MINI REVIEW – CONTINUING MEDICAL EDUCATION

Cardiac magnetic resonance imaging: A teaching atlas with emphasizing current clinical indications

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Abstract Cardiovascular magnetic resonance (CMR) is an amazing technology that continues to provide new innovative approaches for evaluating the heart and blood vessels. It can assess cardiac morphology, function, perfusion, viability, coronary and peripheral arteries, and metabolism and tissue characterization. The basic pulse sequences of CMR include; Spin Echo, Gradient echo, and Steady state free precision. Current clinical indications of CMR are multiple and continuously evolving. CMR often works in complementary fashions to other cardiac imaging techniques or to resolve residual diagnostic dilemma. The purpose of this illustrative review is to review current clinical applications of CMR and to provide physicians and technologists with simple, and regular CMR cases from daily practice. Each case discusses briefly the related clinical history, followed by CMR imaging findings, and simple discussion to highlight the role of CMR in a particular cardiovascular disorder.

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1. Introduction

Cardiovascular magnetic resonance (CMR) is an amazing technology that continues to provide new innovative ap-
is to define the clinical question; this is generated under the most optimal circumstances through close collaboration between the referring physicians and interpretive physicians (car-

**Figure 1** Anomalous origin right coronary artery is shown in 23-year old man with intermittent chest pain. 3D coronary magnetic resonance angiography (MRA) shows anomalous origin of right coronary artery arising with common ostia with left coronary artery from the left coronary sinus (arrow) with an interarterial course between the aorta and the pulmonary artery (malignant course). Coronary MRA is clinically useful in a selected population including: (1) identification and characterization of anomalous coronary arteries, (2) characterization of coronary artery aneurysm in patients with Kawasaki disease, (3) coronary artery stenosis in patients with heavy calcification, (4) assessment of artery bypass graft patency, (5) coronary artery stenosis in patients with renal failure. Coronary MRA also, appears to be useful in assessment of native coronary artery in a selected population with suspected left main/multivessel disease. Despite its excellent diagnostic accuracy, coronary computed tomography angiogram (CTA) has several limitations, particularly radiation exposure. Coronary MRA and coronary CTA are more complementary with one another than competitive (Manning et al., 2007).

**Figure 2** Adenosine stress cardiovascular magnetic resonance (As-CMR). Short axis; basal, mid, and apical left ventricular segments demonstrate a stress perfusion defect in the inferior wall (arrow in basal segment) and a reversible perfusion defect in the mid anterior wall, a finding that is consistent with stress-induced ischemia in the anterior and inferior walls. These findings are consistent with adenosine stress myocardial ischemia in the right coronary artery and the left anterior descending artery distribution. Coronary angiography revealed more then 70% occlusion of the right proximal coronary and mid left anterior descending coronary artery, and both were successfully treated with intervention. AS-CMR is usually combined with late gadolinium-enhancement MR imaging to determine the area of perfusion defect in viable or infarcted myocardium. This distinction is important for differentiation between viable myocardium supplied by an artery having significant stenosis (inducible ischemia) from area of infarcted myocardium supplied by a large artery occlusion or microvascular obstruction (myocardial infarction). Recently, a multicentral/multivendor study showed that the performance of AS-CMR is equal to stress myocardial perfusion scintigraphy (MPS), and suggested that AS-CMR could be a valuable alternative to MPS for the detection of coronary artery disease (Schwitter et al., 2008).

**Figure 3** Dobutamine stress cardiac magnetic resonance. Rest (top right) 4-chamber cine images demonstrate normal wall thickness of the left ventricle. At a higher dose of dobutamine infusion, 30 mcg/kg/min (lower left), the apical and apical septal hypokinesis and decreased wall thickness is evident, a finding that indicates stress inducible wall motion abnormality (WMA). Stress-induced WMA is the clinical counterpart of angina and indicates hemodynamical coronary artery stenosis. Although such studies are usually performed with echocardiography, the image quality is usually suboptimal with low inter- and interobserver agreement. Cardiac magnetic resonance images are more reliable with high both temporal and spatial resolution and is considered a reasonable sequential test, if stress echocardiography is not diagnostic (Hundley et al., 2002).

