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Review article

APPLICATIONS OF ROUTINE CARDIAC MRI PULSE SEQUENCES – A CONTEMPORARY REVIEW

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ABSTRACT:

Cardiac magnetic resonance imaging is a relatively novel method, which has recently vastly expanded its applications and usefulness. It is a non-ionizing method, with very few contraindications, allowing for characterization of the full spectrum of cardiac diseases. This is done by means of performing a multitude of specially-tailored pulse sequences, each of which images different aspects of morphology and pathology. When putting together all the data, acquired from the separate sequences, a skilled radiologist can provide a comprehensive and insightful interpretation to great clinical benefit. There are morphological, functional, quantitative, and contrast-based imaging sequences, but not all of them are performed on every patient – due to time constraints every imaging protocol is individually calibrated to suit the corresponding clinical query.

Keywords: Magnetic Resonance Tomography, Cardiac Imaging, Electromagnetic Pulse Sequences, Functional Imaging, Medical Imaging, Diagnostic Imaging,

BACKGROUND:

Magnetic resonance imaging (MRI) is a relatively young imaging modality (the first MRI images of a human being were acquired in 1977 [1]). At the same time, MRI is one of the most rapidly and expansively developing imaging techniques. It has experienced further advancements in recent years, with many new imaging sequences having been introduced in a short time – each bringing new insights into pathology. Magnetic resonance tomography (MRT) has now established itself as a standard of care in diagnosing cardiac tumors and infiltrative disease, exceeding the traditional gold standard of transthoracic ultrasonography (US) in terms of morphological capacity and achieving levels of accuracy in functional imaging similar to those of real-time US. Cardiac magnetic resonance (CMR) is also capable of evaluating cardiac viability via perfusion techniques, making it a well-rounded diagnostic modality, albeit requiring expensive equipment and highly experienced personnel. Unfortunately, despite its great advances in imaging technology, cardiac MRI continues to be a time-consuming examination, demanding periods between 40 and 60 minutes for the acquisition of a comprehensive set of image sequences [2].

Some advantages of CMR over Röntgen-ray-based computed tomography (CT) include a strong native contrast between the varying soft tissues, the ability to decrease the field of view with retaining the same matrix size (and thereby improve resolution), the ability to attain data from any plane (unlike axial-only CT). Most importantly, CMR is completely devoid of ionising radiation, making it superior to CT and nuclear medicine examinations in terms of patient dose. Cardiac MRI also provides superior spatial and temporal resolution when compared with nuclear medicine modalities, and, unlike ultrasonography, does not observe the limitations of acoustic windows [2].

Cardiac MRT is not devoid of drawbacks, however.

There is a necessity for sedation in children and claustrophobic patients. Additionally, metallic implants with ferromagnetic effects as well as pacemakers are considered contraindications.

Cardiac MRT is a noninvasive tomographic imaging method that can yield important morphological and functional data with a high image resolution. It has the added advantage of imaging surrounding structures when anatomical sequences are employed, as well as the possibility of adding intravenous contrast (Gadolinium chelates) and characterizing its passage. Measurements performed on still images or cine series allow for accurate calculation of chamber volume, mass, and size. The imaging process is electrocardiographically (ECG) synchronized – either ECG-gated (creates cine series of the whole cardiac cycle) or ECG-triggered (static image acquisition in a specific part of the cardiac cycle – usually diastole). Cine series are small movies of a single slice, acquired from several consecutive and averaged out full cardiac cycles that enable for characterization of contractility and calculation of left ventricular ejection fraction [2]. Finally, respiratory synchronization needs to be applied to adequately account for non-cardiogenic motion artefacts. This is usually done with short (18-25 second) breath-hold commands in T1-weighted images or with respiratory gating in T2-weighted images. The reason for this is that in T1, there are short time gaps in between imaging cycles, allowing for short breath-holds. Conversely, with respiratory gating, no breath-hold commands are given, instead, the patient's diaphragmatic movements are automatically monitored, because, in T2-weighted images, the long gaps between cycles make breath-hold techniques inapplicable [2].

Potential indications for CMR include cardiac masses, quantifying myocardial ischemia or infarction (viability), cardiomyopathies, valvular disease, coronary artery disease (perfusion), pericardial disease, and complex congenital anomalies. [2, 3]

REVIEW RESULTS:

There is a myriad of different pulse sequences. These are unique combinations of field gradients and RF pulses, performed at different intervals that create differently weighted images (T1-weighted, T2-weighted, diffusion-weighted, etc.). Each such image provides different information about the same anatomical area. For example, water appears very bright (high signal or hyperintense) on T2-weighted sequences, and dark on T1-weighted sequences; fat appears bright on both T1 and T2. Both T1 and T2 series can additionally be performed with suppression of the signal from fat. Only when taking all pertinent imaging sequences into consideration, one can acquire a comprehensive understanding of a pathological finding. Additionally, as computing power increases and the intrinsic engineering complexities of magnets stack up, newer sequences emerge at an almost alarming rate. It is this vast array of different types of images that a radiologist must be familiar with that makes MRT exceptionally difficult to interpret, time-consuming to perform, and additionally – rather expensive [2].

