

Myocardial Tissue Characterization

Technical Foundations: How is it done?

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Even within the context of MRI, the term “myocardial tissue characterization” could encompass a wide variety of techniques. In this presentation, the focus will be entirely on those methods designed to evaluate myocardium based on magnetic resonance relaxation times T1 (pre- and post-contrast), T2, and T2*. These relaxation time constants that form the basis for image contrast in many pulse sequences can be sensitive indicators of pathological changes in the myocardium, as they are for most tissues of the body. While the basic concepts behind T1-, T2-, and T2*-weighted imaging of the heart have been in place for a number of years, there has been a recent resurgence of interest in techniques designed to quantify and map myocardial relaxation times on a pixel-by-pixel basis. These quantitative methods have led to improved techniques to evaluate global as well as regional changes in myocardial tissue. This talk will cover the basic techniques utilized for T1- and T2-weighted imaging of the heart, as well as more recently described methods for quantitative relaxation time parameter mapping.

Late Gadolinium Enhancement Imaging

It was recognized in animal experiments in the early 1980's that regions of infarcted myocardium demonstrated higher signal than viable tissue in T1-weighted spin echo images acquired several minutes after injection of gadolinium (Gd) contrast agent. This concept formed the basis for myocardial Late Gadolinium Enhancement (LGE) imaging [1] that has found widespread clinical application. Most Gd contrast agents behave similarly; they rapidly diffuse across the capillary membranes and into the interstitial space, but do not penetrate intact viable cell membranes. LGE imaging of the heart is typically performed from 5 to 30 minutes after contrast injection. During this time, the contrast agent reaches a quasi-equilibrium state, although with slow continual washout if no additional agent is infused. It has been shown that the equilibrium volume of distribution of Gd is higher in acutely necrotic myocardium and chronic scar tissue than in viable myocardium [2]. It is hypothesized that the density of intact cells in viable tissue leaves less space for the contrast agent to distribute than in regions of tissue containing ruptured cell membranes or collagenous scar. As a result, the relative concentration of Gd per gram of tissue is higher in necrotic and fibrotic regions than in viable myocardium [3]. The T1 shortening effect of Gd is proportional to concentration, thus regions of myocardium with higher Gd concentration exhibit a shorter T1 and appear brighter on T1-weighted images. Myocardial pre-contrast T1 is approximately 977 ms; 15 minutes after injection of 0.15 mmol/kg Gd, the T1 of viable myocardium is approximately 500 ms, while the T1 of infarcted myocardium is typically less than 400 ms [4], although these values vary depending on dose and the time elapsed since injection [5]. This T1 difference is the basic mechanism exploited by the LGE technique to differentiate non-viable from viable myocardial tissue.

The basic pulse sequence strategy followed for the past 15 years is to use inversion recovery (IR) to maximize the T1-based contrast between viable and non-viable myocardium [6]. By adjusting the inversion time to null viable myocardium, high image contrast is created between dark, viable tissue, and bright, non-viable tissue. This is the basic concept behind all of the variety of pulse sequences used for myocardial LGE imaging. Since high image contrast depends on accurate setting of inversion time (TI), pulse sequences have been designed to assist in determining the correct TI for optimal contrast [7]. Alternatively, phase-sensitive image reconstruction (PSIR) generates an image with contrast much less sensitive to inversion time setting [8]. These methods are finding routine use in clinical practice where the imaging technologist may not have the time or experience to optimize TI by trial and error.

The most commonly employed pulse sequence is a segmented, inversion recovery, spoiled gradient echo acquisition, typically collecting one image over a short 10 – 16 heartbeat breath-hold [6]. A multitude of variations on this theme are possible, including segmented 3D, single-shot 2D, navigator respiratory gating, parallel imaging, and steady-state free precession (SSFP) readout. The details of these acquisition methods and the advantages and disadvantages of each will be discussed in detail in the presentation. Arguably the most important of these sequence variations is the single-shot IR-SSFP technique [9, 10]. Because it is a single-shot acquisition, this method is insensitive to respiratory motion artifacts and cardiac arrhythmia, both of which can cause severe artifacts in the standard, 2D segmented k-space acquisition. Single-shot imaging, however, comes at the cost of reduced spatial and temporal resolution, and SNR. 3D sequences with navigator gating have also found clinical application in situations where thin slices and high spatial resolution are desired. Delayed-enhancement has also been successfully demonstrated at 3.0 Tesla, with improved SNR compared to 1.5T [11].

