Review of Cardiovascular MRI: Clinical Results and further developments

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Abstract

Magnetic resonance (MR) has many intrinsic advantages for cardiovascular applications: it offers excellent soft tissue contrast and has the ability to acquire three-dimensional and/or oblique images. Furthermore, one can non-invasively view the proximal branches of the coronary arteries, evaluate myocardial perfusion, and quantify blood flow. With the new myocardial viability technique, one can even evaluate the size of an infarct in around 10 seconds. Dedicated cardiovascular MR has emerged recently from the research arena into clinical reality. A key feature of these dedicated systems is that they offer much faster techniques than ever before. The new techniques are expected to further expand the clinical utility of MR for diagnosing cardiovascular diseases.

Key words: Cardiovascular MR, Coronary angiography, Myocardial perfusion, Dedicated cardiac MR system

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Introduction

Cardiovascular MR is considered the last great frontier of magnetic resonance (MR) imaging. Cardiac MR requires excellent temporal as well as spatial resolution and is therefore the most challenging application within magnetic resonance. In the past, the images frequently took a long time to acquire and were unavoidably affected by breathing artifacts. Over the years, different approaches have been developed to overcome motion problems encountered in cardiac and thoracic imaging. These techniques enable images to be acquired free from motion artifacts[1, 2]. Furthermore, new applications have been developed to evaluate the function, anatomy, and pathology of the heart. Cardiovascular MR has recently emerged from the research domain into clinical reality. This article gives a brief overview of the major techniques used in cardiovascular MR and takes a look into dedicated cardiac MR systems.

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1. Characteristics of Cardiovascular MRI

When imaging the heart or the thorax, ECG triggering is typically used to avoid motion artifacts. This necessarily increases the scan time as raw data are collected only from a particular time point (usually during diastole) within the cardiac cycle. As a result, conventional techniques using ECG triggering take several minutes to acquire for a 2-dimensional acquisition whereas 3-dimensional imaging with triggering would require a long scan time.

Respiratory motion artifacts can be avoided by using the navigator echo technique[3], in which the navigator echo MR signal is used to monitor the level of the diaphragm during the breathing cycle. Data points that fall within a selected window in the position of the diaphragm are included for generating the image. Clearly, this is a time-inefficient approach as only a fraction of the data points are used for producing the image. Nice results have, however, been demonstrated with this technique although the actual scan time can be around 10 minutes long[4, 5].

Ultrafast techniques enable images to be acquired 10-20 times faster than conventional respiratory-compensated techniques. For example, using high performance hardware that gives a short echo time (TE) and a short repetition time (TR), 2D images can be acquired in 10 seconds and less. With these fast techniques, one can readily avoid respiratory motion artifacts by completing the acquisition within a single breathhold.

With the state-of-the-art MR systems, it is now possible to acquire a cardiac-triggered 3D acquisition even within a single breathhold. This substantially shortens the scan time, thus making the complete examination more practical for clinical routine. A shorter examination time is highly desirable for cardiac patients, particularly for sick patients. Furthermore, the patient can better co-operate with the examination and this leads to better image quality.

2. Major techniques for clinical applications

A variety of techniques have been developed over the years for imaging the heart and the vasculatures. For imaging the heart, the key techniques include the following:

a) Tissue characterization

Magnetic resonance is excellent for noninvasive tissue characterization. Even without the use of a contrast agent, one is able to visualize changes in the signal intensity and tissue contrast. For example, an infarcted area of the myocardium can be depicted by using T2-weighted imaging[6]. In addition, other techniques can be used in combination for further characterization of the lesion. Fat has a predictable signal appearance and the fat suppression technique, for example, can be used to confirm the presence of fatty infiltration within the tissue. MR has superior spatial resolution in comparison with nuclear medicine studies for the detection and delineation of an infarct, particularly for subendocardial infarcts. Furthermore, MR has an important role to play in evaluating the efficacy of medication or revascularization as it can readily be used in follow-up studies[7].

b) Evaluation of myocardial perfusion

Myocardial perfusion can be measured following the bolus injection of a small dose of a contrast agent (for example, Gadolinium-DTPA). First pass imaging is performed to visualize the arrival and the dynamic passage of the contrast agent through the myocardium[8, 9]. The contrast agent causes an increase in the signal of the perfused region by shortening the T1 relaxation time. A perfusion deficit (poorly perfused region) is identified as the region having low signal intensity during the first pass.
c) Wall motion analysis
Cardiac cine images can be acquired with ECG-triggered multi-phase images which depict the temporal contraction of the myocardium\(^{(10)}\). Different techniques have been developed. For example, grid tagging\(^{(11)}\) can be used to locally mark the tissue elements so that one can observe their movements over the cardiac cycle\(^{(12)}\). Abnormality in myocardial contraction can be detected by viewing the images dynamically in a cine mode\(^{(13-15)}\). In addition, ejection fraction, stroke volume, and cardiac output can be quantified using automatic segmentation and cardiac post-processing. **Fig. 1** shows an example of cardiac grid-tagging of a patient with an infarct demonstrated in a T2-weighted image.

d) Coronary MR angiography
Coronary MR angiography is a challenging task due to the small size of the coronary vessels and their tortuosity\(^{(16, 17)}\). Furthermore, the coronary vessels do move substantially with the beating motion of the heart. In addition, respiratory motion can create motion artifacts. There are a variety of techniques for doing coronary MRA\(^{(18, 19)}\). Respiratory gated techniques can be used, for example, using the navigator echo approach\(^{(3-5)}\). The navigator echo approach is a robust but time-consuming method for imaging the coronary vasculature.

