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# Cardiovascular Magnetic Resonance Imaging: From Morphology to Function

*Chengxi Yan and Qi Yang*

## Abstract

Cardiovascular magnetic resonance imaging (CMRI) which combines high image quality with advanced techniques to probe cardiovascular system is developing rapidly. Also, as a noninvasive imaging equipment, it has been accepted widely in clinical application. CMRI techniques produce high spatial, contrast, and temporal resolution image data for evaluation of cardiac and great vessel anatomy, coronary artery imaging, regional tissue characterization, vascular blood flow, cardiac chamber filling and contraction, and myocardial perfusion, myocardial viability. This chapter will cover the basic techniques of CMRI, practical tricks of how to perform CMRI, and clinical application in a variety of congenital heart disease, coronary artery disease, and non-ischemic heart disease, etc.

**Keywords:** cardiovascular magnetic resonance, morphology, ventricular function, myocardial perfusion, late gadolinium enhancement, coronary artery disease

## 1. Introduction

CMRI is complementary to other imaging techniques, such as echocardiography, cardiac CT, and nuclear medicine. The technique has a key role in evidence-based diagnostic and therapeutic pathways in cardiovascular disease. In the past 10 years, the development of CMRI is an active field of research and continues to see a rapid expansion of new and emerging techniques. CMRI applications include assessment of myocardial ischemia and viability, cardiomyopathies, myocarditis, vascular diseases, and congenital heart disease [1].

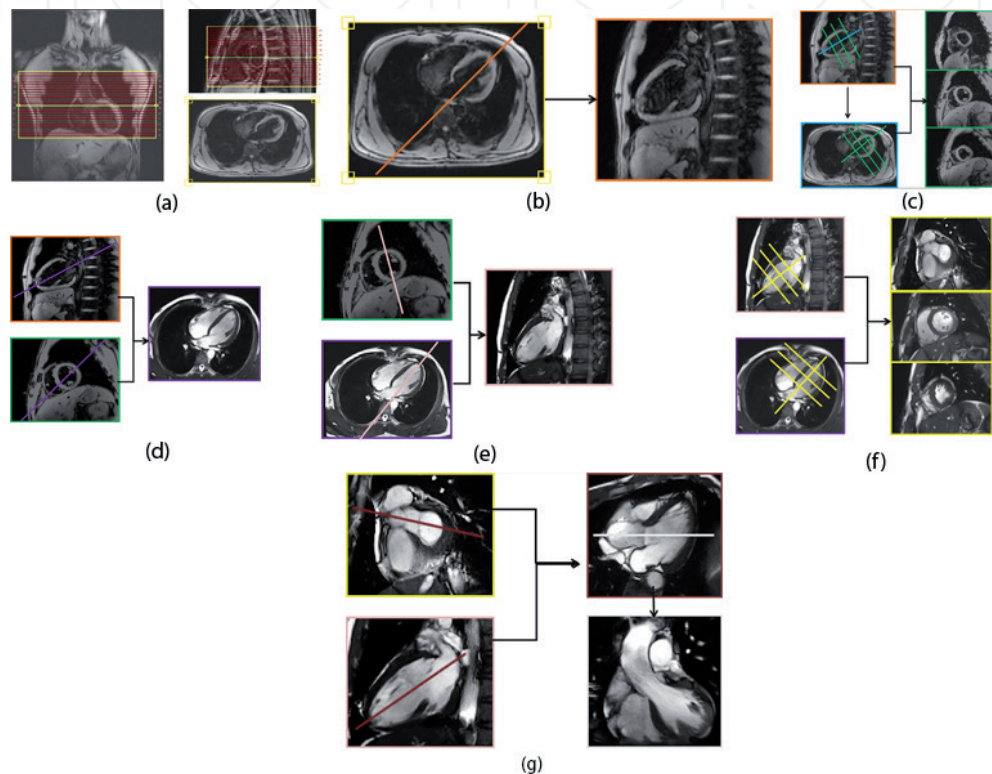
## 2. Technical consideration for CMRI

CMRI uses the same basic principles of image acquisition and reconstruction as other MRI techniques. Imaging of the cardiovascular system is usually performed with cardiac gating using an adaptation of electrocardiograph gating (ECG). ECG signal is used to either prospectively trigger data acquisition or retrospectively gate data reconstruction. Respiratory gating techniques have also been utilized to compensate respiratory motion. This can be implemented with either acquisition during a consistent part of the respiratory phase (typically the end-expiratory phase) or post-processing of continuously acquired data [2].

