Cardiovascular magnetic resonance imaging

Theodoros Karamitsos

Stefan Neubauer

Abstract

Magnetic resonance imaging (MRI) uses the magnetic properties of the hydrogen nucleus, radio waves and powerful magnets to provide high-quality still and cine images of the cardiovascular system, with and without the use of an exogenous contrast (gadolinium). Cardiovascular MRI (CMR) is considered the gold standard method for the three-dimensional analysis of cardiothoracic anatomy, the assessment of global and regional myocardial function, and viability imaging (late gadolinium enhancement technique). It is also an excellent method for the identification of myocardial ischaemia using the first-pass perfusion technique. Coronary imaging with CMR is feasible, and indicated particularly for anomalous coronaries. However, its spatial and temporal resolution is inferior to computed tomography or conventional angiography, and the identification and grading of stenoses remains challenging. In future, molecular imaging may allow visualization of unstable plaque. Oedema detection is another promising tool, which adds a new dimension to imaging in patients with acute coronary syndromes. CMR also provides important prognostic data for many cardiovascular diseases. CMR is now an essential component of advanced cardiovascular imaging, and it is anticipated that its role will continue to grow in the future.

Keywords cardiac anatomy; cardiac function; coronary angiography; magnetic resonance imaging (MRI); oedema; perfusion; viability

What's new?

- Cardiovascular magnetic resonance imaging (CMR) has further advanced in the last four years, becoming faster and more patient-friendly
- The evaluation of myocardial perfusion using CMR has undergone significant improvement and is now a robust technique applied in everyday clinical practice in many centres
- Oedema imaging using CMR is a promising new technique, which is expected to become of major use in the evaluation of salvage strategies in primary percutaneous coronary intervention
- While still at the research stage, molecular imaging may in future allow specific detection of unstable plaque
- The prognostic role of CMR has been shown for several cardiac disease states, and more data are anticipated in the near future

Cardiovascular magnetic resonance imaging (CMR) has undergone major technical progress over the last decade. CMR scanning has become faster and more patient-friendly accompanied by further improvement in image quality. A study of cardiac anatomy, left and right ventricular function and fibrosis can be performed within 30 min by an experienced operator with a modern CMR scanner. These advances have led to the widespread adoption of CMR in clinical practice.

Background

Magnetic resonance imaging (MRI) is typically based on the magnetic properties of the hydrogen nucleus, though other nuclei can also be used.[1] In an MRI examination, the patient is placed in a powerful magnetic field with which the protons in the body become aligned. Radio waves, in the form of a radio-frequency pulse transmitted into the patient, cause the alignment of the protons to change (e.g. by 90°). When this radio-frequency pulse is turned off, the protons in the patient's body return to their neutral position, emitting their own weak radio-wave signals, which are detected by receiver coils and used to produce an image. The phase and amplitude of each returning radio-wave signal can be determined using powerful computers and additional magnetic field gradients, and this information can then be used to map the position of the excited protons. The resulting image reflects not only proton density, but also the highly complex manner in which protons resonate in their local environment. Cardiovascular MRI (CMR) requires advanced technology, including a high-field magnet (typically 1.5 Tesla, although 3.0 Tesla systems are now increasingly used), fast-switching gradient coils, and coils for transmission and signal reception. Compared to other imaging techniques, MRI has the unique ability of tissue characterization. Image contrast is influenced by proton density and T_1 and T_2 relaxation times which can vary substantially for different tissues (Table 1). Another way to modify image contrast is by modulating the way that radio-frequency pulses are played (the MR sequence – Table 2). MRI scan subjects and operators are not exposed to ionizing radiation and there are no known detrimental biological side effects of MRI provided that safety guidelines are followed.

Ferromagnetic objects can be attracted by the scanner and become projectiles that could lead to significant patient or operator injury and also damage the scanner. The presence of certain medical implants and devices (e.g. pacemakers, defibrillators, cochlear implants, cerebrovascular clips) is a contraindication for routine MR scanning but nearly all prosthetic cardiac valves, coronary and vascular stents, and orthopaedic implants are safe in a 3 Tesla (or less) MR environment. Claustrophobia may be a problem in a small percentage of patients, and mild sedation usually helps to overcome this. Recently, gadolinium-containing contrast agents have been linked with the development of a rare systemic disorder called nephrogenic systemic fibrosis. The patients at risk for developing this disease are those

Theodoros Karamitsos *MD PhD is Honorary Consultant and Clinical Fellow in Cardiology at the John Radcliffe Hospital, Oxford, UK. Competing interests: none declared.*

Stefan Neubauer *MD FRCP FACC FmedSci is Professor of Cardiovascular Medicine and Honorary Consultant Cardiologist at the John Radcliffe Hospital, Oxford, UK. Competing interests: none declared.*

Relaxation times in MRI

- In MRI, two independent relaxation times are described with respect to the direction of the main magnetic field — longitudinal relaxation and transverse relaxation. Conventionally, these are termed 'T_1' and 'T_2' relaxation times.
- Long T_1 times reflect slower relaxation parallel to the main magnetic field; long T_2 times reflect slower relaxation in the transverse plane. T_1 values are typically several times greater than T_2 values.
- T_1 and T_2 times vary considerably between different tissues, and these differences are the basis of much of the remarkable contrast resolution of MRI. Tissues with high water content have particularly long T_1 and T_2 times.

