scar.[3]

Combining techniques for tissue characterization with cine movie loops having high spatial and high temporal resolution yields a robust evaluation of myocardial tissue and contractile function. Moreover, dynamic MR imaging during contrast infusion under conditions of induced coronary vasodilation (with intravenous adenosine for example) delineates regions of underperfusion due to upstream coronary artery stenosis. In its ability to detect significant coronary obstruction, CMR stress perfusion is superior to nuclear pharmacologic stress perfusion.[4]

Another powerful tool in the CMR arsenal is so-called phase-contrast MRI where image brightness is proportional to tissue velocity. Importantly, this technique permits dynamic *quantification* of blood flow (in cc/min) through large vessels enabling calculation of regurgitant valve severity and shunt fraction. As with echo, CMR can also characterize the severity of valvular stenosis.

The typical CMR study can be completed within 45 to 60 minutes. The patient is required to undergo a series of breath-holds while lying flat, which are generally well tolerated. The duration of the breath-holds is variable and can be adjusted based on the patient's capability. Generally, the imaging of patients with arrhythmias is non-problematic, and MR imaging, like CT, is not significantly hampered by body habitus.

Advantages, disadvantages, and appropriate indications of CMR are listed in Tables 1 and 2.[5]

Table 1. Advantages and Disadvantages of cardiac MR (CMR) and cardiac CT (CCT)

	CMR	CCT
Advantages	No ionizing radiation	Short scan times
	Image anatomy, function & physiology	Image anatomy/function
	Can scan patients with arrhythmias	Convenient for patient
	High temporal resolution	High spatial resolution
	Moderate spatial resolution	Moderate temporal resolution
	Tissue characterization (e.g. scar)	
Disadvantages	Longer scan times	Ionizing radiation
	Contrast carries risk of NSF	Requires heart rate control
	Claustrophobia	Risks of iodinated contrast
	Artifacts from foreign matter	
	MRI contraindications (e.g. pacemaker)	

Table 2. Appropriate indications for CMR.(Modified from Table 19 in Hendel et al[5]).

Stress CMR (e.g. Adenosine perfusion)
- Chest pain syndrome
  - Intermediate PTP of CAD & either ECG uninterpretable or unable to exercise
- Stenosis of unclear significance on coronary angiography

Detection of Myocardial Scar and Viability
- Location & extent of myonecrosis after acute MI
- Viability prior to revascularization or medical therapy
- Viability after "equivocal or indeterminate" results on SPECT or dobutamine echo

Ventricular and valvular function
- Congenital heart disease
- LV function after MI or in heart failure patients when echo is limited
- Quantification of LV function when prior tests give discordant data
- Evaluation of specific CMs (infiltrative [amyloid/sarcoid], HCM, or due to cardiotoxic therapies)
- Native & prosthetic valves, with planimetry & quantification, when echo is limited
- Evaluation for ARVC in patients with syncope or ventricular arrhythmia
- Myocarditis or MI with positive cardiac enzymes & no obstructive coronary lesions

Cardiac masses using contrast to assess vascularity

Pericardial disease (e.g. mass, constrictive pericarditis)

Suspected coronary anomalies (CT is preferred)

Pulmonary vein mapping pre- and post-RF ablation for atrial fibrillation

PTP: pre-test probability.
CAD: coronary artery disease.
LV: left ventricle. MI: myocardial infarction.
CM: cardiomyopathy.
HCM: Hypertrophic cardiomyopathy.
ARVC: Arrhythmogenic right ventricular cardiomyopathy.
SPECT: Single-photon emission computed tomography.
RF: Radiofrequency.