Each individual sequence consists of a mandatory imaging engine and non-mandatory image modifiers. Examples of current imaging engines are Fast (or Turbo) Spin Echo (FSE/TSE), Gradient-Recalled Echo (GRE) and its successor balanced Steady-State Free Precession (SSFP), Echo-Planar Imaging (EPI), while examples of modifiers are Inversion Recovery (IR), Fat Saturation (Fat Sat, suppressing signal from fat by means of chemical shift), and Phase-Contrast Imaging [3].

Morphologic sequences

Morphologic sequences yield anatomic still images of the heart and great vessels as a mandatory part of any clinical CMR investigation. They provide the most value when analyzing complex congenital anomalies and estimating the span of cardiac masses. Most commonly at least one of the anatomical series will be done in the standard thoracic axial plane, however, quite often additional oblique planes, specific to the heart, are imaged as well – horizontal and vertical long axis views, two- and four-chamber views, short axis view, views of the valves, outflow tracts, and great vessels [4-6].

CMR sequences can be separated into two categories, based on their myocardium-blood pool native contrast – *dark (black) blood* and *bright (white) blood* sequences. It is often desirable to use both of them for easier comparison. Dark blood sequences are aimed at optimal representation of morphology as they provide a very clear distinction between the vessel wall and blood. They are usually performed at multiple slice locations during diastole to produce a stack of 4-5mm thick slices. This partial coverage only of relevant anatomy is optimal in the view of time constraints. Dark blood images utilize a series of Inversion Recovery prepulses to null unwanted signal – respectively a double IR prepulse to null blood signal, or a triple IR prepulse to null blood and fat. Examples of the imaging engines used are TSE, and its faster variant Half-Fourier Acquired Single-shot Turbo spin Echo (HASTE). Additionally, the Short-Tau Inversion Recovery (STIR) modifier can be of great use for identifying high-signal myocardium at risk in the setting of acute myocardial infarction. T2 STIR can also be used to search for edema associated with acute infarction [3-7].

Cine functional sequences

Bright blood sequences are built upon the SSFP and EPI gradient engines and are an integral part of CMR examinations. They display high-intensity signal from fast-flowing blood (with an excellent distinction between blood and myocardium – figure 1) and are excellent at evaluating cardiac function. These sequences continuously image a single slice across several whole cardiac cycles, creating a short averaged-out movie (cine) of the heart in motion. The cine contains 20-30 frames, acquired with 30-50 msec temporal resolution – a set of 4 example frames is shown in figure 2. Typically, a stack of multiple closely spaced short-axis slices (6-8 mm thick, with 1-2 mm gaps in between) is each turned into individual cine series to achieve adequate coverage. Thus they facilitate accurate assessment of the systolic and diastolic motion

of the ventricular walls, both quantitative and qualitative. Also, measurements can be made of left ventricular end diastolic and end systolic volumes, ejection fraction and myocardial mass can be estimated. Some sources recommend cine SSFP as an alternative to echocardiography (cardiac US) [3].

Fig. 1. A single axial slice from a bright blood sequence, clearly demonstrating left ventricular hypertrophy.

