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-
individual variation can be very substantial [11]. If indications vary between techniques by small amounts, but that techniques with CMR show that mean values in population are significant. Comparisons of the current clinical evidence in order to reduce the sample size [10], which reduces the number of CMR has been recognised by the pharmaceutical industry, and is now considered the new gold standard. The interstudy reproducibility of CMR is more accurate and reproducible than CMR [9], which has become the new gold standard. 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 underway.

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 exclusive 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.