## 2.1 Evaluation of cardiac morphology

Dark-blood fast spin echo is usually applied for the observation of cardiac anatomy. Another advantage of cardiac MRI is that blood can also become bright when using gradient echo sequence, such as SSFP. By using one RF pulse to generate the signal, gradient echo sequence avoids the washout effect and the signal from flowing blood appears apparently bright. Contrast between the blood and the myocardium can be generated without contrast agent [3].

The evaluation of cardiac morphology usually starts from three basic planes: axial, coronal, and sagittal planes like standard views of the thorax. **Figure 1** illustrates the standard cardiac imaging views.



**Figure 1.**

*Basic CMRI views. A. Localizer scans showed three standard coronal, sagittal, and transverse planes. B. Planning of the vertical long axis (VLA) image from the trans-axial image (orange line). C. Planning of the helical long axis (HLA) from VLA (blue line). Short axis (SA) images from VLA and HLA images (green line). D. Planning of 4-chamber (4-ch) image from VLA and SA images (purple line). E. Planning of 2-ch image from 4-ch image and SA image (pink line). F. SA image was obtained from 4-ch and 2-ch image (yellow line). G. Left ventricular out flow (LVOT) view from SA image and 2-ch image (brown line), and LVOT coronal view from the original LVOT image (white line).*

## 2.2 Assessment of ventricular function

The standard approach to measure LV volume and function includes steady-state free precession (SSFP) gradient echo sequence, with one slice acquired during a breath hold of about 10–15 heartbeats [4]. It acquires in two-chamber view, four-chamber view, short-axis view, and left ventricle/right ventricular inlet-outlet view which also allow evaluation of the valvular insufficiency, outflow tract obstruction, mobility of the cardiac tumors. CMRI is the reference standard for the assessment of cardiac structure and function and is valuable for diagnosis and surgical planning in congenital heart disease. Since the sequence are vulnerable to magnetic susceptibility artifact at 3.0 T, spoiled gradient recalled echo can be used as a substitute. By tracing the endocardial and epicardial borders at end-diastole and

end-systole from short-axis images occupying the heart from base to apex throughout the cardiac cycle, the parameters such as LV and RV mass, volumes, wall thickness, wall motion and ejection fraction are obtained and quantified through multiple breath hold [5].

A useful variant of cine imaging for use with motion evaluation is to combine it with magnetization tagging. These tag lines provide 3D analysis of cardiac rotation, strain, displacement, and deformation of different myocardial layers during a cardiac cycle.

### **2.3 Myocardial perfusion**

The fundamental principle of first-pass perfusion imaging is relatively simple. Multiple imaging planes through the heart are taken every heartbeat. These images are used to track an intravenous bolus of contrast dynamically as it courses through the cardiac chambers and into the myocardium. Because the gadolinium primarily shortens T1 relaxation, the heart appears dark until contrast is delivered via blood flow or perfusion.

First-pass perfusion is divided into rest and stress perfusion. Rest perfusion detects myocardial perfusion deficits through first-pass kinetics of a contrast agent bolus, thus, it also named dynamic first-pass perfusion imaging. Ultrafast sequences like inversion recovery prepared fast gradient echo, interleaved gradient-echo echo-planar imaging, and saturation recovery SSFP sequence can assess signal intensity changes. Since myocardium has a relatively strong reserve capacity, perfusion deficits at rest is insensitive to myocardial ischemia. Induced by pharmaceutical agents, such as adenosine and dipyridamole, stress perfusion provokes coronary vasodilation and increases the contractile function compensated by increasing myocardial perfusion. Normal arteries can be dilated and respond to stress, whereas severely narrowed arteries limit flow, thus resulting deficits of the perfusion which may cause the wall motion abnormalities. Hence, an asymptomatic CAD can be identified by perfusion imaging through depicting perfusion defects under stress. There are different levels for the analysis of myocardial perfusion, which are qualitative, semi-quantitative, and fully quantitative evaluation. Since the dynamically acquired images include the whole information of first-pass perfusion, most clinicians used qualitative visual interpretation of clinical studies [6, 7].

