T1 and T2 Quantification for short T2 tissues: Challenges and Solutions

M. Carl[1], J. Du[2], J-T. Chiang[2], E. Han[1], and C. Chung[2]
[1]GE Healthcare, Waukesha, WI, United States, [2]University of California, San Diego

Introduction: The relaxation properties T_1 and T_2 of MRI images are important parameters in assessment of pathology. Many musculoskeletal (MSK) tissues (cortical bone, tendon, ligaments, etc) have very short transverse relaxation times and require specialized pulse sequences such as UTE for optimal signal acquisition and quantification [1]. UTE imaging of MSK tissues can pose unique challenges for the quantification of the longitudinal or transverse relaxation. We describe these challenges and offer simple solutions to help overcome them.

Theory: T_2 quantification: UTE imaging is based on a radial acquisition (followed by magnitude reconstruction) in which the number of radial spokes is often undersampled in the interest of scan-time reduction. However, such angular undersampling results in smearing and streaking of the aliased signal intensity across the entire image [2], therefore creating a background "haze". Near the MSK tissues of interest there are often a variety of other structures containing long T_2 tissues. Some of the aliased signal of such long T_2 tissues may therefore enter the region of interest (ROI) of the short T_2 tissues. This can lead to a non-zero signal offset even for TEs that are long compared to the relaxation times of the short T_2 tissues, and therefore can result in a systematic overestimation of T_2, if this background "haze" is not accounted for in the exponential fitting model.

T_1 quantification: Due to the rapid transverse relaxation during the RF pulse, the magnetization vector of short T_2 tissues does not rotate through the presumed flip angle, but is given by Eq.[1]. Since Eq.[1] requires a priori knowledge of T_2, T_1 quantification using saturation-recovery or inversion recovery sequences are impractical for short T_2 tissues in MSK. Instead, T_1 measurements may be performed using UTE imaging with short RF duration τ (resulting in low flip angles) so that the T_2 decay during the RF pulse can be assumed negligible and Eq.[1] reduces to the classical SPGR equation. The signal intensity measured at variable TR can then be used fit T_1.

$$S = S_0 \frac{\theta(1-E_1)\exp\left(-\frac{\tau}{2T_2}\right)\sin\left(\sqrt{\theta^2-\frac{\tau^2}{4T_2^2}}\right)}{\sqrt{\theta^2-\frac{\tau^2}{4T_2^2}}\left\{1-E_1\exp\left(-\frac{\tau}{2T_2}\right)\left[\cos\left(\sqrt{\theta^2-\frac{\tau^2}{4T_2^2}}\right)+\frac{1}{2\sqrt{\frac{\theta^2T_2^2}{\tau^2}-\frac{1}{4}}}\sin\left(\sqrt{\theta^2-\frac{\tau^2}{4T_2^2}}\right)\right]\right\}} \Rightarrow \tau \to 0 \Rightarrow \quad S = S_0\frac{(1-E_1)\sin\theta}{1-E_1\cos\theta} \qquad with \quad E_1 = \exp\left(-\frac{TR}{T_1}\right) \qquad (1)$$

Experiments: T_2 quantification: The experimental setup shown in Fig.1 was used to study T_2 quantification in the presence of aliasing. A test tube containing water doped with $MnCl_2$ ($T_2 \approx 0.6$ ms) was partially inserted into a rectangular mesh structure filled with ordinary water (long T_2). The purpose of the mesh was to create fine spatial structures, since angular undersampling in radial imaging is most severe at the edge of k-space, resulting predominantly in aliasing of high spatial frequencies. Two cross-sectional slices were imaged at variable TEs, one within the mesh structure (Fig.2a), and the other in a region of the test tube without the mesh (Fig.2b). The signal intensities measured in ROIs within the test tube are plotted vs. TE in Fig.3. Shown for both slices are the results of severely undersampled and fully sampled UTE images, using exponential fitting with and without an offset model. The measured values of T_2 are summarized in Table I.

T_1 quantification: Two test tubes (tube #1 with $T_2 \approx 2.7$ ms, tube #2 with $T_2 \approx 18$ ms) were placed side by side and imaged using UTE at variable TRs. Four different hard RF pulse were used to study the effects on their pulse duration τ and flip angle θ. The MR signal intensities for the four pulses are plotted in Fig.4 vs. TR, while the measured values of T_1 are summarized in Table II.

Discussion: The data in Fig.3 shows that aliasing of surrounding long T_2 water signal can cause a nonzero signal offset (prominent in Fig.3b), which is absent (or reduced to the noise floor) when no surrounding long T_2 tissues are present (Fig.3a,c). Table I shows that especially the undersampled measurement within the surrounding water-filled mesh yields a significant overestimation of T_2. However, when a signal offset was incorporated into the fitting model, the obtained T_2 values were far more consistent. Table II shows that short T_2 tissues can lead to a systematic underestimation of T_1 due to T_2 decay during RF excitation. Only if the RF duration is short compared to T_2, as is the case for tube #1 using the 24µs RF pulse and for tube #2 approximately also for the longer RF pulses, Eq.[1] reduces to the classical SPGR signal equations which does not require knowledge of T_2. Table II also shows that for a given RF duration, the T_1 deviation increases for higher flip angles. A potential drawback of T_1 measurements using low flip angles is that it reduces dynamic range of T_1 recovery, and is more sensitive to B_1 inhomogeneities.

