Magnetic Resonance of the Heart

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Introduction

Cardiovascular magnetic resonance (CMR) is a developing field with enormous potential because of its major attributes of high image quality and resolution combined with non-ionising radiation and versatility. With recent major technological advances, there have been great improvements in acquisition speed and quality that makes the use of CMR in a wide range of cardiac conditions robust and valuable. This article reviews the fundamentals of CMR and its current clinical applications.

Fundamentals of Cardiovascular Magnetic Resonance

There are essentially three types of imaging sequence that are used in the cardiovascular system: In *spin-echo imaging*, the blood appears black and good-quality anatomical imaging is obtained. In *gradient-echo imaging*, the blood is white and the high-quality cine imaging is used to identify regional myocardial function and abnormal flow patterns. The gradient-echo technique of *velocity mapping* uses the phase of the MR signal to measure velocity; it usually behaves like 2-dimensional Doppler, but unlike Doppler it can measure flow directly and can be extended into seven dimensions for complex flow-dynamics problems [1]. CMR therefore consists of applications of these sequences and their variants, which allows determination of cardiac physiology, anatomy, metabolism, tissue characterisation, and vascular angiography.

For dedicated CMR, the environment typically incorporates medical gases, full invasive and non-invasive physiological monitoring telemetry, stress infusion pumps for adenosine and dobutamine, a power injector for contrast studies, and full resuscitation equipment and drugs. Experience has demonstrated that acutely ill and anaesthetised patients can be safely managed within the magnet in experienced centres. Modern CMR scanners incorporate ultrafast technology that allows real-time imaging (up to 50 frames per second), and ultrafast applications for assessing coronary artery disease (CAD). Currently, most scans are still gated to the electrocardiogram, and in some cases also to the respiratory cycle using advanced diaphragm-monitoring techniques.

CMR is as safe as echocardiography. It is also safe for scanning all prosthetic heart valves and for patients with sternal wires, joint replacements, and retained epicardial pacing leads. There is abundant evidence that stents are safe to scan any time after insertion [2]. Pacemakers are problematic. Although recent MR experience is encouraging, this should only be considered in centres of specialist experience. Other implantable electronic devices, including defibrillators and cerebrovascular aneurysm clips, are currently a contraindication to CMR. Claustrophobia occurs in about 4% of patients but such patients frequently respond to low-dose diazepam.

Established Clinical Indications

Aorta

The aorta is well-imaged by CMR over its entire length. Three-point plane definition techniques are useful for imaging in the long axis of the aorta with reference to points in the ascending and descending limbs and the arch. The ‘candy cane’ view shows the extent of dissections and the location of coarctation. Closer interrogation of specific regions can also be made with orthogonal planes. CMR has been shown to be more accurate than transoesophageal echocardiography (TE) and computed tomography (CT) in evaluating acute dissection [3], although TE is often simpler to organise. CMR is ideal for the long-term follow-up of these patients in order to exclude aneurysm formation and other complications. In coarctation, Doppler is often problematic, and CMR is ideal in answering clinical issues, as well as being cost-effective [4]. In addition, CMR can demonstrate the net flow in collaterals as an index of stenosis severity.

Congenital Heart Disease

Echocardiography is ideal for monitoring congenital disease in the young, but with growth into adulthood and after corrective surgery, CMR plays a larger role and is of-

ten complementary to TE. TE is better at defining fine structure, such as valve morphology, whereas CMR is superior for flow, conduits and great-vessel anatomy [5]. In centres with expertise in both techniques, invasive catheterisation is reserved mainly for pressure measurements.

Angiography

For non-coronary angiography, CMR has become the investigation of choice. MR angiography (MRA) is fast, non-invasive, simple and safe, requiring only a peripheral intravenous injection of gadolinium, and 4-20 s of 3D acquisition on modern scanners. The data can be displayed in a rotating cine, which can, on the latest scanners, be time-resolved (4D angiography). This has proved useful for visualising the pulmonary arteries. Major applications have been shown for the aorta, renal and leg arteries [6], but the technique is not limited to these areas. Recently, thrombus imaging with CMR in the venous system has been demonstrated [7], and comparisons with established techniques for detection of deep-vein thrombosis and pulmonary embolism are under way.

Masses and Tumours

CMR defines the size, extent and relation of cardiac masses to surrounding tissues [8]; in addition, tissue characterisation and enhancement with gadolinium yield valuable information. T1- and T2-weighted images vary between masses according to their biochemical composition; for example, pericardial cysts have a characteristic high signal on T2 imaging, and the fat content of tumours can be selectively ascertained using fat suppression. Gadolinium enhancement reflects tumour vascularity; therefore, positive enhancement typically occurs in malignancy, although this is not excusive as vascular benign tumours such as myxoma and haemangioma also enhance. These additional characterisation features are very useful clinically in the guidance of diagnosis and surgery.

