

Free-Breathing 3 T Magnetic Resonance T_2 -Mapping of the Heart

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OBJECTIVES This study sought to establish an accurate and reproducible T_2 -mapping cardiac magnetic resonance (CMR) methodology at 3 T and to evaluate it in healthy volunteers and patients with myocardial infarct.

BACKGROUND Myocardial edema affects the T_2 relaxation time on CMR. Therefore, T_2 -mapping has been established to characterize edema at 1.5 T. A 3 T implementation designed for longitudinal studies and aimed at guiding and monitoring therapy remains to be implemented, thoroughly characterized, and evaluated in vivo.

METHODS A free-breathing navigator-gated radial CMR pulse sequence with an adiabatic T_2 preparation module and an empirical fitting equation for T_2 quantification was optimized using numerical simulations and was validated at 3 T in a phantom study. Its reproducibility for myocardial T_2 quantification was then ascertained in healthy volunteers and improved using an external reference phantom with known T_2 . In a small cohort of patients with established myocardial infarction, the local T_2 value and extent of the edematous region were determined and compared with conventional T_2 -weighted CMR and x-ray coronary angiography, where available.

RESULTS The numerical simulations and phantom study demonstrated that the empirical fitting equation is significantly more accurate for T_2 quantification than that for the more conventional exponential decay. The volunteer study consistently demonstrated a reproducibility error as low as $2 \pm 1\%$ using the external reference phantom and an average myocardial T_2 of 38.5 ± 4.5 ms. Intraobserver and interobserver variability in the volunteers were -0.04 ± 0.89 ms ($p = 0.86$) and -0.23 ± 0.91 ms ($p = 0.87$), respectively. In the infarction patients, the T_2 in edema was 62.4 ± 9.2 ms and was consistent with the x-ray angiographic findings. Simultaneously, the extent of the edematous region by T_2 -mapping correlated well with that from the T_2 -weighted images ($r = 0.91$).

CONCLUSIONS The new, well-characterized 3 T methodology enables robust and accurate cardiac T_2 -mapping at 3 T with high spatial resolution, while the addition of a reference phantom improves reproducibility. This technique may be well suited for longitudinal studies in patients with suspected or established heart disease. (J Am Coll Cardiol Img 2012;5:1231–9)   2012 by the American College of Cardiology Foundation

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The T₂ relaxation time is a physiological tissue property that can be exploited with cardiac magnetic resonance (CMR) to generate contrast between healthy and diseased tissues. This contrast is mainly caused by the dependency of the T₂ value on the relative amount of free water (1). Edema is part of the tissue response to acute injury and affects this free water content. Therefore, T₂ changes have been reported in edematous regions in patients with infarction (2),

See page 1240

hemorrhage (3), graft rejection (4), or myocarditis (5). In recent years, *qualitative* T₂-weighted CMR has therefore gained considerable interest. However, the traditional dark-blood T₂-weighted fast spin echo (FSE) pulse sequence that is used for this

purpose is limited because of its motion sensitivity and subsequent risk for misinterpretation of the images. Simultaneously, a *quantitative* characterization of the tissue is not easily possible and image interpretation remains subjective. Therefore, a more objective, quantitative, and motion-insensitive technique is required. In response to this strong need, initial T₂-prepared variants of balanced steady-state free precession sequences have been proposed for quantitative T₂-mapping at 1.5 T (6). Using such methods, the successful differentiation between edematous and healthy tissue after myocardial infarction has been demonstrated (7), and an improved performance relative to conventional FSE imaging was reported in both patients with edema after myocardial infarction (8) and acute inflammatory cardiomyopathies (9).

The availability of a quantitative, accurate, and highly reproducible T₂-mapping methodology at 3 T would be of great importance for the use in longitudinal studies aimed at monitoring and guiding therapy, because a T₂ value measured within a specific target area could act as its own control measurement. However, to our knowledge both the accuracy and reproducibility of T₂-mapping have not been ascertained. For these reasons, we have developed and tested a free-breathing T₂-mapping technique at 3 T that incorporates radial gradient echo (GRE) image acquisition and adiabatic T₂ preparation (T₂prep-GRE). Bloch equation simulations were performed to optimize both sequence parameters and the analysis procedure. The resultant magnetic resonance methodology was then

validated in vitro. Quantitative results were compared with those of a gold-standard spin-echo T₂-mapping sequence to determine the accuracy of the T₂ measurements. The reproducibility of the technique was then investigated in healthy volunteers, both in separate scanning sessions and with and without a T₂ reference phantom positioned in the field of view. Using this setup, the hypothesis was tested that the use of a reference phantom improves reproducibility of the T₂-mapping. Finally, the thus-optimized and characterized methodology was applied to test the ability to discern healthy from diseased myocardium in patients with established subacute myocardial infarction.

METHODS

Numerical simulations. The goal of these simulations was to maximize the amount of signal per unit time while establishing optimal fit parameters to increase the accuracy of the T₂ measurement. Therefore, a numerical simulation of the Bloch equations (10) was performed using Matlab (The Mathworks, Natick, Massachusetts). Simulation parameters included myocardial relaxation times T₂ = 45 ms and T₁ = 1,470 ms (11) at 3 T; a segmented k-space radial GRE acquisition with a repetition time (TR) of 7.6 ms and an echo time (TE) of 2.8 ms; a navigator delay of 40 ms; and incremental T₂prep durations (TE_{T2prep}) of 0, 30, and 60 ms for T₂ fitting. The average transverse magnetization (M_{xy}) of radial readouts during 27 heartbeats was then considered representative for the resultant M_{xy} for a given T₂prep duration. To determine the fitting equation that leads to highest accuracy, the magnetization M_{xy} for 3 TE_{T2prep} values was fitted with both a standard exponential decay and an empirical equation:

$$M_{xy}(TE_{T2prep}) = M_0 \left[e^{\frac{-TE_{T2prep}}{T_2}} + \delta \right] \quad [1]$$

where M₀ refers to the longitudinal magnetization at TE_{T2prep} = 0 and δ is an empirical offset that accounts for T₁ relaxation. Independent variables that were used to study the quality and robustness of the fit and to maximize M_{xy} included heart rate, radiofrequency excitation angle (α), the number of acquired radial profiles in k-space per heartbeat and the number of RR intervals between acquisition trains. After having selected the parameter set that led to a maximum M_{xy}, the range of stability of the T₂ fitting algorithm was determined for both the

ABBREVIATIONS AND ACRONYMS

CI	= confidence interval
CMR	= cardiac magnetic resonance
FSE	= fast spin echo
GRE	= gradient echo
STEMI	= ST-segment elevation myocardial infarction
T ₂ prep	= T ₂ preparation module
TE	= echo time
TE _{T2prep}	= T ₂ prep duration
TI	= inversion time
TR	= repetition time

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