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Figure 4  Acute Myocardial infarction is shown. Cine images (top), T2-weighted (T2W) cardiac magnetic resonance (CMR) images (middle), and late gadolinium enhancement (lower). This patient presented to the emergency room with new onset chest pain, mildly elevated cardiac enzymes, and non-specific ST-segment changes. Cine images demonstrated hypokinesis in the distribution of the left anterior descending artery (LAD). T2W short-tau inversion recovery (STIR) fast spin technique (TSE) images show hyperintense signal in the septum (arrow). The hyperintense signal indicates an acute event. Late gadolinium enhancement images show no abnormal enhancement that suggests myocardial infarction. This case demonstrates the value of edema-weighted imaging in acute myocardial infarction. Increased free water content does not necessarily reflect myocardial necrosis, and the extent of myocardial infarction could be overestimated. T2W CMR indicates myocardial area at risk (AAR), the portion of AAR irreversibly injured (infarcted) ranges from 0% (aborted infarction) to as much as 88%. The proportion of the AAR that survives – salvage myocardium – is dependent on multiple factors including: time to perfusion, ischemic pre-conditioning, collaterals flow, distal embolization, reperfusion injury and microvascular dysfunction. T2W CMR performed early after successful reperfusion myocardial infarction enables retrospective quantification of the myocardial AAR and salvageable myocardium (Wright et al., 2009).

Figure 5  Transmural Inferior wall Myocardial infarction is shown. An inversion recovery delayed enhancement image shows transmural inferior wall myocardial infarction (arrow) subendocardial borders in adjacent inferolateral and inferoseptal segments. The inversion time (a timing option) was adjusted to null normal myocardium, thus the normal myocardium appears uniformly black in this midventricular short axis image. An area of infarction appears brighter than normal myocardium due to a combination of delayed wash-in and washout kinetics of the fibrotic scar tissue. In chronic myocardial infarction, the presence of fibrotic tissue increases the interstitial space per unit volume, causing Gadolinium agents to diffuse rapidly into the interstitial, but not the intracellular space (Kim et al., 2003).

Figure 6  Anterior wall myocardial infarction with microvascular obstruction (no-reflow phenomenon) is shown. Short axis late gadolinium enhancement image shows a transmural myocardial infarction in the anterior wall with subendocardial borders in the adjacent mid anteroseptal and mid anterolateral segments. Small area with no signal (arrow) indicates microvascular obstruction. Microvascular obstruction may occur because one or more of the following mechanisms: (1) ischemic damage of the microvessel; (2) severe tissue swelling that prevents perfusion at tissue level; (3) thrombotic or white blood cell plugging in the small vessel; and (4) Atherosbolism. Microvascular obstruction is associated with more prolonged ischemia and more severe myocardial injury. Importantly, post infarct microvascular obstruction appears to have prognostic significance and portends severe long-term compromise of regional myocardial function (Wu et al., 1998).
Figure 8  (A, B) Right atrial thrombus is shown. Cine 4-chamber cine (A) and 4 first pass perfusion images (B) demonstrated a filling defect in the right atrium on cine image with no enhancement following gadolinium administration, a finding that indicates right atrial thrombus. Right atrial thrombus is usually associated with in situ catheters in the right atrium or in patients with enlarged cavities (e.g., restrictive cardiomyopathy). On CMR imaging, signal intensity of thrombus may vary depending on the age of the thrombus. Acute thrombus will appear bright on both T1- and T2-weighted images where as subacute thrombus will appear bright on T1-weighted images with a low signal intensity on T2-weighted images. Chronic organized thrombus will have low signal intensity on both T1- and T2-weighted images because of depleted water, with or without calcification of the thrombus. Gadolinium contrast is useful for differentiating thrombus from tumor. During first pass perfusion, the thrombus typically does not enhance (Figure B) and on late enhancement, thrombus usually does not enhance but tumors usually enhances. In clinical practice, a combination of different CMR pulse sequence, history, and other clinical finding help reach to the final diagnosis (Mollet et al., 2002).
Cardiology or radiology specialist). The basic pulse sequences of CMR include (1) Spin Echo (SE) for black blood imaging, mainly for cardiac morphology, (2) Gradient echo (GRE) for white blood imaging and cardiac function, (3) Inversion recovery (IR) which optimizes the contrast for tissue characterization and morphology, and (4) Steady state free precision (SSFP) for high speed acquisition. Given the large number of pulse sequences and the wide variety of clinical applications