### **2.4 Late gadolinium enhancement**

Late gadolinium enhancement (LGE) image has been extensively validated in clinical studies and capable for detecting myocardial viability. By using segmented (or single shot) inversion-recovery prepared fast (or turbo) gradient sequence, combined with intravenous infusion of gadolinium-based contrast agent, LGE image can be obtained. By applying appropriate inverted time, the normal myocardial signal is null, and the difference between infarcted and normal myocardium is optimized. Myocyte degradation and membrane permeability increased contrast accumulation in acute myocardial infarction. Chronic myocardial infarction is characterized by fibrous tissue with larger interstitial space in which contrast agent accumulates [8].

### **2.5 Myocardial T1 and T2 mapping**

Paramagnetic mapping techniques such as T1 mapping and T2 mapping offer a robust and reproducible quantitative assessment of both focal or diffuse fibrosis, edema and amyloidosis. T1 Mapping is performed with inversion recovery



(Look-Locker, MOLLI, ShMOLLI) or saturation recovery pulse technology (SASHA, SAPPHIRE) within a single breath hold. Myocardial T2 mapping is a technique used to reconstruct a parametric image based on the T2 value measured in each voxel. The accumulation of water in the myocardium is associated with different types of pathology, such as acute myocardial infarction, myocarditis and graft rejection [9–11].

## **2.6 Vascular imaging**

CMRI can assess large and medium-sized vascular structures and are particularly useful in the pediatric population with congenital abnormalities of the aorta. Vascular imaging techniques includes non-contrast enhanced magnetic resonance angiography (NCE-MRA) and contrast enhanced-magnetic resonance angiography (CE-MRA).

### *2.6.1 NCE-MRA*

Time of flight MRA (TOF-MRA) is a widely used technique for vascular imaging. By using a flow-related enhancement, it gives rise to bright blood contrast with very short TR spoiled gradient echo pulse sequences. Through one rapid RF pulse, the tissue of whose magnetization remains in the image slice, has become partially saturated. Thus, the flowing blood that moves into the slice has not received any previous pulses and appears bright or enhanced and tissues surrounding it appears dark. TOF-MRA has been used in noninvasive angiography of the intracranial angiography and carotid angiography.

More recently, 4D flow MRI referring to three-dimensional data acquired in a time-resolved, ECG-gated, manner with velocity encoding in all three spatial directions has appeared. In addition to the measurements of basic flow volumes and velocities, the estimation of derived hemodynamic biomarkers such as wall shear forces, pulse-wave velocity, pressure gradients, and other measures have been proposed. 4D flow imaging can be used in the clinical evaluation and management of patients with aortic disease. As an emerging tool for the comprehensive evaluation of cardiovascular hemodynamics with full volumetric coverage, 4D flow is a continuously developing field of research [12].

### *2.6.2 CE-MRA*

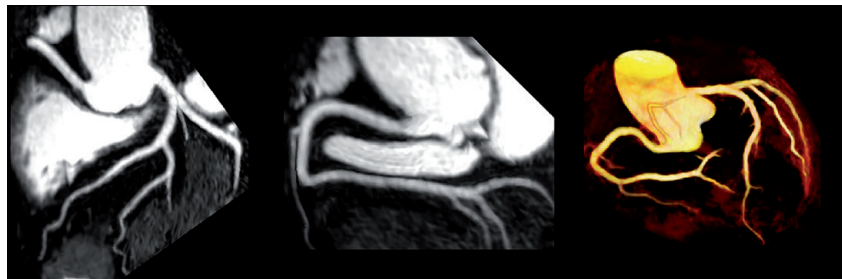
Bolus injection of MRI contrast agent can increase the signal of the heart instantly, which can be used to generate image contrast between vessel and surrounding tissues. Imaging is usually performed on 3D-T1 weighted spoiled gradient-echo pulse sequence with short TR and TE. Blood was consistently hyper-intensity and background tissue was hypo-intensity on the contrary due to saturation effects, thus, a better MRA images is obtained, and by subtracting plain images before, a high quality MRA images are obtained.

Taking thoracic aorta CE-MRA for example. A 3D-T1 weighted spoiled gradient-echo pulse sequence is performed to acquire non-enhanced images (mask image); then, small dose of contrast agent (2 ml) is injected to test the time course of individual contrast kinetics. Imaging delay time can be calculated as estimated contrast travel time + Injection time/2 – Imaging time/2.

By injecting gadolinium-based agent intravenously (0.2 mmol/kg, 3 ml/s), another 3D-T1 weighted spoiled gradient-echo pulse sequence (same parameter as pre-contrast) was used. Image quality can be further improved by image subtraction, where a non-contrast (“mask”) images is subtracted from each post-contrast images.

