Magnetic resonance imaging in cardiology

The high resolution images yielded by magnetic resonance (MR) have established its role in the assessment of structural abnormalities of the heart and great vessels. New MR technology also now allows accurate and fast non-invasive assessment of cardiac function. Tissue characterisation, myocardial perfusion and non-invasive coronary angiography are under development and show much promise. The versatility of this technique has fuelled the growing support for the use of MR in cardiology.

Structural abnormalities

Cardiovascular MR (CMR) allows the acquisition of accurate, highly reproducible tomographic images in any desired anatomical plane without exposure to ionising radiation and usually without contrast agents. As such, it offers a safe, non-invasive assessment of structural abnormalities and allows the temporal sequence of pathological or therapeutic changes to be followed precisely. It is thus of particular use in the assessment and follow-up of aortic and congenital heart disease (Fig 1), valvular disease (Fig 2), intracardiac thrombus or tumours, cardiomyopathies and other myocardial and pericardial diseases.

In both congenital heart disease and the acute setting, CMR has a central role in patient management. CMR and transthoracic echocardiography (echo) are complementary in the former, allowing a non-invasive work-up of the majority of patients. In acute dissections, CMR provides fast and detailed images of the origin and extent of the dissection, and any valvular, thoracic or renal vessel involvement. Furthermore, MR allows an assessment of the velocity of flow in the true and false lumen, and has the capacity for...

Key Points

- Magnetic resonance imaging (MRI) provides accurate, highly reproducible tomographic images in any desired anatomical plane, making it ideal for imaging all structural abnormalities
- The reproducibility of MRI makes it ideal for serial analysis and follow-up
- MRI is safe, non-invasive and does not require ionising radiation
- MRI provides accurate information on cardiac function, valvular disease, blood flow, ischaemic heart disease, and the presence of viable myocardium
- Applications of MRI to myocardial perfusion, metabolism and coronary angiography are being developed, and may become a realistic alternative to more invasive x-ray based procedures
CMR is also proving useful in many other circumstances, for example:

- Following cardiac surgery, echo may be challenging because the anatomy may be distorted and echo windows limited in a supine, ventilated patient. These considerations do not affect the quality of CMR of the myocardium and surrounding structures.
- In valvular regurgitation, Doppler echo is the main diagnostic tool, but it offers only a semi-quantitative estimate of severity — information vital to management. CMR provides several methods of obtaining this information, including velocity-encoded cine CMR which measures the volume of both anterograde and retrograde flow (Fig 2).
- CMR is also useful in defining certain cardiomyopathies, such as acute viral myocarditis, hypertrophic cardiomyopathy, arrhythmogenic right ventricular dysplasia, haemochromatosis and sarcoid.
- Imaging of the pericardium. This is difficult with echo, which may not reliably detect thickened pericardium in the absence of pericardial fluid; loculated effusions can also be difficult to diagnose, especially along the right atrial border. Conventional CT scanning can overcome some of these problems, but suffers from poor tissue contrast and the requirement for a contrast agent and ionising radiation. It also acquires images only in axial planes. MR has the advantage of good tissue contrast and spatial resolution, and good visualisation of both thickening and effusion.

Cardiac function

Accurate three-dimensional spatial registration enables CMR to obtain reproducible volumes of both left and right ventricles. CMR is accurate serial images of a changing situation. This is all achieved without the additional stress of a transoesophageal echo or the limited planes available and contrast agents required with computed tomography (CT).

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**Fig 1. Magnetic resonance image of coarctation of the aorta** (LVOT = left ventricular outflow tract).

**Fig 2. Cine-magnetic resonance image of mixed aortic valve disease:** (a) in the systolic frame, showing the black high-velocity jet of aortic stenosis; (b) in the diastolic frame, showing the black regurgitant jet. Below: a plot of the flow velocities through the aortic valve. The degree of regurgitation can be calculated from the reverse flow in diastole after closure of the aortic valve (after frame 7) (AR = aortic regurgitation; AS = aortic stenosis).
right intracardiac cavities that are not dependent on geometrical assumptions. This is achieved by obtaining contiguous short-axis slices of the entire left and right ventricle at end-systole and end-diastole. Summation of the endocardial borders allows accurate quantification of intracardiac volumes, irrespective of the particular shape of each chamber. By contrast, echo relies on theoretical geometry to derive the volumes which do not hold true, for example, in ventricles distorted by myocardial infarction (MI). Other indices, such as myocardial mass, stroke volume and ejection fraction, can be derived from the volume measurements. The reliable determination of the above parameters is valuable, given their importance as prognostic indices in clinical cardiology. Trials are now under way comparing echo, nuclear cardiology and CMR in defining prognosis after MI.