Cardiac CT: The Basics

CT is an x-ray based modality in which a ring, or gantry, containing an x-ray tube diametrically opposite a series of detectors rotates around a patient as the patient is moved through the ring. With modern scanners, volumetric data with submillimeter spatial resolution is collected over the scanned area of interest allowing images to be reconstructed in any orientation with equal clarity. Early CT systems lacked the spatial and temporal resolution to adequately visualize cardiac structures. The advent of very rapid gantry rotation, ECG-gating, and sub-mm resolution now permits stop-action imaging of very small rapidly moving structures such as the coronary arteries (Figure 3). With intravenous iodinated contrast, CT readily depicts cardiac morphology and vascular anatomy and can be useful for unraveling congenital and acquired cardiovascular anomalies. While cardiac masses and thrombi are generally evident with CT, MRI is usually preferred for mass characterization because of its superior tissue contrast resolution.

Cardiac CT scans can be performed rapidly, with typical table times of ~10 minutes and actual scan times of less than 10 seconds. With current CT technology lower heart rates generally provide better scan quality, and patients are often given intravenous beta-blocker prior to the scan. Contrast and radiation are necessary elements of the study. The newest scanners and imaging protocols have decreased average patient radiation exposure, and doses are usually at or below those of nuclear myocardial perfusion imaging using ^{99m}Tc-sestamibi. In contrast to CMR, only a few breath holds are necessary with CCT.

Advantages, disadvantages, and appropriate indications of cardiac CT are listed in Tables 1 and 3.[6]

Roles of CMR and CCT in Specific Cardiac Diseases

Evaluation of Ischemic Heart disease

As the number one cause of death in the US, identification and qualification of coronary artery disease is a critical area for diagnostic evaluation.[7] Diagnosis of acute plaque rupture in a coronary artery is typically made using a combination of history, electrocardiogram, and cardiac biomarkers, and risk-scoring systems help to predict which of these patients require urgent coronary angiography. In patients with acute coronary syndromes not indicated for emergent angiography, and those patients with progressive luminal narrowing, non-invasive imaging techniques are important tools for accurate diagnosis and further management decisions. Ideally, a comprehensive non-invasive diagnostic test is able to assess coronary anatomy and lumen defects, plaque composition, tissue perfusion, cardiac function as a result of stenosis, and viability of myocardium.

Most of these items can be met when patients with ischemic heart disease are evaluated using CMR. A large prospective study compared adenosine stress CMR with adenosine stress nuclear imaging (Single Photon Emission Computed Tomography, SPECT) in suspected ischemic coronary disease and found similar specificity for both modalities but a superiority in sensitivity, negative predictive value, and overall diagnostic accuracy for CMR.[4] Cardiac function assessment using CMR is highly accurate and CMR is considered the reference standard for non-invasive assessment of chamber volumes and ventricular

Figure 3. In (a), a widely patent mid-right coronary artery (RCA) stent (double arrow) is depicted on 3-D (left) and reformatted (right) CCT images. Image (b) demonstrates a severe stenosis (arrowhead) of the proximal left anterior descending coronary artery in another patient. Note the extensive soft plaque (arrows) in the coronary artery wall. RV/LV: Right/left ventricle. RA: Right atrium.

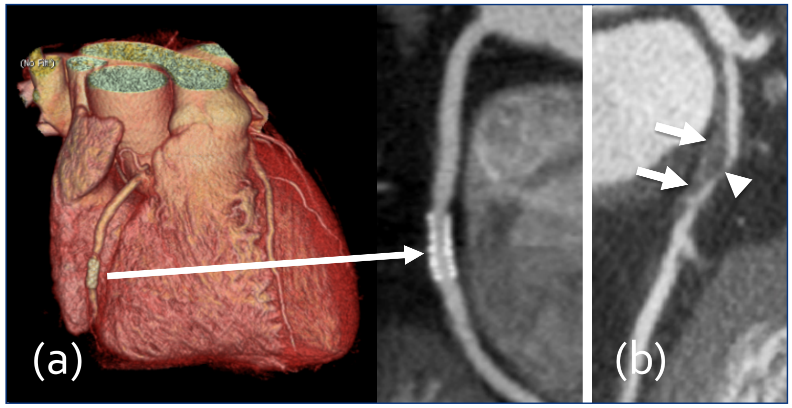


Table 3. Appropriate indications for CCT (Modified from Table 8 in Taylor *et al.*[6] CHD: Coronary heart disease. Other abbreviations are in Table 2.)