Assessment of Cardiac Volumes, Mass and Function

Ventricular function, volumes and mass are important prognostic indicators in CAD and other cardiac disease. Current clinical techniques (echocardiography, radionuclide ventriculography) have now been shown to be less accurate and reproducible than CMR [9], which has become the new gold standard. The interstudy reproducibility of CMR has been recognised by the pharmaceutical industry, which is using CMR for drug development studies in order to reduce the sample size [10], which reduces costs significantly. Comparisons of the current clinical techniques with CMR show that mean values in population vary between techniques by small amounts, but that individual variation can be very substantial [11]. If individual patient clinical decisions are based on numerical thresholds, then CMR is the preferred technique. The acquisition of these parameters by CMR is now achievable in a few minutes, and analysis techniques can also be completed quickly.

Flow and Shunts

CMR is useful for the measurement of flow in the heart and great vessels. The signal phase can be encoded for velocity and used to produce 2D velocity maps corresponding with the anatomical images. By measuring the area of a vessel and the mean velocity within the vessel, absolute measurements of instantaneous flow can be derived. When run in cine mode, flow curves are generated in which the area under the curve represents true flow in the vessel. This is very valuable in the non-invasive measurement of the pulmonary to systemic flow ratio in cardiac shunting and in a number of other clinical scenarios.

Valvular Heart Disease

Echo is excellent for investigating valvular disease, but CMR has its particular uses. In valvular regurgitation, echo may not easily determine the severity of the regurgitant flow. With CMR, the regurgitation can be measured directly using reverse-flow measurement in diastole [10]. Extension to assessment of mitral regurgitation involves the subtraction of aortic flow from true left-ventricular stroke volume, measured using the multislice technique. This approach is especially useful when surgery is being considered and clinical and echo results are not concordant, or there is doubt. For valvular stenosis, Doppler is very reliable for assessment and CMR is required less often, but useful if echo assessment fails. Experience suggests that CMR is a valuable alternative to echocardiography when flow across the valve is very eccentrically orientated.

Pericardium

The pericardial thickness is a guide to the presence of constriction and can be measured using CMR. The thickness is slightly greater than that measured with pathological studies due to chemical-shift artefact, caused by fat overlying the thin fibrous pericardial tissue. The normal CMR thickness of pericardium is therefore quoted as <4 mm. The pericardium appears black on CMR because of its low water content, although in acute inflammation it can enhance with gadolinium and appear bright. The thickness of the pericardium needs to be distinguished from any pericardial effusion. Pericardial effusion is commonly black on spin-echo images, but bright on gradient-echo cines, and this is a useful means of differentiation. Pericardial calcification is not well-seen by CMR, as calcium appears black, and therefore may simply appear as a localised area of pericardial thickening. CT is the best technique for showing calcium.

Cardiomyopathy

CMR is very useful in the assessment of cardiomyopathy such as arrhythmogenic right ventricular cardiomyopathy (ARVC), thalassaemia and dilated/hypertrophic cardiomyopathy. ARVC, which typically affects young men, causes right ventricular tachycardia and sudden death. It is familial and many gene abnormalities of the cellular desmosome have been discovered, which reveals the disease to be one of impaired intercellular integrity. Fibrofatty replacement occurs on the basis of injury and repair. The disease presents with abnormalities of the right ventricle (15% also have left ventricular involvement). These are best delineated by CMR, as they can be subtle and localised [12]. The late stages, with a large poorly functioning right ventricular and widespread fat infiltration, is readily identified, but the early stages, characterised by discrete areas of fat infiltration, regional hypokinesia, localised myocardial thinning and abnormal trabeculations pose a greater challenge, and CMR appears to be the best technique. Experience is required to differentiate these findings from normal variants. In particular, the normal patterns of epicardial fat distribution associated with the coronary arteries must be understood.

The assessment of myocardial iron overload has been problematic in clinical practice, but recently a T2* CMR technique has been established that allows reproducible quantification of the iron concentration [13]. Results show that iron loading in the myocardium is not correlated with that in other tissues, such as the blood and liver, and must be examined separately. T2* values <20 ms indicate iron overload, and nearly all cases of heart failure (the commonest cause of death in these patients) occur when the myocardial T2* is <10 ms. The technique has shown that removing cardiac iron is best achieved using oral chelators. T2* CMR combined with targeted chelation has considerably reduced the premature mortality from heart failure in thalassaemia.

In dilated cardiomyopathy, CMR has shown intramural mid-wall striae of fibrosis in one-third of patients, and no fibrosis in about half. These findings are very useful for distinguishing dilated cardiomyopathy from heart failure due to coronary artery disease. Recently, the presence and extent of late gadolinium enhancement has been shown to predict outcome in dilated cardiomyopathy.

