The Use of Cardiac Magnetic Resonance Imaging in Coronary Artery Disease

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Abstract

A new noninvasive imaging technique, magnetic resonance imaging (MRI), has been developed that has the potential to assess anatomical and functional data of patients with coronary artery disease. None of the other cardiac investigations to date can combine all aspects of information. Cardiac MRI is a challenging task because of the motion of the structure during cardiac contraction and the motion with respiration. We reviewed the technique and the use of cardiac MRI in various aspects. The emerging area in cardiac MRI is the analysis of the plaque morphology information, and the use of the new contrast agents. Further investigation is needed in order for cardiac MRI to achieve a better image information within a shorter period of time.

Key word : Magnetic Resonance Imaging, Coronary Artery Disease

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During the past 10 years, there has been a rapid growth in knowledge and technology of cardiac magnetic resonance imaging (MRI). Among all non-invasive cardiovascular investigations, cardiac MRI is probably the first investigation that covers all aspects of anatomical and functional information. Anatomical information includes wall thickness and muscle mass, coronary anatomy, structural analysis, ventricular volumes and plaque morphology whereas functional information includes wall movement, perfusion, valve function, coronary flow, and energy management (spectroscopy). None of the other cardiac investigations either noninvasively or invasively, is able to combine all of these aspects.

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Basic principles of MRI[1,2]

MRI uses a strong magnetic field and low energy radiofrequency signals to gather information from certain atomic nuclei within the body. Hydrogen is the most frequently used nucleus. MRI does not require ionizing radiation to obtain the images. Under normal circumstances, these tiny magnets are randomly distributed in space, the magnetic moments cancel each other out and the net magnetic vector is zero. When a patient is in a strong external magnetic field, the nuclei orientations are in either a parallel or an antiparallel direction. The energy difference between the 2 states or the net magnetization is very small. In the presence of an applied magnetic field, the spin vectors of the nuclei experience a torgue which causes them to rotate around an axis of the applied field with a precise frequency called Larmor frequency. The frequency is given by the equation: $F = \gamma B_0/2\pi$ where F is the processional frequency, B_0 is the strength of the magnetic field, and γ is the gyromagnetic ratio of the nucleus.

To obtain information from the spin, the direction of the net magnetization vector has to be altered. The processing spins are excited by applying energy in the form of radiofrequency (RF) energy pulses of exactly the Larmor frequency (resonance frequency). When the RF signal is given at the resonance frequency into the patient, two phenomena occur: first, enough protons absorb energy to jump from the parallel state to the higher level of the antiparallel state, and second, the spins are whipped to process in phase which cause the net magnetization to flip 90 degrees and rotate in the transverse plane at the Larmor frequency. This rotating magnetization can be measured because it will induce an alternating current in the receiver coil placed around the patient. The induced signal in the receiver coil will decrease with time. The decreasing signal is called the free induction decay (FID). The time required for the signal to return to equilibrium is the relaxation time. Two relaxation processes exist: transverse relaxation and longitudinal relaxation. T1 relaxation time is defined as the time required for the system to recover to 63 per cent of its equilibrium value after it has been exposed to a 90 degree pulse. Various human tissues have different T1 values. Transverse relaxation process is characterized by T2 relaxation time. T2 relaxation time is the time it takes for dephasing to decay the signal to 37 per cent of its original value. T2 relaxation time from various tissues is different, but the T2 time is always shorter than the T1 time. T1 and T2 times depend on the tissue characteristic.

To create an image, the MR signal from the H proton has to contain information about where these protons are positioned in the body. This included 3 steps: slice selection; frequency encoding, and phase encoding. To select an imaging slice through the body, a magnetic gradient is added along the main magnetic field in the caudal to cranial direction. The frequency and phase encoding are used to obtain information for the individual points within a slice, the picture elements or pixels. Combining phase and frequency information allow the creation of a grid in which each pixel has a defined combination of phase and frequency codes. This grid of raw data is called the K-space. With a Fast Fourier Transformation, the raw data, which represent an amplitude as a function of time, are transformed into a curve that represents an amplitude as function of the frequency. The amplitude of each frequency represents the intensity of each pixel. The resolution is determined by the pixel size, the smaller the higher resolution, but the signal to noise ratio is the limiting factor if the pixels become too small and do not contain enough spinning protons to produce a measurable signal.