## 2.7 Coronary MRA

Whole heart CMRA, as a method of providing visualization of all three major coronary arteries in a single 3D volume, has been successfully introduced at 1.5 T MRI. Recently, some single and multicenter studies suggest that 1.5 T whole heart CMRA can eliminate the need for diagnostic coronary catheterization in many patients who are at risk of CAD. 3.0 T cardiovascular MR has become active for the evaluation of CAD in recent years (**Figure 2**). Contrast-enhanced coronary MRA at 3.0 T improves SNR and contrast-to-noise ratio and shows high accuracy in the detection of significant coronary artery stenosis. Both MDCT and CMRA can lumenographic information about the coronary arteries in the determination of existence and extent of CAD. Even though, the accuracy is inferior to coronary CT angiography and spatial resolution needs a further improved, CMRA has the potential to be a valuable adjunct in cases where coronary calcification precludes adequate evaluation or iodinated contrast agents are contraindicated [13].



**Figure 2.**  
*3D free-breathing contrast enhancement coronary angiography at 3.0 Tesla MRI.*

## 3. Clinical application of CMRI

### 3.1 Assessment of congenital heart disease

CMRI has been shown to provide helpful diagnostic information in most types of congenital heart disease. The clinical indications for a CMRI examination involve one or more of the following situations:

1. When trans-thoracic echocardiography is incapable of providing the required diagnostic information.
2. As an alternative to cardiac CT with its associated radiation in pediatric patients.
3. To obtain diagnostic information for which CMR offers unique advantages.

Detailed pre-examination planning is crucial due to the complex nature of the clinical, anatomical, and functional issues in patients with congenital heart disease. Careful review of the patient's medical history are always needed. For example, in patients with ventricular septal defect (VSD), measurement of ventricular dimensions and function is a key element of the CMRI evaluation. This can be done from the ventricular short-axis cine MRI image stack. Larger left-to-right shunts will result in left ventricular dilation but not right ventricular dilation. Quantification of the VSD shunt can be performed by calculating the  $Q_p/Q_s$  ratio. This can be accomplished by measuring the net blood flow in the main pulmonary artery ( $Q_p$ ) and the ascending aorta ( $Q_s$ ) using VEC MRI. VEC MRI measurements have been used

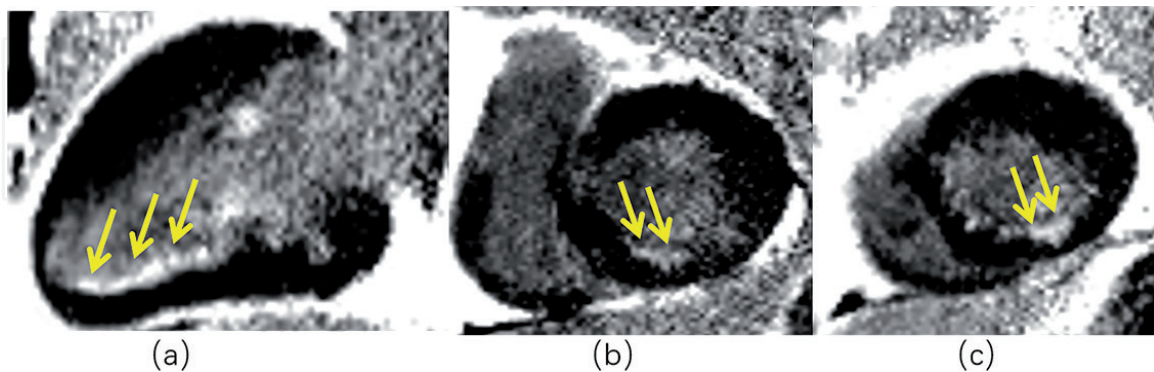
to gain insight into the functional significance of an obstruction. Flow characteristics suggests a hemodynamically significant coarctation through decreased peak flow, decreased time-averaged flow, decreased acceleration rate, and prolonged deceleration with increased antegrade diastolic flow, delayed onset of descending aorta flow compared with the onset of flow in the ascending aorta [14, 15].

### 3.2 Assessment of CAD

CMR can provide data in all of these aspects of coronary heart disease (CAD), including cardiac morphology, global and regional myocardial function, myocardial ischemia, viability of myocardium, and the presence of coronary stenosis. Comprehensive CMRI protocols have been mainly applied to two clinical scenarios: the detection of CAD and the assessment of viability.