Hypertrophic cardiomyopathy can usually be diagnosed by echocardiography, but there are circumstances when CMR is very useful. If the condition is suspected but not confirmed by echo, CMR is ideal as a second-line investigation. CMR also shows the distribution of hypertrophy, especially in isolated basal and apical hypertrophy, and is superior for quantification of myocardial mass. Late gadolinium enhancement occurs in hypertrophic cardiomyopathy and is associated with a worse prognosis. Finally, CMR is valuable for the assessment of septal ablation techniques in locating the size and extent of infarction and assessing rest and stress outflow tract gradients.

Coronary Anomalies

Coronary anomalies occur in approximately 1% of the population and are usually clinically silent. Their importance lies in the occurrence of sudden death in patients who have a coronary artery passing between the great vessels (aorta and pulmonary artery). This may occur because of compression or kinking during exercise. X-ray coronary angiography commonly identifies the anomalous origin of the coronary artery, but is poor at defining the proximal course and the relation to the great vessels. Coronary CMR is now a robust technique for showing the origin and course of the proximal coronaries and also the three-dimensional relations of the great vessels. Several studies have shown that CMR is superior to X-ray angiography for this purpose. More recently, coronary CMR has been applied to evaluate patients with congenital heart disease, in whom the incidence of coronary anomaly is up to 30%. Defining the course by X-ray angiography is even more complex due to altered positions of the great vessels and ventricles [14].

Developing Indications

Detection of Myocardial Infarction

The technique of late enhancement with gadolinium has been developed, in which the heart is imaged 10-15 min after injection. The gadolinium concentrates in the necrotic (acute infarction) or scar tissue (chronic infarction) due to an increased partition coefficient, and the infarcted area becomes bright [15]. There is very close correlation of the volume of signal enhancement and infarct size in animal models of acute infarction. The technique has high resolution and can define the transmural extent of necrosis and scar. In addition, a different technique, known as *early enhancement* (at 1-2 min after gadolinium injection) can be used to define the extent of microvascular obstruction in infarctions. Microvascular obstruction has already been shown to predict remodelling and adverse cardiac events after infarction.

Assessment of Myocardial Viability

The technique of late enhancement has clinical application to the assessment of viability in that the percentage transmural replacement of normal myocardium by scar can thus be determined. Segments with <50% transmural replacement showed improved function with revascularisation, whilst those with higher grades of transmural replacement fail to improve [16]. It is anticipated that the late enhancement technique will make substantial clinical impact in the management of infarction and its sequelae.

Dobutamine stress testing

Dobutamine CMR was first used for the detection of ischaemia in CAD a decade ago, but modern comparisons with stress echocardiography have shown significantly improved diagnosis related to improved results from those patients in whom echocardiographic image quality was suboptimal or poor [17]. Results from several centres have begun to establish this technique, and where available, it can be considered as a first-line approach if acoustic windows are limited.

CMR Techniques in Development

Myocardial Perfusion

SPECT is a widely used technique to assess perfusion, but a safer technique would be medically welcome, providing it can maintain the same valuable diagnostic and prognostic information and is cost effective. Perfusion CMR may be a contender for this role. This technique consists of a baseline first-pass perfusion study and a repeat study during adenosine stress. Gadolinium is used as the contrast agent. Areas of reduced perfusion appear as dark areas in the myocardium surrounded by normal-enhancing areas. One of the advantages of perfusion CMR is high resolution, which allows the visualisation of subendocardial perfusion defects in vivo for the first time. Quantitative analysis tools have been developed that examine the slope of signal increase during the first pass and the myocardial perfusion reserve index [18]. Other advantages of perfusion CMR include the speed of the examination (1 h compared with typically 2-6 h for a nuclear examination), and the easy combination with other techniques, such as late enhancement. Recent multicentre studies suggested that CMR is more accurate than myocardial perfusion SPECT for detection of coronary artery disease.

Atherosclerotic Plaque

Further down the road for clinical use is the technique of plaque imaging. CMR can be used to depict plaques and interrogate their lipid constituents as well as the integrity of the fibrous cap, which are factors that determine the propensity to plaque rupture and thrombus formation. T2 imaging has proved so far to be the most helpful, and validation of results against pathology has been achieved in the aorta and carotids. Latest results have also shown plaques in the coronary arteries [19].

Coronary Imaging

Much work has been devoted to the non-invasive assessment of the coronary artery lumen by CMR. There have been tremendous improvements in techniques, notably in the development of 'navigators' which allow patients to breathe freely during the acquisition, whilst increasing resolution [20]. Most recently, 3D breath-hold techniques during contrast-agent infusion have shown good results. It is likely that coronary CMR will prove useful in CAD at some point in the future, but currently its clinical robustness needs improvement, and the issue of preventing coronary motion during the acquisition has to be improved further. However, the success of the technique for coronary anomalies is established and vein-graft imaging by CMR is now straightforward. In this area, coronary CT has advantage because of superior resolution, although in established coronary disease, interpretation is considerably hindered by coronary calcium. CT is good for detecting early coronary disease, prior to excessive calcium deposition.

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