Cardiac structure (Fig. 1)

There are 2 main types of MR images: spin echo images, in which the blood appears dark, and gradient echo images in which the blood appears white (Fig. 2). Spin echo imaging is optimal for some purposes, whereas gradient echo imaging is better for others. Spin echo imaging is generally used to assess cardiac structure and gradient echo imaging for cardiac function. Myocardial mass can be accurately evaluated by MRI, both in an animal model[3] and in humans, by comparing the mass measured from cadaveric hearts[4].

Cardiac function

It has been shown that end-systolic, end-diastolic LV volume and LV ejection fraction are prognostic indices in patients after myocardial infarction and valvular heart disease[5,6]. With other imaging techniques, accurate volumes have been difficult to obtain. Because volumes can be inaccurate, errors can be made when calculating ejection fraction. With its excellent temporal, spatial and contrast resolution, MR imaging has pro-

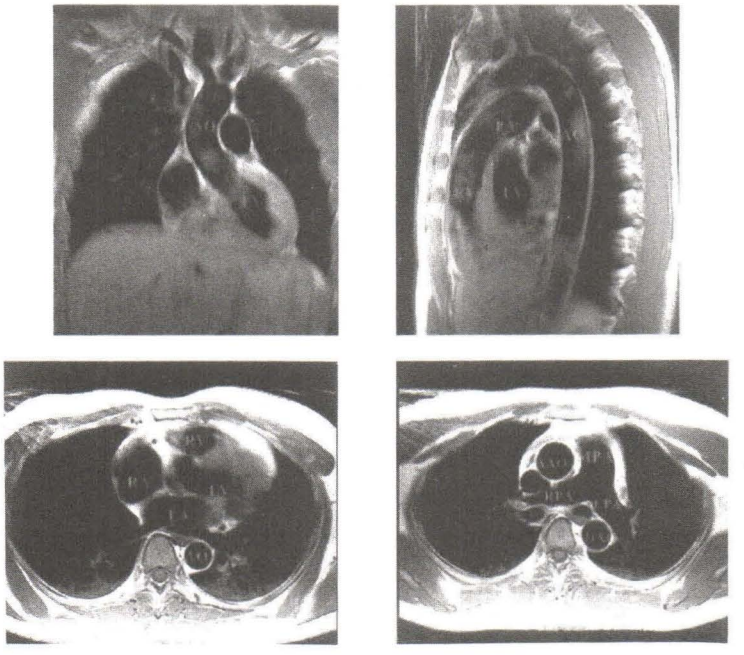

Fig. 1. Coronal (upper left), sagittal (upper right), and transverse (lower left and right) spin echo images showing various cardiac and vascular structure. AO = aorta, LV = left ventricle, PA = pulmonary artery, RV = right ventricle, RA = right atrium, LA = left atrium, AAO = ascending aorta, DAO = descending aorta, MPA = main pulmonary artery, RPA = right pulmonary artery, LPA = left pulmonary artery.