Despite the widespread clinical success of this method of viability imaging, several pitfalls and artifacts remain. For example, a bright blood-pool can obscure sub-endocardial infarcts [12]; dark regions of “no-reflow” may be mistaken for viable tissue; partial volume effects may result in ambiguous contrast; bright epicardial or intra-myocardial fat may be confused with infarcted tissue [13]; surface coil intensity variations can contaminate tissue contrast. These issues continue to motivate technical development efforts to create improved pulse sequences.

One of the more important recent advances in LGE imaging is the development of practical methods for pixel-wise mapping of T1 values [14-16]. While conventional LGE sequences are highly accurate for detection of focal regions of infarction or scar, diffuse fibrosis may be difficult to visualize. T1-mapping has been used to detect global changes in myocardial tissue that may accompany, for example, hypertrophic cardiomyopathy and other conditions [17]. T1-mapping and other recent successful LGE pulse sequences and problem-solving strategies will be discussed.

T2 Imaging

The basic discovery that T2 increases with acute myocardial infarction was made in the early 1980's, not long after cardiac MRI became feasible. This finding is consistent with other tissues in the body, where acute injury leads to tissue edema, increased free water, and an elevated T2. Similar to LGE, early techniques were based on a gated spin echo acquisition; this sequence is highly sensitive to motion and therefore image quality is unreliable. In the mid-1990's, the advent of turbo spin echo (TSE) imaging reduced the scan time down to a reasonable breath-hold, thereby avoiding respiratory motion artifact. Combining the turbo spin echo readout with a double-inversion or "black-blood" preparation pulse suppressed residual artifacts caused by slow flowing blood [18]. A third inversion pulse with short inversion time (STIR) can be included to suppress fat and enhance sensitivity to fluid. While these strategies have been used successfully to generate high quality, black-blood, anatomical images of the heart and great vessels for many years, there are a number of pitfalls and limitations encountered when attempting to utilize this technique to detect edematous myocardium. Regions of myocardium may appear bright (or dark) depending on motion and timing of the acquisition relative to the cardiac cycle; regional intensity variations caused by local surface coils can mimic T2 enhancement; inadequate blood nulling can give the appearance of sub-endocardial signal enhancement. These and other issues have prevented T2-weighted imaging of myocardial edema from gaining widespread clinical usage, despite the important, unique information it could potentially provide.

Several techniques have been proposed over the past few years to address the limitations of black-blood, T2-weighted TSE, including bright blood techniques such as ACUTE [19] and T2-prepared SSFP [20]. The latter has been extended to create a robust method of myocardial T2-mapping [21] that is relatively insensitive to motion and addresses several of sources of artifact in black-blood TSE. While additional validation studies are still needed, initial studies have shown T2 mapping to be more sensitive than STIR in the detection of edema associated with acute myocardial infarction [22] and myocarditis [23].

T2* imaging

T2* is affected by local (microscopic) static field inhomogeneities such as those caused by intracellular iron stores. Quantitative T2* mapping has been utilized for over a decade as a reliable method of assessing myocardial iron overload, a problem found in patients with iron storage diseases [24]. The multi-echo, gradient echo technique [25] has been successfully used to direct therapy in patients with thalassemia major. The details of this pulse sequence will be described.

In summary, techniques have been used for a number of years to characterize pathological changes in myocardial tissue based on T1, T2, and T2* relaxation times. Most recently, practical methods for quantitative mapping of these parameters have been developed and are beginning to show advantages over traditional imaging sequences.

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