In addition to global function, CMR is able to assess regional cardiac function including segmental wall motion and myocardial wall thickening. Quantitative evaluation of these parameters, which has been long awaited, can now be achieved by two CMR techniques:

1. **Myocardial tagging**, which involves the laying down of planes of magnetic saturation of the myocardium at end-diastole, allowing monitoring of the progressive distortion of the myocardium during the course of the cardiac cycle.

2. **Phase-velocity mapping**, which makes use of velocity images of the heart so that speed and direction of movement can be tracked at individual points within the myocardium.

### Role in ischaemic heart disease

With the advent of fast imaging and real-time cine imaging, ischaemic heart disease can now be investigated:

- chronic MI is seen as an area of well-demarcated wall thinning
- CMR tissue characterisation is also well suited to the evaluation of acute myocardial ischaemia and infarction.

These conditions are associated with an increased myocardial signal, which is further enhanced with the use of a paramagnetic contrast agent. Following MI, both right and left global and regional function can be assessed, and complications diagnosed (including aneurysm formation, quantification of valvular regurgitation and septal defects).

Cardiac stress in the magnet (usually pharmacological) shows areas of reversible ischaemia amenable to re-vascularisation by the induction of new wall motion abnormalities. These results compare favourably with thallium emission tomography and stress echo. Furthermore, improved wall motion during low-dose dobutamine CMR can be used to detect the presence of viable myocardium, yielding results similar to positron emission tomography (PET) and stress echo.

Perfusion studies have also been performed using paramagnetic contrast agents. A bolus of contrast is given by intravenous injection and followed through the myocardium. The time taken to reach peak signal intensity, the level of peak signal intensity, and the slope of increase can be measured. This is done both at rest and during pharmacological stress, yielding results similar to traditional nuclear imaging techniques (Fig. 3).

Ultrafast imaging, as well as ECG and respiratory gating, has enabled MR coronary angiography to be performed (Fig. 4). This may be of use in the assessment of native coronary arteries, anomalous coronaries and bypass grafts. Contrast-enhanced coronary angiography may improve the results further by analogy with peripheral MR.

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**Fig 3.** Perfusion imaging by nuclear medicine (upper panel) and magnetic resonance (lower panel). An inferior perfusion defect is present (a) at stress but not (b) at rest, with good concordance.
angiography (now well established) (Fig 5).

Another area of development is CMR spectroscopy; this provides information on high-energy metabolites of the heart which are vital for contraction and viability. Such information may prove to be of value in the assessment of ischaemic heart disease, particularly in patients with suspected hibernating myocardium.

Thus, a single non-invasive CMR scan may be envisaged which could provide a comprehensive cardiac evaluation showing:

- the extent and localisation of ischaemic and viable myocardium
- the size of infarction
- coronary anatomy
- global and regional ventricular function.

Vascular flow measurement

One of the most powerful advantages of MR is its ability to provide views of complex three-dimensional flow (Fig 6). Doppler echo is accurate for measuring velocity, albeit in limited planes, but poor at assessing flow. MR can provide simultaneous information on the velocity in three dimensions as well as time, allowing accurate assessments of flow and flow patterns previously investigated only in vitro. In practical terms, any vessel can be assessed for the degree of flow within it. This remit therefore extends beyond just the heart and great vessel to carotid, renal, hepatic and even coronary artery flow. This relatively new area is undergoing intensive research.

Practical considerations

The scan technique requires the patient to lie within the bore of the magnet, which may not be tolerated by patients with claustrophobia. Experience shows, however, that the failure rate can be substantially reduced by the prior administration of low-dose benzodiazepines.

In the acute setting, CMR-compatible equipment can now provide monitoring of all the routine parameters including those obtained from invasive methods. Care must be taken not to use any non-MR-compatible equipment in the vicinity of the magnetic field, including routine crash trolley equipment. CMR suites can be designed to accommodate ventilated, monitored patients, and such patients are now routinely scanned at the Royal Brompton Hospital. Furthermore, cardiac-dedicated scanners are being launched which are shorter and allow better access to the patient.

ECG gating is required, so a few patients with significant arrhythmias will be unable to undergo the procedure. Patients with pacemakers should not generally be scanned except in special circumstances. A further source of image artefact is respiratory motion, but this problem has largely been overcome by the use of MR respiratory gating techniques through navigator diaphragm tracking.

Contraindications. There are few contraindications to MR but, in addition to pacemakers, the presence of implantable devices such as defibrillators, cochlear implants or cerebral aneurysm clips usually prevents scanning. A wide range of prostheses are
Comparison of cardiovascular magnetic resonance with other imaging modalities

The most commonly used imaging technique in cardiology is echo; it is inexpensive, widely available and safe. In practice, however, not only is echo operator-dependent, but it requires adequate acoustic windows which may be poor due to body habitus, position of the patient, cardiac surgery and anatomical variation (Fig 7). As mentioned above, echo also relies on geometric assumptions in determining cardiac function, which is not true of CMR. Nuclear medicine offers an array of imaging techniques for perfusion, viability and metabolism, although these suffer from poor spatial resolution and a radiation burden. Cardiac catheterisation is invasive and combined with exposure to X-rays and contrast media.