References: [1] Robson MD, et al. J Comput Assist Tomogr 2003;**27**:825–846 [2] Scheffler K, et al. MRM **40**:474-480 (1998)

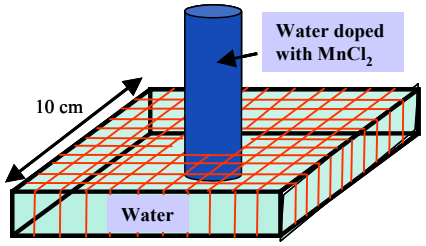

Fig.1: Experimental setup to study aliasing effects in radial imaging for T_2 quantification.

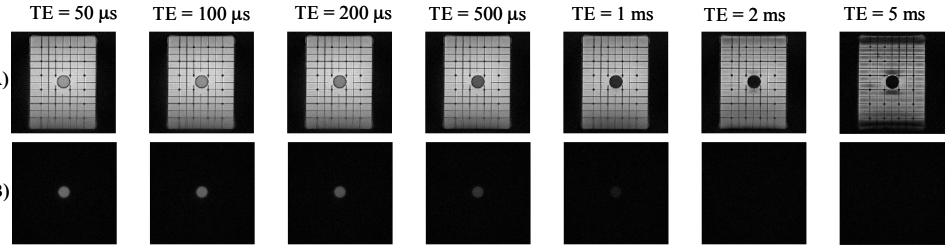

Fig.2: 256 by 256 UTE images at different TE's. A) Cross-sectional slices through test tube and water bath. B) Cross-sectional slices through test tube only.

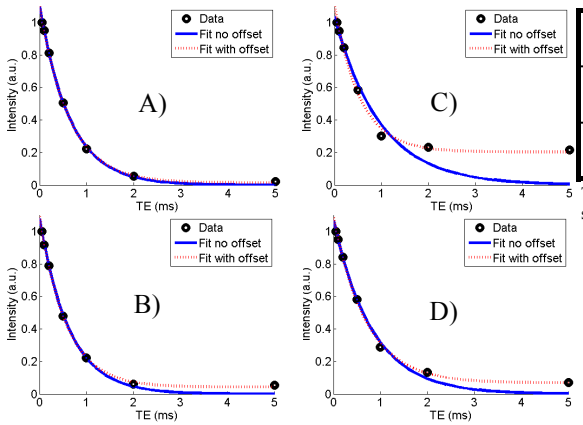

Fig.3: Experimental T_2 fitting curves. A) Severely undersampled (51 spokes) test tube surrounded by air. B) Nyquist sampled (801 spokes) test tube surrounded by air. C) Severely undersampled test tube surrounded by water. D) Nyquist sampled test tube surrounded by water.

T2	Air: 51 spokes	Air: 801 sp.	Water: 51 sp.	Water: 801 sp.
w/o offset	0.64 ms	0.63 ms	0.99 ms	0.79 ms
w offset	0.62 ms	0.56 ms	0.57 ms	0.69 ms

Table I: Measured values of T_2 for the experimental data shown in Fig.3 with columns in order of A)→D).

T1	θ = 5° τ = 24µs	θ = 5° τ = 1ms	θ = 30° τ = 1ms	θ = 60° τ = 1ms
#1	126 ms	99 ms	47 ms	42 ms
#2	362 ms	318 ms	300 ms	290 ms

Table II: Measured values of T_1 for data shown in Fig.4.

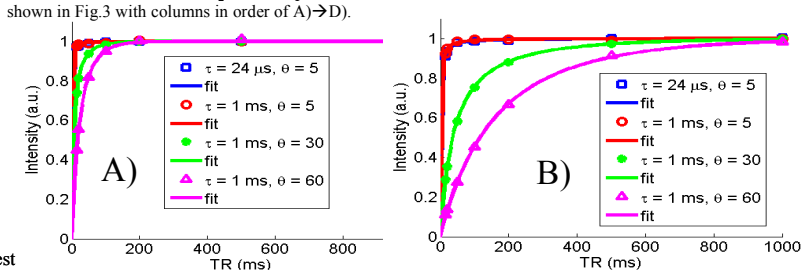

Fig.4: Experimental T_1 fitting curves for different RF pulses. A) Short T_2 phantom (#1) with $T_2 \approx 2.7$ ms. B) Longer T_2 phantom (#2) with $T_2 \approx 18$ ms.