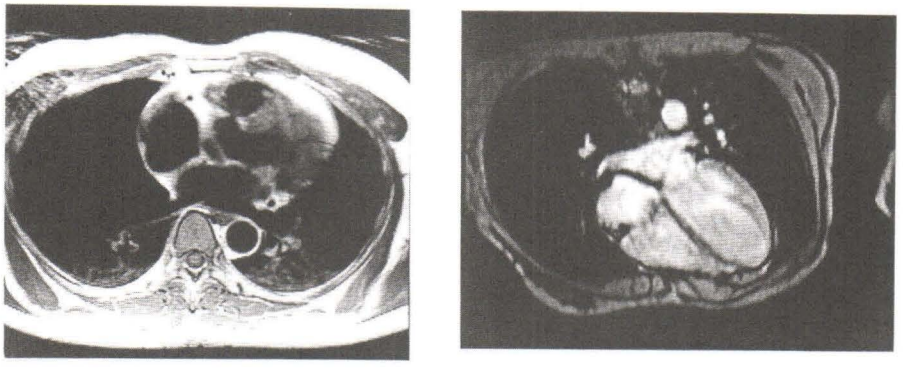

Fig. 2. Transverse spin echo or black blood image (left) and transverse gradient echo or white blood image (right).

ven to be effective and accurate for assessing LV volumes and ejection fraction by using multislice short axis views of the left ventricle at many phases for the whole cardiac cycle (Fig. 3). Because MR images can be acquired in virtually any plane, dimensional chamber measurements can be made with great reliability. The multislice axial approach does not rely on geometric assumptions for calculation of LV volumes and ejection fraction, and is easy to acquire. LV volume and ejection fraction had a good correlation with contrast angiography both in normal subjects and diseased patients[7,8]. All

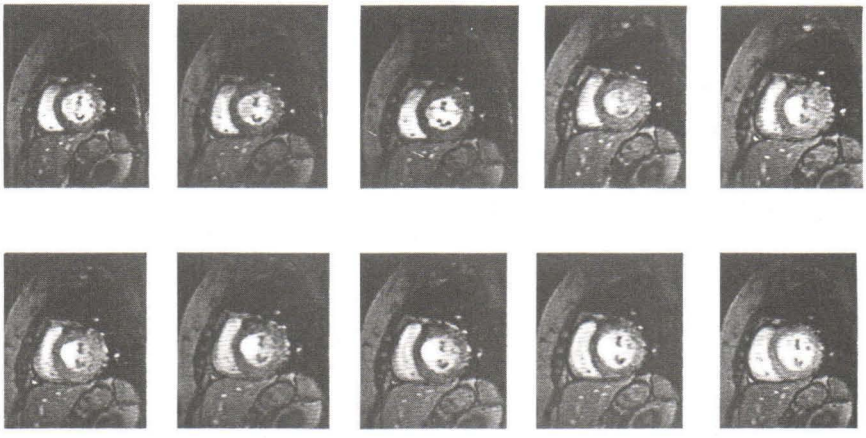

Fig. 3. Ventricular volume and mass and ejection fraction calculation done by the multislice axial method.

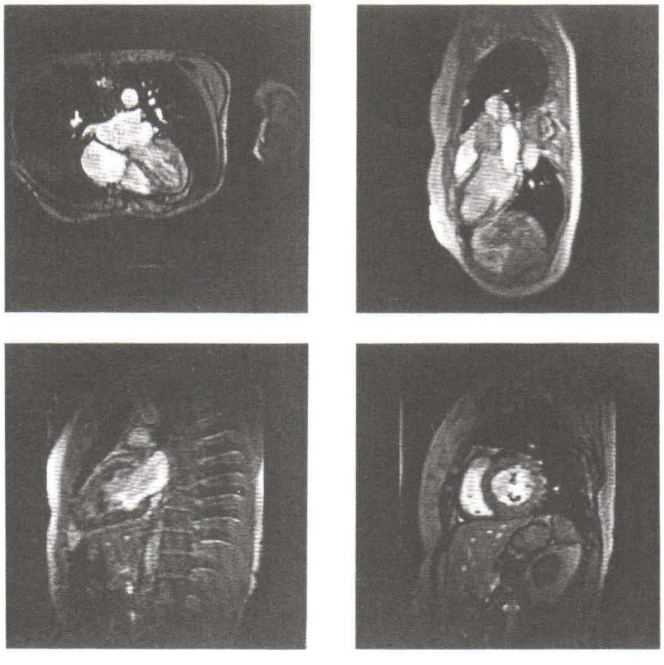

Fig. 4. Gradient echo images (white blood) in 4 different views: 4-chamber (upper left), long axis (upper right), left ventricular outflow tract (lower left), and short axis (lower right).