As well as cost and the availability of hardware, software and cardiac expertise, the other main limitation of CMR is the requirement for patients with acute syndromes to be transferred to the scanner.

Availability and cost

At present, CMR is available in only a few specialised centres in the UK, but its use is expanding rapidly and it should become more widely available. The initial cost of the scanner is clearly a consideration, but ultrafast imaging techniques now allow the cost of individual scans to be competitive with echo because they can be completed rapidly. In addition, one MR scan may yield information that would normally come from a number of other investigations, which helps the cost-effectiveness equation.

Cardiovascular magnetic resonance in perspective

Although the availability of CMR is currently limited, and many of its applications are still in the process of development, CMR is already the gold standard for assessment of structural abnormalities, measurement of global cardiac function, and qualitative assessment of regional function. These studies are routinely performed at the Royal Brompton Hospital and can be completed in about 20 minutes. Many methods of providing quantitative assessment of regional wall thickening and motion have been validated, but perhaps the most exciting, myocardial tagging, requires further development (now well under way) before it can be considered as part of a routine clinical assessment.

Much has already been achieved in the development of CMR myocardial perfusion, but large-scale validation and cost-effectiveness studies are still awaited. Nevertheless, the technique is largely established, and has already been shown to yield results similar to nuclear cardiology. MR inherently offers greater spatial resolution which, together with the lack of exposure to ionising radiation, makes it attractive. Continuing research and the availability of newer intravascular contrast agents mean that MR perfusion could be used for absolute perfusion measurements, as a competitor to PET.12

The imaging of coronary arteries has attracted a great deal of interest, as a
result of which there have been significant technical advances in this area. Problems of cardiac and respiratory motion have been largely overcome and the resolution is now approaching 0.5 mm (a factor only about two worse than x-ray angiography). MR coronary artery imaging is now routinely used in the clinical assessment of anomalous coronary arteries, where it has been shown to be superior to angiography. MR imaging of coronary artery bypass grafts is also well established. Work is progressing rapidly on the imaging of native coronary arteries and, while it remains essentially a research tool, the sensitivity and specificity for the detection of coronary stenoses is quite reasonable. There is also the potential to measure the coronary flow velocity, and thus non-invasively demonstrate reduced flow reserve with haemodynamically significant coronary stenoses.

The future

CMR can potentially offer a comprehensive analysis of cardiac anatomy, function, perfusion and coronary angiography. The entire imaging is likely to be completed in a single session lasting only one hour without the need for ionising radiation or invasive procedures. Cardiac-dedicated scanners are becoming available which are smaller and faster, and expertise in the field is growing. In the future, open scanners may become available to allow greater access to the patient.

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**Echocardiography**

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Echocardiography is established as a basic tool in cardiology. New technologies and their application to cardiovascular research and clinical practice continue to expand its role. The basic modalities of echocardiography are briefly reviewed in this article. Extended applications are also considered and new echocardiographic techniques described. Finally, some of the common clinical indications for echocardiography are discussed. This article is purposely restricted to the adult heart; paediatric applications are not discussed.

**Basic echocardiographic modalities**

**Two-dimensional imaging**

As the name suggests, two-dimensional (2-D) echocardiography provides a two-dimensional view of the heart in real time, allowing the operator to define cardiac anatomy and identify structural and functional abnormalities. It also acts as a guide to the alignment of M-mode and Doppler beams (Fig 1).

**M-mode**

In M-mode echocardiography the reflected echoes from a single narrow ultrasound beam are displayed against time (Fig 2). This allows the operator to examine in detail myocardial and valvular motion throughout the cardiac cycle. Events may be timed in relation to a simultaneously displayed ECG, and cardiac dimensions measured with a high degree of accuracy.

**Doppler**

In its most basic form, Doppler echocardiography is a technique for measuring the velocity of blood flow. When blood is flowing towards the transducer, the frequency of the reflected ultrasound waves increases in proportion to the velocity of blood flow (the Doppler shift). The reverse occurs with blood flow away from the transducer. The blood flow velocity may be calculated from the Doppler shift.

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**Key Points**

- The data from different echocardiographic modalities provide detailed information about cardiac structure and function.
- Stress echocardiography may be used to diagnose coronary artery disease, to stratify risk in coronary artery disease, and to detect myocardial viability.
- Several new techniques have been developed to enhance myocardial imaging and therefore aid the detection of wall motion abnormalities.
- Echocardiography is indicated in almost all patients presenting with symptoms and signs of heart failure.
- Echocardiography has an important role in the investigation of stroke patients.