Coronary angiography

- Nonacute symptoms, possibly an ischemic equivalent
  - Intermediate PTP of CAD and ECG interpretable and able to exercise
  - Low/Intermediate PTP of CAD and either ECG uninterpretable or unable to exercise
- Acute chest pain
  - Normal ECG and cardiac biomarkers and low/intermediate PTP of CAD
  - Low/Intermediate PTP of CAD and ECG uninterpretable
  - Low/Intermediate PTP of CAD and either nondiagnostic ECG or equivocal biomarkers
- New onset or newly diagnosed clinical heart failure to assess etiology
  - Low/Intermediate PTP of CAD and reduced LV ejection fraction
- Intermediate preoperative coronary assessment prior to noncoronary cardiac surgery
- Continued symptoms after normal ECG exercise test
- Intermediate risk findings on Duke Treadmill Score
- Discordant ECG exercise and imaging results or equivocal stress imaging results
- Evaluation of graft patency after coronary bypass in symptomatic patient
- Evaluation of left main stent patency in asymptomatic patient
- Calcium Score: Family history or premature CHD and low global CHD risk estimate OR asymptomatic with no known CAD and intermediate CHD risk estimate

Congenital heart disease

Evaluation of LV function after acute MI or in HF patients in the setting of inadequate images from other noninvasive methods

Quantitative evaluation of right ventricular function/morphology (ARVC)

Evaluation of suspected dysfunctional native or prosthetic valves or of a cardiac mass in the setting of inadequate images from other noninvasive methods

Pericardial anatomy

Pulmonary vein mapping prior to ablation for atrial fibrillation

Coronary vein mapping prior to biventricular pacemaker placement

Localization of coronary bypass grafts and other retrosternal anatomy prior to reoperative chest or cardiac surgery

ejection fraction.[8] As mentioned earlier, necrotic tissue and the corresponding wall-motion abnormalities can be accurately distinguished from viable tissue, despite regional functional defects, with contrast CMR.

The use of cardiac CT (CCT) in the detection of significant coronary artery disease relies on its excellent spatial resolution.[9] CCT can accurately diagnose coronary stenoses >50%.[10,11] Further, the high negative predictive value of this technique for detecting significant obstructive disease has permitted chest pain units to safely, efficiently, and cost-effectively 'rule out' coronary disease in low-intermediate risk populations.[12-14] The spatial resolution of CT also lends itself to an assessment of coronary bypass grafts, large coronary stents (Figure 3), and congenital coronary anomalies.[15,16] Registry data suggest that the presence of even non-obstructive atherosclerotic plaque confers increased risk of major adverse cardiovascular events.[17]

While efforts to evaluate artherosclerotic plaque composition to determine likelihood of plaque rupture are not yet mature, coronary artery calcification is a definite marker of atherosclerosis. Coronary artery calcium (CAC) scoring using non-contrast CT technology is a well-established tool for risk assessment in asymptomatic patients, particularly those with intermediate pretest risk for coronary disease.[18,19]

Non-ischemic cardiomyopathies

Diagnosis and characterization of non-ischemic cardiomyopathies has historically been difficult, sometimes requiring biopsy to make a definitive diagnosis. In most patients with new onset cardiomyopathy, it is important to first exclude ischemic heart disease, which both CCT and CMR can confidently do owing to their high negative predictive values.[5,6] Further, cardiac MR can help delineate between the heterogeneous group of NICMs, and potentially give important information regarding prognosis.[1,20] Select cardiomyopathies are discussed below.