MR imaging methods for evaluating LV volumes and ejection fraction have also proven reproducible and reliable. Not only LV function, but the evaluation of RV volumes and ejection fraction can also be made with MR imaging[9].

Regional myocardial function

The assessment of regional myocardial function with MR imaging is performed by observing movement of the heart wall in a cine MR imaging acquisition (Fig. 4). These images need to

have both high time resolution and spatial resolution. For measuring regional myocardial function, changes in myocardial position on the order of millimeters are significant; therefore some form of compensation for patient breathing must be used.

Breath-hold scanning has been the method of choice for functional MR imaging because it is the simplest method to ensure that the heart is in the same position for the entire data acquisition period. Breath-hold method, however, obviously suffers a signal-to-noise ratio (SNR) limitation because the imaging must be performed within a maximal total scan time of approximately 15-20 seconds, eliminating the possibility of extensive averaging. There are 2 basic modes of acquiring data for MR imaging: segmented k-space spoiled gradient echo imaging, and echo-planar imaging.

Cardiac tagging uses the technique of tagging nuclear spin which was first described by Morse and Singer[10]. It is the technique used for the better evaluation of regional myocardial function. The process of myocardial tagging requires 2 steps: first, a saturation pattern is placed in myocardial tissue with selective radiofrequency pulses, and secondly, a sequence of MR images is obtained in which the motion of the saturation pattern can be observed during systole and diastole, and is used to interpret the motion of different regions of the heart (Fig. 5). There are many softwares used for the quantitative evaluation of regional myocardial function, mainly by using velocity encoding technique.

Coronary MR angiography

X-ray contrast angiography is widely accepted as the definitive method to define coronary anatomy. This procedure is, however, associated with significant radiation exposure to both patient and physician, and carries a small risk (1.7%) for potentially serious complication[11]. An alternative noninvasive technique that could reliably provide both anatomic and functional information about the coronary circulation would represent an important advance in diagnostic cardiology. TTE, TEE and CT scans had limited success in adequately defining both anatomy and function of the coronary circulation[12,13]. Stress-testing with echocardiographic or nuclear perfusion imaging is not suitable for anatomic evaluation of the coronary arteries. Coronary MR angiography has made possible the visualization of the major epicardial coronary arteries (Fig. 6). It has also allowed for the noninvasive assessment of absolute coronary blood flow and flow reserve.

Limitations of technique

The coronary tree is a three-dimensional structure that changes shape during cardiac contraction. Motion during ventricular systole is highly variable among different individuals[14]. Motion also follows the diaphragmatic and chest wall respiratory movements. The variable position during the cardiac and respiratory cycles is the major challenge of coronary MR angiography. Manning et al[15]

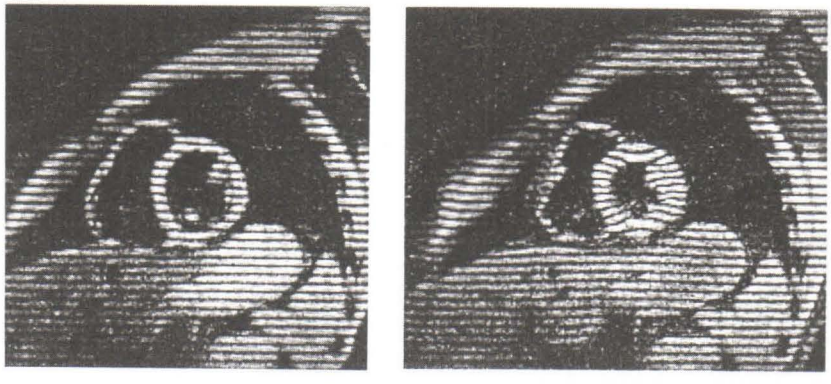

Fig. 5. The end-diastolic and end-systolic images from a movie sequence showing the myocardial tagging technique for the analysis of regional wall motion.