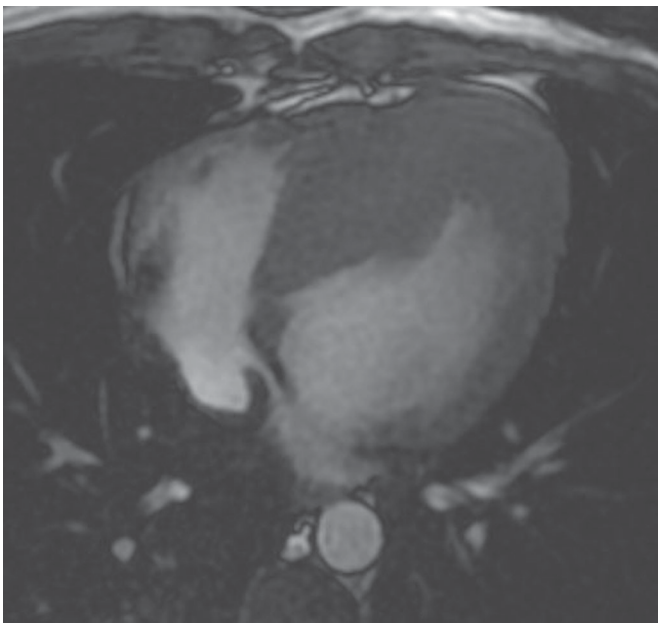
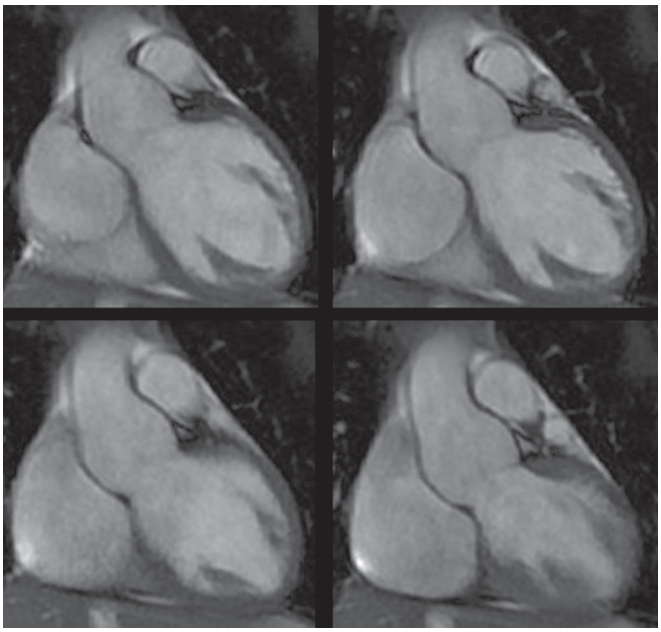


Fig. 2. Four frames from a coronal bright blood cine sequence, showing the heart in motion. A dilation of the aortic root is evident.



Additionally, blood velocity and flow direction can be measured using the modifier Phase Contrast (velocity-encoded, VENC) – a task impossible for CT, and not necessarily easily reproducible with US. Phase Contrast measures the phase shift from blood protons moving through the magnetic field (without the need for intravenous contrast material), which is proportional to their speed, allowing for estimation of said speed and its direction. A cine series encompassing several phases of the cardiac cycle is created. Velocity is encoded in a way reminiscent of colour Doppler in ultrasound. The imaging plane is usually perpendicular to a vessel, chamber, or valve of interest, with antegrade flow coded in light grey to white, and retrograde flow coded in dark grey to black, while stationary tissues appear intermediate grey. Time-velocity and time-flow curves can be generated. VENC is valuable for evaluating shunts and shunt fractions, determining pressure gradients across stenotic valves, and determining regurgitated flow [5, 6].

Quantitative MRI

In the last five years CMR mapping techniques have been introduced, enabling the objective numerical measurement of signal strength in every pixel of either T1-, T2-, or T2*-weighted mapped images (which is impossible to do in images acquired via a different sequence). This technique is mostly used for analyzing diffuse myocardial changes. T1 mapping, for example, is very precise in detecting infiltrative disease – myocarditis, amyloidosis, sarcoidosis, and cardiomyopathies. It is usually performed in two phases – pre- and post-contrast. T2-mapping is excellent for distinguishing edema, while T2*-mapping is less frequently used, as it demonstrates only iron overload (e. g. in haemochromatosis). It should be stipulated that T2-mapping sequences assess myocardial edema quantitatively (objective T2 relaxation time) and not qualitatively (arbitrary signal intensity) like the T2-STIR sequences. Popular sequences include Modified Look-Locker (MOLLI) and Saturation Recovery (SASHA) [3, 8, 9].

Myocardial perfusion

CMR perfusion accurately diagnoses coronary artery disease with high sensitivity and specificity. Perfusion can be performed at rest and at (adenosine-induced) stress. Perfusion sequences usually based on the balanced SSFP, GRE or EPI engine, aim to create a short movie of the blood (either by using an exogenous intravenous Gadolinium-based tracer or endogenous arterial spins). As the blood washes in and passes through the myocardium, areas with lower signal (hypointense areas) are easily recognized as hypoperfused. Because of the need to acquire multiple images within a single cardiac cycle, image quality invariably diminishes, especially in tachycardic patients, where RR intervals are much shorter. Additionally, better signal-to-noise ratios for this method can be achieved at field strengths of 3 Tesla than at 1.5 Tesla. It also needs to be stipulated that Greenwood et al. claim that CMR perfusion can demonstrate higher accuracy than single-photon emission computed tomography (SPECT) in detecting ischemic myocardium [10].