T_1 and T_2-weighting

- In T_1-weighted images, areas with a long T_1 time give a low signal. Water-rich areas therefore appear dark.
- In T_2-weighted images, areas with a long T_2 time give a high signal. Water-rich areas therefore appear bright.

Table 1

with acute or chronic severe renal insufficiency (glomerular filtration rate <30 ml/min/1.73 m^2); or acute renal dysfunction of any severity due to the hepato-renal syndrome or in the perioperative liver transplantation period. To date, there is no evidence that other patient groups are at risk. Moreover, it is unknown whether immediate haemodialysis protects against nephrogenic systemic fibrosis. Therefore, gadolinium based contrast media should be avoided in high risk patients unless the diagnostic information is essential and not available with non-contrast enhanced CMR or other imaging modalities.

Applications of CMR

Normal and pathological anatomy

Historically, the first application of CMR was the three-dimensional analysis of cardiothoracic anatomy. By providing excellent soft tissue contrast, cardiovascular anatomy can be assessed in virtually any imaging plane (coronal, transverse, sagittal) including tailored double oblique planes — particularly valuable in complex congenital heart disease. CMR has a very high sensitivity and specificity for detecting diseases of the thoracic aorta, such as aneurysm, acute dissection and intramural haemorrhage.[2] CMR also allows investigation of the consequences of dissection (e.g. thrombosis, aortic incompetence, pericardial effusion) (Figure 1). The discovery of thoracic masses on chest radiography or echocardiography is also an indication for CMR, which can reveal their anatomical relationship to cardiac and thoracic structures[2,3] and provide tissue characterization. CMR is currently the most accurate method for the diagnosis of arrhythmogenic right ventricular cardiomyopathy, showing regional wall motion abnormality, regional wall thinning and, in advanced cases, fibrofatty infiltration.[4] In hypertrophic cardiomyopathy, CMR can

MRI sequences

An MRI sequence comprises a series of radio-frequency pulses that provide the magnetic resonance signal. These are interleaved with a series of field gradient pulses, which provide the spatial encoding of the signal and hence the image.

Spin-echo sequences have traditionally been the 'workhorse' of routine MRI. A 90° pulse is followed by a 180° pulse, and the delay between the two is reflected in the echo time (T_E); the process is repeated after a repetition time (T_R).

- A spin-echo sequence with a short T_R and a short T_E produces an image in which long-T_1 areas give a low signal (i.e. black).
- Use of long T_R and long T_E values produces an image in which long-T_2 areas give a high signal (i.e. white).
- Long T_R and short T_E values produce a proton density-weighted image.

As a 'rule of thumb', T_1-weighted and proton density-weighted images tend to be similar to CT images and are particularly helpful for anatomical orientation. T_2-weighted images can be more prone to artefact, but are particularly sensitive to pathological lesions. Many diseased areas appear bright on T_2-weighted images, partly as a result of their high water content.

One of the limitations of spin-echo sequences is that they can be relatively slow. Fast spin-echo sequences are similar to conventional imaging, but the data are collected more quickly. Image quality is greater for the same acquisition time, but artefact problems may be worse.

Gradient-echo sequences: the 180° pulse is replaced by a reversal of magnetic field gradients. This technique is generally much faster than conventional spin-echo, but can be more prone to artefact. T_1- and T_2*-weighting can be undertaken and a refinement of this technique, now widely used to image cardiac function, is termed 'steady-state free precession' (SSPF), providing the highest contrast between chamber blood (white) and myocardium (dark) of all available MR sequences.

Echoplanar imaging: ultrafast techniques, particularly echoplanar imaging, are now increasingly used. They offer short imaging times (e.g. 30—40 ms per slice) but require advanced hardware.

Inversion-recovery sequences: the 180° pulse is followed by a 90° pulse after a specified time interval. An important variant (STIR sequence) uses short time intervals to suppress the signal from fat and highlight the signal from diseased tissues. Another important example is the late enhancement sequence used to image viable myocardium.

Navigator sequences: additional information can be acquired during the image sequence to enable correction for patient movement which would otherwise degrade the image. Use of this group of methods is now possible on newer clinical machines.

Table 2