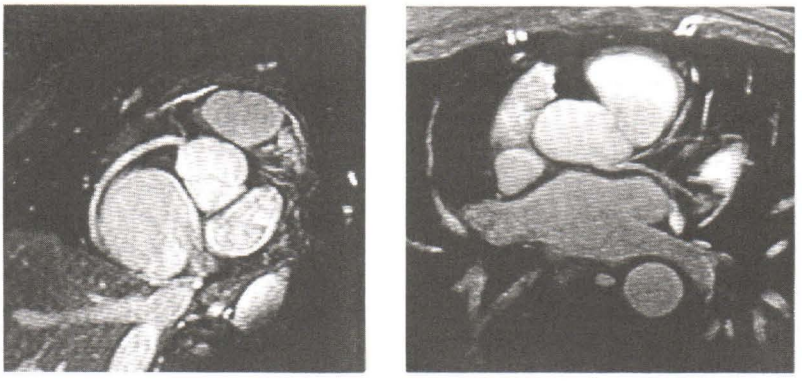

Fig. 6. Transverse slice at the level of aortic route showing right (left) and left (right) coronary system using the navigator technique and accepting window during diastole without the use of contrast agent.

were the first to describe the possibility of CMR for noninvasive coronary diagnostics in 1993. They reported sensitivity and specificity of 97 per cent and 70 per cent respectively for the detection of significant coronary disease. The best results were obtained in the RCA, and the initial trunk of LCA. With present-day acquisition methods, this would lead to a significant increase in the acquisition time, pushing breath-hold technique to its limits.

Significant improvements have been achieved by the use of navigator gating techniques, in which the position of the heart is determined from the height of the diaphragm for each image data acquisition, and only the data within an adjustable tolerance range, usually during expiration, are acceptable[16]. Optimum suppression of artifact due to respiratory movement is achieved by additional correction for the diaphragm movement within the acceptance window. This makes it possible to achieve high resolution imaging of a small structure, even during normal respiration[17]. Spiral scans offer an alternative possibility for improving the spatial resolution with fewer motion artifacts[18]. This provides a high data density within a maximum acquisition time. More recent approaches depend on the acquisition of three dimensional data sets, as well as the use of contrast agents[19,20].

Future perspectives involve the imaging of the atherosclerotic plaque[21,22].

Assessing myocardial perfusion with MR first-pass imaging

Nuclear cardiology and echocardiography were used for noninvasive risk prediction in patients with CAD. Significant progress has been made in the development of MR methods for the assessment of myocardial perfusion and function. Coronary stenosis or occlusion may result in 3 types of functionally altered states: stunning; hibernating, and infarcted or scarred myocardium[23,24]. Stunned and hibernating myocardial segments have a good chance to recover fully in time when treated properly.

False negative results from Tl-201 scintigraphy may occur when a lesion appears to cause significant luminal narrowing but is not hemodynamically significant. There has to be at least a 30-40 per cent blood flow reduction to be detectable with Tl-201 scintigraphy as a mild perfusion defect may not be discerned. By contrast, Kivelitz et al[25] demonstrated in patients that changes of 20 per cent in resting blood flow can be detected with MR perfusion imaging, and this may explain a reduction in false-positive results as compared to Tl-201 scintigraphy.

Modern MR systems allow up to 5-6 complete heart images to be acquired per heart beat (Fig. 7). This allows the first-pass kinetics of a rapidly injected bolus of contrast agent (Gd-DPTA)