CMRI can accurately assess cardiac morphology, global and regional cardiac function as well as deformed ventricles. Cine imaging forms an essential component of any CMRI study in CAD. Myocardial ischemia as the principal manifestation of CAD can be detected by first-pass perfusion test. Rest myocardial blood flow will keep constant unless the significant stenosis exists, thus, physiological or pharmacological stress is necessary for the detection of myocardial ischemia. LGE images of myocardial scar using current segmented inversion recovery gradient echo pulse sequences can be obtained in one breath hold.

Gadolinium-based contrast agents are extra-cellular, thus, they can diffuse freely in to the interstitial space. In acute myocardial infarction, the cell barriers were destroyed, and distribution volume is increased. In chronic infarction myocardial cells are replaced with a fibrotic matrix which also cause the distribution volume increasing. LGE always extends from the endocardium outwards due to the process of myocyte necrosis spreading from sub-endocardium to the epicardial borders. **Figure 3** is an inversion recovery delayed-enhancement image acquisition program with phase-sensitive detection was used to acquire LGE images from an inferior non-transmural myocardial infarcted patient (yellow arrow). LGE can not only determine the presence, location and extent of infarcted myocardium, but also can identify the stunned myocardium prior to revascularization [7].



**Figure 3.**

An inversion recovery delayed-enhancement image acquisition program with phase-sensitive detection was used to acquire LGE images from an inferior wall non-transmural myocardial infarcted patient (yellow arrow). The inversion time (a timing option) was adjusted to null the normal myocardium. Thus, normal myocardium appears uniformly dark in these ventricular sagittal (a) and short axis (b and c) views.

### 3.3 Assessment of non-ischemic heart disease

Non-Ischemic heart disease includes hypertrophic cardiomyopathy (HCM), dilated cardiomyopathy (DCM), restrictive cardiomyopathy (RCM), myocarditis, et al.

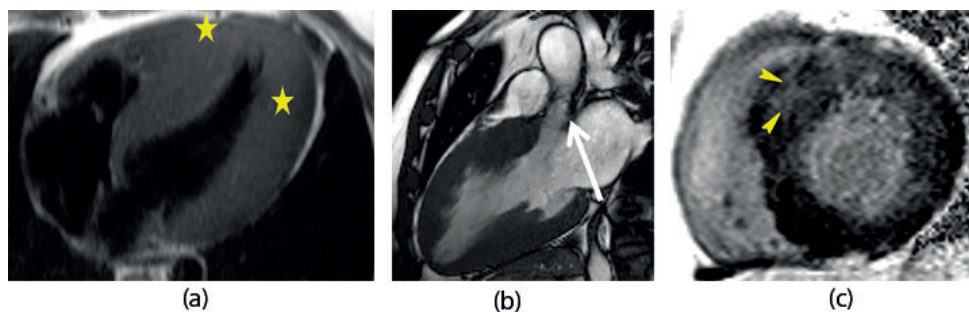


Most of the non-ischemic heart disease is characterized by an alteration of ventricular and myocardial geometry or function. For the measurement of morphology and function, a stack of short-axis slices covering the entire left ventricle from the mitral plane to the apex can be used [16].

LGE further enhances the tissue characterization abilities of CMRI which shortens T1 relaxation time and brightens the area where gadolinium chelates accumulates. Myocardial tissue characterization of non-ischemic heart disease can be quantitatively evaluated through T1 mapping and T2 mapping.

### 3.3.1 Hypertrophic cardiomyopathy (HCM)

HCM is a genetic disease characterized by myocardial disarray, symmetrical or asymmetrical myocardial hypertrophy, most frequently occur in the septum with the loss of diastolic function or (and) possible dynamic systolic obstruction of the LV outflow tract [17]. Cine imaging can accurately assess the wall thickness, and it can be used to detect anterior motion of mitral valve leaflet in systole. Myocardial tagging imaging shows a decreasing of circumferential shortening and fractional thickening in region of thickened myocardium. LGE imaging can determine the areas of fibrosis based on increasing collagen content, which have a positive correlation with risk of lethal arrhythmias [18]. **Figure 4** is typical images of HCM diagnosed by CMR.