Hypertrophic cardiomyopathy (HCM)

In HCM, CMR like echo can identify regions of abnormal myocardial thickening. However, because CMR is a true 3-D modality with no 'blind spots' it occasionally reveals abnormalities not seen on echo. CMR has been able to detect an additional 6-12% of patients with HCM that were not found on echocardiogram.[21] Moreover, CMR with contrast delineates fibrosis in a few typical patterns, further supporting and usually – with the support of morphologic data – cinching the diagnosis. Extent and severity of fibrosis may correlate with an increased risk of sudden cardiac death and in turn modify clinical management.[21]

Cardiac sarcoidosis (CS)

Cardiac sarcoidosis is a challenging diagnosis that has traditionally relied on complex criteria issue by the Japanese Ministry of Health.[22] Knowledge of cardiac involvement may prompt changes in clinical management. While cardiac involvement is clinically evident in only 5% of patients with sarcoidosis,[23] post-mortem evaluation indicates that the prevalence is far greater.[24] CMR has recently been shown to be superior to conventional criteria in identifying areas of myocardial damage due to sarcoid manifested as patchy enhancement in affected areas, typically in the subepicardial basal septum, in patients with the appropriate clinical context (Figure 4).[25]

Myocarditis

Viral myocarditis can often have patchy midwall or subepicardial enhancement – typically in the inferolateral left ventricle or the septum – with extent and distribution of the enhancement associated with prognosis and probable viral pathogen (Figure 2).[26,27]

Figure 4. (a) Short axis and (b) vertical long axis post-contrast CMR images of a patient with cardiac sarcoid demonstrate anterior and anteroseptal enhancement (arrows) consistent with myocardial damage.

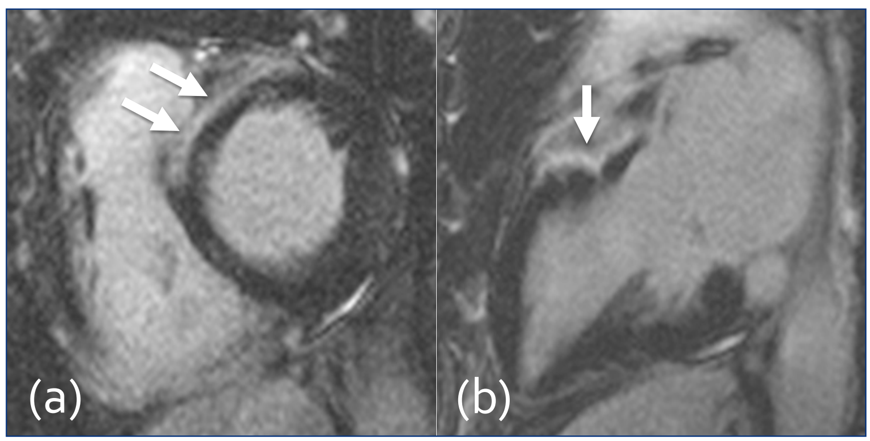
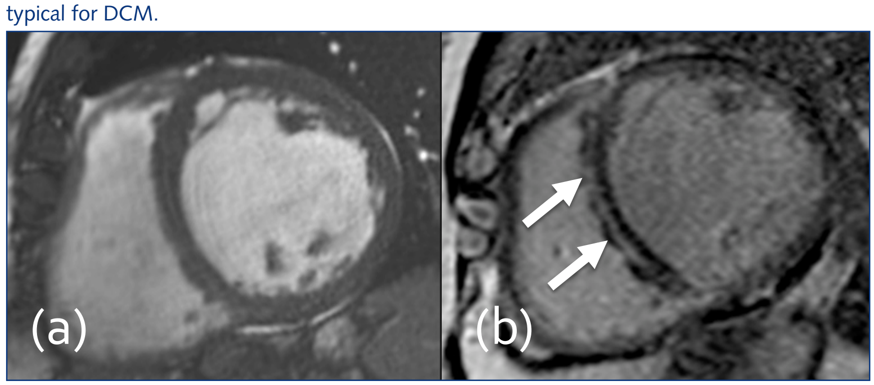


Figure 5. Short axis (a) bright-blood and (b) post-contrast CMR images from a patient with dilated non-ischemic cardiomyopathy (DCM). (Coronary arteries were normal at catheterization.) Note the midwall stripe of enhancement in the septum typical for DCM.