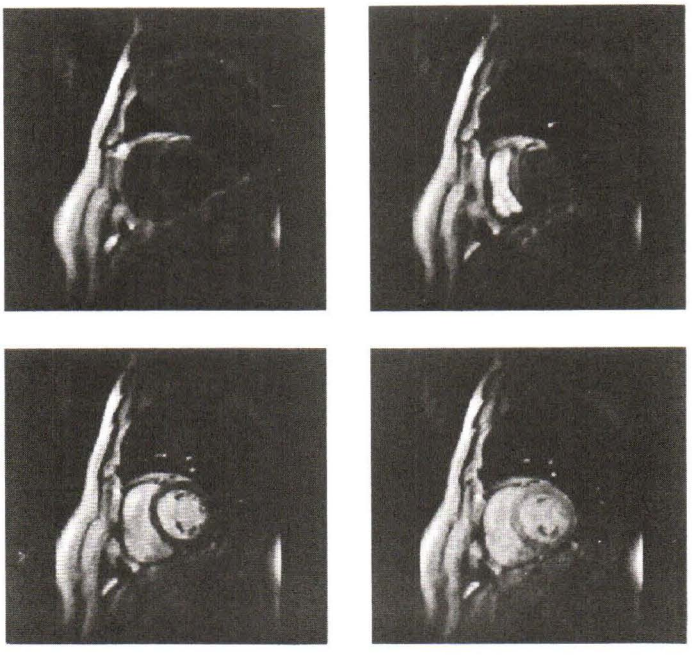

Fig. 7. First-pass contrast (Gd-DTPA) study in multiple short axis slice to assess myocardial perfusion. The images show only 1 slice in the mid part of left ventricle in 4 different phases during the passage of contrast agent. The left upper image is the image before contrast arrival, followed by the image during contrast enter right ventricle (upper right), left ventricle (lower left) and after the contrast is distributed into the myocardium in which the myocardial signal is equally enhanced.

to be analysed[26], and a qualitative analysis of the myocardial perfusion to be performed. This is superior to that of nuclear medicine techniques. In regions of the myocardium supplied by a coronary artery with a high degree of stenosis, a slower initial signal rise and a lower maximum signal intensity can be observed following application of pharmacological stress with Dipyridamole or dobutamine. Negel et al[27] reported that dobutamine stress MR had better sensitivity and specificity than dobutamine stress echocardiography, with harmonic imaging with a sensitivity of 86.2 per cent and specificity of 85.7 per cent compared to coronary angiography. Dobutamine stress MR usually had a better image quality than dobutamine stress echocardiography.

Integrated approach to IHD: the one-stop shop

Cardiac MR can provide a thorough assessment of myocardial structure, function and perfusion, assessment of coronary anatomy and flow and spectroscopic evaluation of cardiac energetics. One advantage of cardiac MR is as a tool for integrated examination called one-stop shop. Further prospective study is needed to show the advantages of this integrated examination.

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ประโยชน์ของ Cardiac Magnetic Resonance Imaging ใน coronary artery disease

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Cardiac MRI เป็น investigation ที่สามารถให้ข้อมูลที่มีประโยชน์ในผู้ป่วย coronary artery disease หลายอย่าง เช่น wall thicken, muscle mass, regional wall motion, coronary anatomy, perfusion และ energy management ยังไม่มี cardiac investigation ใดที่สามารถให้ข้อมูลได้หลาย aspect เท่า cardiac MRI เรื่องของ cardiac MRI เป็นงานที่ท้าทาย เนื่องจาก technique การทำต้องคำนึงถึง motion ของ cardiac structure ที่มีการเปลี่ยนตามการบีบตัวของหัวใจ และตามการเคลื่อนไหวของ diaphragm ซึ่งเปลี่ยนตามการหายใจ เรา review ประโยชน์และ technique ของ cardiac MRI ใน aspect ต่างๆ area ที่น่าสนใจของ cardiac MRI ในอนาคตคือการให้ข้อมูลเกี่ยวกับ morphology ของ atherosclerotic plaque และการใช้ contrast agent ใหม่ๆ ที่จะทำให้ image ของ coronary artery ชัดเจนขึ้น cardiac MRI ยังต้องมีการพัฒนาอีกมากในอนาคตเพื่อให้ได้ข้อมูลดีขึ้นโดยใช้เวลาน้อยลง

คำสำคัญ : การตรวจหัวใจโดยใช้สนามแม่เหล็ก, โรคหลอดเลือดหัวใจ

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