**Figure 4.** Hypertrophic cardiomyopathy. A. Black blood image showed symmetric myocardial hypertrophy (yellow asterisks). B. Left ventricular outflow tract obstruction and a turbulent flow within the aorta (white arrow, B). C. LGE image demonstrated heterogeneous enhancement of the hypertrophied myocardium (yellow arrowheads).

### 3.3.2 Dilated cardiomyopathy (DCM)

DCM is characterized by progressive LV enlargement and deteriorated LV function with normal LV wall thickness. A diffuse myocardial fibrosis is usually detected in histopathological studies. LGE can accurately demonstrate the enhancement of ischemic DCM begins from sub-endocardial layers, while, focal fibrosis in non-ischemic DCM spares the sub-endocardial layers and shows either mid-wall patchy enhancement pattern or lack of enhancement. CMR Cine reveals an increasing LV mass, LV volume and ejection fraction as well as hypo-kinetic wall motion. Focal septal fibrosis in DCM, the so-called mid-wall sign, has been linked to ventricular arrhythmia which is a main cause of sudden death.

### 3.3.3 Restrictive cardiomyopathy (RCM)

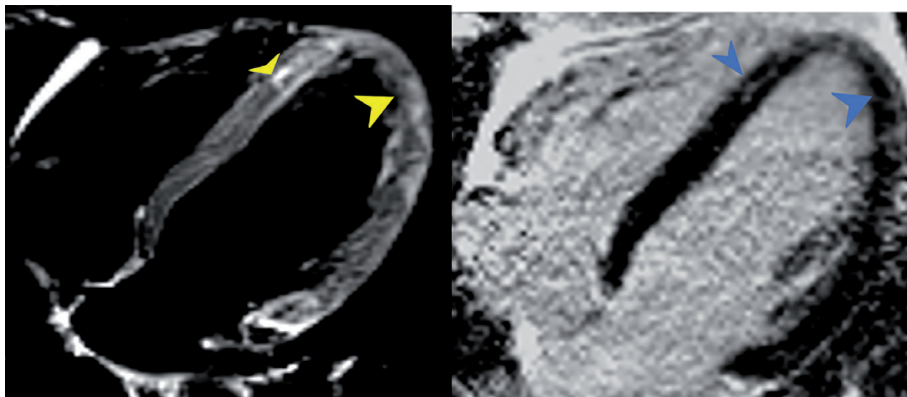
Primary RCM is characterized by impaired diastolic volume of both ventricles without dysfunction of systolic, a biatrial dilation and normal or small LV size can also be detected. CMR can assess RCM accurately based on its high contrast



resolution and the ability of comprehensive evaluation of cardiomyopathies. Phase contrast imaging allows quantitative assessment of flow across the atrioventricular valves. In early stage, reduced diastolic function causes the decrease of early ventricular relaxation velocities and the increase of late atrial contraction velocities. In later period, a restrictive filling will appear with rapid and tall early filling waves and much reduced atrial waves. In RCM patients, contours of ventricular cavities are maintained with atrial enlargement. Myocardial thickness is frequently increased in RCM.

### 3.3.4 Myocarditis

Endocardium biopsy is “golden standard” but invasive diagnosis for myocarditis. CMR is the best imaging technique to confirm suspected myocarditis and detect focal inflammation and scarring. The diagnostic criteria of CMR for myocarditis was proposed for the first time in the year of 2006 [19], which depicted that myocarditis would have the following characteristics: 1. hyper-enhancement on LGE images, not confined to specific coronary territory, but in typically sub-epicardial or intramural (**Figure 5**); 2. The hyper-enhancement lesions is less bright than myocardial infarction and most frequently arise in the inferolateral wall. Furthermore, T2-weighted CMR T1 mapping can detect the edema which appears local or diffusing hyper-enhancement.



**Figure 5.** A T2 Stir image from a myocarditis patient. High T2 signal indicating edema is seen in subepicardial area of septum, lateral wall, etc. (yellow arrowheads). LGE shows enhancements occur in the same area (blue arrowheads).

## 4. Conclusion

CMRI has revolutionized cardiac imaging. CMRI gives complementary information on LV function, perfusion, and myocardial viability. Recent advances in cardiac imaging include T1 mapping, T2 mapping, and MR-guided therapy. With the promise of higher spatial-temporal resolution and 3D coverage at higher field strength, in the near future, CMRI will become an routine tool in the diagnosis of cardiac diseases.

## Conflict of interest

No conflict of interest.

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