3. Dedicated Cardiovascular MR System
Dedicated cardiovascular MR scanners are designed around the concept of patient-friendliness, speed, and performance. With the availability of new and powerful systems, the advanced imaging techniques

**Fig. 1** Grid-tagged image from a patient with cardiac infarction.
Infarcted area shown in T2W image has no deformation of grid by cardiac movement.
(courtesy of Dr. Yamada, National Cardiovascular Center, Japan)
enable one to achieve greater diagnostic confidence in shorter time than ever before.

a) Patient-friendliness
Previous generations of MR scanners tend to have a long magnet and a narrow opening, which can cause anxiety and claustrophobia in some patients. The new scanners are more spacious due to a wide magnet bore (e.g. 60 cm) and a short magnet (1.6 m) design. Furthermore, the systems are equipped with adjustable lighting and ventilation systems for patient comfort. The systems are also equipped with an MR-compatible patient monitoring device. The new scanners are more user-friendly as well as hospital-friendly than earlier systems. For example, the space requirement for installation is now as little as 30 m² and the need for a separate computer room has recently been eliminated.

b) Speed and Performance
The availability of high performance hardware, in particular, powerful magnetic field gradients, has revolutionized the way we perform cardiac MR. In the past, 3 dimensional (3D) imaging would take quite a long time to acquire, particularly with ECG triggering. Now, with the powerful hardware, 3D acquisition has been reduced over 20 folds to 15 - 20 seconds. This makes it possible to perform 3D imaging within a single breathhold, thus eliminating respiratory motion completely.

c) Real Time Imaging
With the use of very short repetition times (TR) of less than 2 msec, acquisition time of the complete data set can be as short as a fraction of a second. For example, a 2D image with a reduced matrix of 60 image lines and a TR of 1.6 ms would take less than 100 msec to acquire. This time period is far shorter than the time needed to do conventional MR imaging. This makes it possible to perform real time imaging without the use of ECG triggering. Furthermore, patients can be scanned in the presence of free breathing.

Interactive real time imaging (20, 21) is an important feature which allows the user to freely change the imaging plane while acquiring the data. With the use of a special control device, the user has 6 degrees of freedom (similar to flying an airplane) and one can interactively fly through the chest and view the heart in various angles and orientations. One can quickly position the acquisition to the desired short axis or other anatomical orientations. Although real time imaging does not yet have the spatial resolution as the breathhold techniques, it is useful for performing quick surveys (e.g. in congenital heart disease and for uncooperative or very sick patients).

d) 3D Coronary MR Angiography
While there are a number of methods available to perform MR angiography of the coronary arteries, the future really lies in the ultrafast techniques. There are 2 major categories of techniques for MR imaging of the coronary arteries. The first one is respiratory-motion corrected techniques such as the use of navigator echoes. This has been demonstrated to produce excellent results in healthy volunteers. The technique, however, is not time-efficient and does not work all the time in patients. There is a need for an alternative high speed technique. Ultrafast 3D imaging (using short TR and TE) can complete scanning within a single breathhold (22). This is significantly faster than the navigator-echo based techniques. Initial results of this technique has been very promising (Fig. 2). The use of contrast agent may further increases the signal of the coronary vessels.

Coronary MR angiography has the ability to identify significant stenoses within the major coronary arteries with a relatively high degree of accuracy (23, 24). It is reported to have a sensitivity and specificity higher than that compared with exercise test or scintigraphy. Although the spatial resolution of coronary MRA does not rival that of conventional angiography, the fact that it is a noninvasive
Fig. 3 Viability study with contrast enhancement (courtesy of Northwestern University Hospital, Chicago)

Fig. 4 3D pulmonary MRA (courtesy of Northwestern University Hospital, Chicago)

examination does have a great appeal for its possible usage as a screening technique.

e) Myocardial Viability
The MR viability technique is a fast and robust method to identify the location and the extent of an infarct(25). This is, in principle, a late enhancement technique, in which normal tissue does not retain the contrast agent and therefore appears dark. Infarcted tissue traps the contrast agent and therefore appears bright (Fig. 3). Early results have demonstrated this technique to be of great clinical utility. The ease of use of this method makes it an essential technique for fast detection of myocardial infarct.

f) Superfast 4D MR Angiography
The use of ultrashort repetition time (TR<2 msec ) enables one to perform superfast 4D imaging in which one acquires a series of 3D volumetric acquisitions rapidly. Given this ultrafast speed, one can readily visualize the arrival of contrast agent following intravenous injection. Good depiction of the pulmonary vasculature can be achieved (Fig. 4). Applications include high temporal resolution pulmonary and carotid MRA.
4. Further developments

Current techniques can be used for a variety of clinical applications [26, 27], which include imaging of cardiac morphology (in patients with congenital heart disease), imaging of infarct (both the size of the infarct and the associated myocardial deficit), imaging of wall motion abnormalities, and non-invasive MR angiography (of coronary arteries and other vascular diseases such as aortic dissection, aneurysm, co-arctation, etc.). Future applications include real time evaluation of ejection fraction and cardiac functions and further extension of current techniques to applications with higher temporal resolution and/or higher spatial resolution.

In summary, magnetic resonance offers a broad spectrum of techniques for cardiovascular imaging. The techniques available with the state-of-the-art systems are fast, robust, and well-suited for clinical applications.

References


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