Figure 9  (A, B) Acute myocarditis is shown. A 32-year-old man with no significant past medical history presented with new onset of severe chest pain. He has no cardiovascular risk factors. Upon presentation, the EKG showed ST-segment elevation and elevated Troponin. A diagnostic X-ray angiography was normal. Cardiac magnetic resonance (CMR) cine images (not shown) demonstrated global hypokinesis and impaired left ventricular function at 30%. Short axis T2-weighted (A) images showed hyperintense signal (as indicated by arrows involving anterior, lateral and septal walls) which indicated tissue edema. Late gadolinium-enhancement images showed patchy pattern of enhancement, this pattern generally resolves in patients that have resolution of myocarditis, and it becomes more generalized in patients who have prolonged functional abnormalities. Distinguishing this pattern from more conventional ischemia-related disease can be done by noting the location of the hyperenhancement in the myocardial wall. Hyperenhancement related infarction always includes the endocardial surface. While the hyperenhancement associated with myocarditis (arrows) is seen in the mid wall and epicardial portion of the muscle (B) and often spares the endocardial surface. This pattern is also patchy and does not follow the expected vascular territory (Abdel-Aty et al., 2005).
Figure 10  (A, B) Idiopathic dilated cardiomyopathy. (A) Demonstrating a 4-chamber cine image shows dilated IV cavity with global hypokinesis and impaired systolic function of 35%. Late gadolinium-enhancement image demonstrates absence of any scar tissue that would explain impaired LV function (B). Coronary angiography confirmed absence of coronary artery disease (CAD). Dilated cardiomyopathy (DCMP) is characterized primarily by systolic dysfunction, 4-chamber enlargement, and ventricular dilatation is out of proportion to wall thickness. This can be further divided into ischemic versus non-ischemic based on etiology. The most common form of cardiomyopathy is ischemic cardiomyopathy. CMR technique allows regional and global function assessment, viability determination and determination of the presence or absence of epicardial coronary disease. The use of gadolinium–enhanced MRI may be helpful in characterizing the myocardium and in differentiating DCMP patients from LV dysfunction related to CAD. Three different patterns of gadolinium-enhancement have been reported in patients with DCMP including; (1) no enhancement; (2) subendocardial or transmural enhancement indistinguishable for CAD; and (3) patchy mid wall enhancement. The subendocardial or transmural enhancements are most likely related to CAD with subsequent coronary artery recanalization (White and Patel, 2007).

Figure 11  (A, B) Hypertrophic cardiomyopathy in 31-year old women with a strong family history of cardiomyopathy. (A) shows a 4-chamber cine image that demonstrates a maximum thickness of the left ventricular wall up to 25 mm (arrow), and left ventricle was calculated and was found to be 75%. Late gadolinium-enhancement image (B) shows signal enhancement in the inferior (arrow) and anterior insertion points of the right ventricle, consistent with myocardial fibrosis. Although transthoracic echocardiography is the primary imaging modality in the diagnosis of hypertrophic cardiomyopathy (HCM), CMR at present provides the most complete description of abnormalities in HCM patients. CMR techniques can be used to determine ventricular mass and precisely define the location and subtype, the systolic anterior motion of mitral valve as well as the presence and extent of myocardial fibrosis (White and Patel, 2007).
for CMR to evaluate cardiovascular patients, it is imperative to organize and standardize the CMR imaging protocol to improve workflow and to maintain consistency between scan operators. The following are common CMR techniques that may be used in CMR protocols, but it is not necessary to acquire these for every patient instated, but should be individualized to answer particular clinical questions (Kim et al., 2007):

(1) Scouting: is the first and simplest to perform, the goal of scouting is to establish the short and long axis of the heart for further imaging.
(2) Function and volume: Cine CMR using GRE and SSFP imaging to measure the left and right ventricular function and mass.
(3) Perfusion stress and rest for detection of CAD.
(4) Viability determination for differentiation of viable from infarcted myocardium before coronary revascularization.
(5) Flow and velocity cine imaging to measure blood velocity and flow in arteries, veins, valves, or intracardiac shunts.
(6) Magnetic resonance angiography for detection of arterial or venous abnormalities.