Perfusion can be performed without intravenous contrast material by using arterial spin-labelling [11]. It is a sensitive technique which allows the spin population

in arterial water to be magnetically labelled by an IR pulse, and thus used as an endogenous diffusible tracer. Unfortunately, this sequence has limited use, due to interference caused by cardiac motion and relatively low signal. For these reasons, Gadonilium-based perfusion is preferred. It allows for strong contrast in T1-weighted images, large coverage of myocardium, and adequate spatial resolution [12].

When doing the stress perfusion examination, adenosine dosed at 140 micrograms per kilogram of patient weight per minute is injected over a period of 2-3 minutes, alongside a dose of Gadolinium (Gd). Adenosine is an endogenous purine nucleoside, which has a very short half-life (less than 10 seconds) and acts as a vasodilator by influencing the A2A receptors. Its effect is a maximum dilation of the distal arteriolar bed. Coronary flow can be thus increased by about 4 times in the absence of stenosis. In significantly stenotic arteries, however, there is no change, since they are already fully dilated prior to the adenosine administration. This results in a "steal phenomenon" from the stenotic to the normal arteries. The zones supplied by normal arteries demonstrate a multifold flow increase, while the ones corresponding to stenotic arteries show little or no flow increase, appearing hypointense. Usually, the stress test precedes the rest test with roughly 15 minutes in between them, necessary for complete washout of the first Gadolinium bolus. Finally, another 10-15 minutes after the rest test, a late Gd enhancement series can be performed. To clarify further, intravenous Gadolinium is given once during the stress test, and once more during the rest test [2].

Delayed contrast enhanced CMR and myocardial viability

Analyzing myocardial viability is of paramount importance when considering coronary revascularization. With cardiac MRT, this can be accomplished on T1 mapping, delayed enhancement series, as well as stress/rest perfusion series. Additionally, supported by corresponding clinical suspicion, delayed enhancement can be indicative of a series of other conditions – myocarditis, infiltrative processes, and tumors. It is also important to note that the differentiation between intracardiac neoplasm and thrombus can only be made by means of contrast enhancement [3-7].

Most frequently, viability studies are performed with late Gd enhancement, using T1-weighted GRE sequences [13]. The images are made with a single IR prepulse, aimed at nulling the signal from normal myocardium so that only the pathologically enhancing structures can be of high signal. Healthy structures are to appear black, while blood within the left ventricle should be of intermediate signal strength – neutral gray. A standard protocol can procure precontrast images, first-pass perfusion images with an initial Gd bolus, followed by a second Gd bolus and then, finally, the most important series – delayed imaging at about 10-20 minutes [3].

The underlying mechanism responsible for late Gd enhancement is postulated as follows: after being administered intravenously, the extracellular contrast agent Gd DTPA (diethylenetriamine penta-acetic acid) shortens the T1 relaxation times of irreversibly damaged myocardium, making it hyperintense (of higher MRI signal) in T1-weighted images. This is thought to be due to the fact that in acutely infarctioned myocytes, the ruptured membranes allow for Gd to pass intracellularly via diffusion. Conversely, chronic infarctions consist of scar tissue with greater interstitial space than normal myocardium – therefore, Gd would accumulate in greater volume within the scar [2].

Delayed Gd enhancement CMR is a highly sensitive method for detection of acute myocardial infarction (99%), as well as chronic infarction (94% sensitivity for a scar). The technique can demonstrate infarctions as small as 1 cubic cm, greatly outdoing other relevant imaging modalities. Unfortunately, the edematous border of acute infarctions is included in the total area of hypersignal, effectively slightly exaggerating the nonviable area. Despite that, delayed enhancement CMR is recognized as the reference standard for myocardial viability testing [14, 15, 16].

CMR angiography

Even though MRT is capable of performing angiography without exogenous Gd contrast, this flow-related enhancement method of imaging peripheral vessels is considered suboptimal for imaging the heart, which is in constant motion. Because of this CMR angiography is usually performed with intravenous Gadolinium, and based on a fast three-dimensional (3D) spoiled GRE sequence. Being a 3D sequence, it has no gaps inbetween slices and allows for multiplanar reformats of the obtained images. Additionally, this also allows for the construction of cast-like volume renderings of the contrasted vascular lumina and cardiac chambers – true 3D models. These can prove invaluable when evaluating congenital vascular diseases. [17, 18]

CONCLUSION:

CMR is a novel method, with a vast arsenal of imaging sequences, offering a great amount of diagnostic value, but also demanding a very thorough knowledge of the method's intricacies for optimal effect.

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