Dilated Cardiomyopathy (DCM)

The vast majority of patients with DCM demonstrate no enhancement at CMR or a characteristic midwall stripe of enhancement in the septum (Figure 5).[28] In patients presenting with heart failure, these findings aid in the distinction of DCM from ischemic heart disease where virtually all subjects demonstrate subendocardial or transmural scar when scar is present.

Cardiac Amyloidosis

Cardiac amyloidosis is an uncommon cardiomyopathy resulting from the deposition of amyloid protein in myocardial interstitium (as well as other tissues of the body). Myocardial thickness is usually increased, and over time left ventricular function deteriorates. Diagnosis relies on endomyocardial biopsy, but may be inferred from positive fat pad biopsy in the appropriate clinical context. The CMR enhancement pattern for this condition is unique and very suggestive in unclear cases.[29]

Iron overload syndromes

In iron overload syndromes such as Thalessemia and sickle cell disease, CMR has the unique ablility to detect myocardial iron deposition and quantify its severity.[30] This advance has led to optimal detection of patients for chelation therapy prior to developing irreversible cardiomyopathy, significantly impacting mortality.

Valvular heart disease

The visual assessment of valvular heart disease by echo is generally superior to that of CMR and CCT. While CMR estimates of stenosis severity are reliable, CMR offers a unique advantage in its ability to *quantify* regurgitant fraction.[31] Also, CMR is emerging as a useful tool for characterization of pulmonic valvular lesions often difficult to assess with echocardiography.

Pericardial disease

Although CT is able to demonstrate pericardial effusions, thickening, calcification and masses, CMR is generally regarded as the preferred modality for imaging the pericardium.[32] A particular strength of CMR is its ability to distinguish constrictive pericarditis from restrictive cardiomyopathy, two entities with overlapping clinical presentations. In this regard, CMR is the gold standard.

Masses

Both intracardiac and extracardiac masses can be visualized using CMR and CCT, but again CMR is the preferred imaging modality. CMR assessment of a mass can be useful in evaluating its size, location, tissue characteristics including enhancement pattern, and functional significance. Recent studies have indicated that increased T2 signal, gadolinium enhancement, and lack of mobility all are suggestive of malignant neoplasm with reasonably high sensitivity and specificity compared with pathological correlates.[33] CMR is accurate in the detection of intracardiac thrombus and is more sensitive than echo.[34,35]

Congenital Heart Disease

Evaluation of adult congenital heart disease by echocardiography can be hampered by limited views due to body habitus and low pre-test suspicion of a congenital anomaly. Both CCT and MRI are able to detect and characterize congenital cardiovascular lesions. Patients that have had previous surgeries can have a comprehensive anatomic evaluation using either of these techniques. In general, CCT is preferred when anatomy is the principle concern, for example in the detection and evaluation of congenital coronary anomalies.[36] Cardiac MR offers the additional ability to quantify blood flow — for estimating shunt and valve lesion severity — and cardiac chamber volumes and ejection fraction, and characterize wall-motion abnormalities. Patients with stable congenital heart disease can be followed periodically using these non-invasive techniques to detect progression of pathology and support management decisions.

SUMMARY

Cardiac MR and CT have both become mature tools for the clinical evaluation of a vast array of cardiac diseases. These 'new' modalities are in many ways complementary to one another and to other tools in the traditional clinical armamentarium and offer unique and powerful insights into cardiac pathology and pathophysiology. Their uses for diagnosing disease, predicting prognoses and outcomes, and modifying clinical management continue to emerge and evolve. CMR offers a dynamic range of capabilities for assessment of the cardiovascular system, allowing for a single, radiation-free imaging study to answer a multitude of clinical questions, especially with regards to cardiomopathy. CCT has become an excellent non-invasive technique for anatomic assessment of the heart, and is a quick and useful tool for rapid evaluation of low-intermediate risk chest pain syndromes. The future is bright for CCT and CMR and for the physicians and patients who benefit from their use.

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