Current clinical indications of CMR are multiple and continuously evolving. CMR often works in complementary fashions with other cardiac imaging techniques and/or to resolve residual diagnostic dilemma these indications include (Hendel et al., 2006):

1. Coronary artery imaging: to detect the proximal course of anomalous coronary artery.
2. Assessment of right and left ventricular function: CMR has excellent interobserver and intraobserver variability. CMR can quantify regional wall motion abnormality and myocardial strain using different pulses techniques.
3. Diagnosis of coronary artery disease: Single CMR examination can provide information regarding coronary artery disease, left ventricular function, myocardial perfusion, and viability.

Figure 12  (A, B) Cardiac amyloidosis in a 60-year-old female with a long-standing history of exertional dyspnea. A 4-chamber cine image (A) showed biventricular wall hypertrophy and diminished ventricular function, left ventricular ejection fraction was 30%, with biatrial enlargement, and mild bilateral pleural effusion (arrows). Figure B shows diffuse strong inhomogeneous myocardial enhancement involving most of the left ventricular myocardium. CMR has a potential value in diagnosing cardiac amyloidosis. Besides a morphological description of cardiac abnormalities and assessment of systolic and diastolic function, the CMR provides tissue characterization following administration of gadolinium. Amyloid tissue has a short T1 and T2 relaxation time and shows altered wash-in and washout dynamic after gadolinium injection. Using these criteria, cardiac amyloidosis can be established with a high accuracy that may even render biopsy unnecessary in some cases (White and Patel, 2007).

Figure 13  Cardiac sarcoidosis is shown in a 38-year-old woman with a history of fatigue and mild dyspnea. Cine images (not shown) demonstrated mildly reduced left ventricular function of 47% with normal LV size. Late gadolinium-enhancement image showed a large area of bright signal in the anterior wall (arrow). Cardiac involvement is observed in up to 50% of patients with sarcoidosis, although only 5% present with symptoms of cardiac disease. Cardiac involvement is the cause of death in up to two-thirds of patient’s with this condition. Although CMR can easily detect wall motion abnormalities or aneurysm, the main advantage of this technique is its ability to characterize myocardial inflammation. The combination of early (spin echo) and late enhancement (as in this case) together with T2weighted image provides a more comprehensive approach (White and Patel, 2007).
4. Cardiomyopathy: CMR can characterize cardiomyopathy in unique ways based on magnetic properties of the myocardium.

5. Congenital heart disease: CMR provides a comprehensive examination for patients with congenital heart disease including, (1) anatomical connection or malformation, (2) identification and quantification of intracardiac shunts, (3) valvular anatomy and function, (4) depiction of complex vascular anomalies, (5) measurement of pulmonary blood flow (Qp) and systemic flow (Qs) and calculation of Qp/QS.
Figure 16  Metastatic Ewing’s sarcoma is shown in a 22-year-old man. Axial T1-weighted image at the base of the heart (A) shows a mass (M) abutting the aortic root and invading the pericardium, based on this finding aortic root invasion cannot be excluded. MPA = main pulmonary artery, LA = left atrium. Cine image at the base of the heart demonstrated right coronary artery (RCA) infiltration. Post contrast image (C) shows mass heterogeneity with area of no contrast enhancement, consistent with central necrosis. Metastatic tumors of the heart are 20 to 40 times more common than primary cardiac tumors. Direct extension and hematogenous spared (as in this case) are the most common modes of cardiac involvement. Venous extension and lymphatic spread of metastasis to the heart is relatively rare. CMR can be used as a confirmatory imaging modality following evaluation with echocardiography or computed tomography scans as well as destination diagnostic modality for patients who need follow-up to track tumor progression or recurrence following therapy. The greatest advantage of CMR is its ability to make non-invasive tissue diagnosis of cardiac masses and its essential role in surgical planning (White and Patel, 2007).

Figure 17  Aortic coarctation is shown in a 22-year-old man with hypertension. Volume-rendered 3-D reconstruction of contrast-enhanced magnetic resonance angiography (MRA) figure (A) and maximum intensity projection image (B) demonstrate severe aortic coarctation (arrow) and several collaterals vessels. To evaluate the severity of the obstruction, both magnitude (C) and velocity (D) velocity images of phase contrast CMR. Regarding the aortic anatomy, attention should be given to the transverse arch and isthmus, the brachiocephalic vessels, collaterals vessels that may bypass obstruction, and possible aneurysm or dissection at the site of repair. Abnormal vessels should ideally be measured in cross section as elliptical segments are common. Phase contrast CMR measurement is routinely performed to measure the hemodynamical significance of the obstruction. One approach in assessing its severity is to measure the peak coarctation jet velocity (blue line in D) and estimate a pressure gradient using modified Bernoulli equation. There is a high correlation between severity measured by CMR and continuous wave Doppler. A pressure gradient of 20 mmHg or more is hemodynamically significant (Konen et al., 2004).
6. Assessment of cardiac mass using pulse sequences such as T1- and T2-weighted imaging, first-pass perfusion and delayed enhancement.

7. Valvular heart disease: CMR provides non-invasive information that can influence patient’s management. CMR is particularly useful in patients who have poor echocardiographic window.

8. Pericardial disease: CMR is unique in its ability to image the pericardium. A major capability of CMR is its ability to allow detection of its etiology in patients with restrictive syndrome.

9. Magnetic resonance angiography (MRA) CMR and MRA are able to visualize the aorta and great vessels. CMR is more sensitive that CT, transthoracic echocardiography and transesophageal echocardiography in diagnosing intramural hematoma. CMR is particularly useful in pediatric patients with congenital anomalous and to avoid repeated exposure to ionizing radiation.

The purpose of this illustrative review (see Figs. 1–21) is to review the current clinical applications of CMR and to provide physicians, cardiology and radiology residents and fellows with simplified and regular CMR cases from daily practice. Each case briefly discusses the related clinical history, followed by CMR imaging findings, and simple discussion that highlights the role of CMR regarding a particular cardiovascular disorder. Some cases will highlight the role of CMR compared to other cardiac imaging methods. We believe the information provided in this review will serve as
a simple reference for common applications for CMR and will stimulate the interest of cardiovascular and radiology specialists and trainees to become familiar with this unique cardiac imaging technology.

Figure 20  Repaired tetralogy of Fallot (TOF) is shown. A 4-chamber cine image shows severely dilated right ventricle and right atrium with normal size left ventricle and atrium (figure A). Right ventricular outflow tract (RVOT) cine image shows mildly hypertrophy of the right ventricular wall and two systolic pulmonary jets, indicating pulmonary stenosis (arrow) as shown in figure B. Sagittal velocity encoded sequence through right ventricle and pulmonary valve (arrow) is used to quantify the degree of pulmonary stenosis. In this case, the peak velocity of the pulmonary stenosis jet was 5 mm/s. The calculated pressure gradient per modified Bernoulli equation was 100 mmHg (figure C). 3-D volume rendered reconstruction magnetic resonance angiography (figure D) demonstrated severe right pulmonary artery stenosis. In addition, flow through each pulmonary artery and its branch can be assessed by phase contrast methods. CMR evaluation of patients with TOF includes accurate calculation of right ventricular volume, function and mass, characterization of VSD, assessment of the right ventricular outflow tract for obstruction and pulmonary artery morphology. In the postoperative period, CMR provides images that can confirm the patency, size, and fibrosis of the right ventricular outflow tract as well as residual septal defect and pulmonary valve insufficiency. Pulmonary MRA delineates the morphology and flow of pulmonary arteries (Valente and Powell, 2007).
Severe aortic stenosis of the bicuspid aortic valve in patients with aortic coarctation is shown. Coronal cine image shows severe dilation of the aortic root, and two dark jets on either side of the central area of high velocity with the bright signal (arrow). A turbulent and complex pattern cause dephasing of the blood spins with resulting cancellation of the signal. In dysfunctional valves, the high-velocity stenotic and regurgitant jet appear as areas of diminished or absent signal persist in most systole or diastole. Cine loop display of gradient echo images allows a dynamic evaluation of the flow variable. Phase contrast (PC) method used more for flow qualification expressed as velocity or volume per unit. Transverse velocity-encoded sequence in the ascending aorta that shows the magnitude and phase images (B). By drawing an area around the aorta in magnitude image that automatically applied to the phase image, flow information is produced (red circle). In this example, the peak velocity was 3 m/s, based on modified Bernoulli equation the pressure across the stenosis is 36 mmHg. While echocardiography remains the non-invasive gold standard for direct imaging of normal and diseased valves, CMR can provide a means to depict and quantitate Valvular disease and its severity. CMR and echocardiography are complementary technologies for the assessment of patients with valvular heart disease, providing a comprehensive picture of the severity of disease of the valve and the impact of this disease on atrial and ventricular function (Kupfahl et al., 2004).

Figure 21

References