T2 contrast due to signal decay during radial readout in UTE (ultrashort TE) sequences

J-T. Chiang[1], M. Carl[2], J. Du[1], M. Bydder[1], N. Szeverenyi[1], R. F. Mattrey[1], and G. Bydder[1]
[1]Radiology, University of California, San Diego, CA, United States, [2]GE Healthcare

Introduction: When imaging short T2 tissues using ultrashort TE (UTE) pulse sequences, significant T2 decay can occur during radial readout for T2s comparable or less than the readout duration (typically ~1 ms). One consequence is decreased image resolution, termed T2 blurring [1,2]. Another is signal amplitude loss in the image [2]. Here, we study the relationship between T2 and the amount of such signal amplitude loss – i.e. T2 contrast due to signal decay during radial readout in UTE.

Results and discussion: T2 decay during UTE's radial readout can be described as a radially symmetric multiplicative filter $H(k_r)$ on the 2D or 3D k-space signal (Equation 1), where k_r is the (radial) magnitude in k-space, *slew* is the gradient slew rate, G_{max} is the maximal constant gradient, and k_{ramp} is the value of k_r at which gradient ramping ends and G_{max} is reached (note therefore that the effects of the gradient ramp are explicitly included). The effects of $H(k_r)$ on any acquired k-space signal $S(\vec{k})$ can then be examined by obtaining the final image $S(\vec{r})$ via the Fourier transform in Equation 2 (the step function Π(x) is used to account for termination of sampling at k_{max}, where Π(x)≡1 if |x|<1/2 and Π(x)≡0 otherwise).

$$H(k_r) \equiv \begin{cases} e^{-\sqrt{\frac{4\pi|k_r|}{\gamma \cdot slew}}\frac{1}{T2}} & for\ |k_r| \le k_{ramp} \\ e^{-\left[\sqrt{\frac{4\pi|k_{ramp}|}{\gamma \cdot slew}}\frac{1}{T2}+\frac{2\pi\left(|k_r|-k_{ramp}\right)}{\gamma \cdot G_{\max}}\frac{1}{T2}\right]} & for\ |k_r| > k_{ramp} \end{cases} \quad \text{(Equation 1)}$$

$$S(\vec{r}) = \mathrm{FT}\left[H(k_r)\cdot\Pi\left(\frac{k_r}{2k_{\max}}\right)\cdot S(\vec{k})\right] \quad \text{(Equation 2)}$$

We modeled the effects of $H(k_r)$ at differing T2 values on radially symmetric 2D disks, whose k-space representations are given by $S(k_r) = radius \cdot J_1(2\pi \cdot radius \cdot k_r)/k_r$, where J_1 denotes Bessel function of the first kind. In Figure 1, both $H(k_r)\cdot\Pi(k_r/2k_{\max})\cdot S(k_r)$ in k-space and the image $S(r)$ are plotted for three disks of different radii at multiple T2s. With shorter T2s, there is greater filtering by $H(k_r)$ in k-space and consequently more signal amplitude loss in image space. Of note, because $S(k_r)$ for larger disks are distributed more towards k-space center, they are less affected by $H(k_r)$ and experience less signal amplitude loss in image space. T2 contrast curves for these disks (center pixel signal amplitude versus $\log_{10}$[T2]) over a continuous range of T2s from 10μs to 100ms is given in Figure 2. These curves demonstrate high contrast in T2s ranging from ~100μs to ~1ms, depending on the exact disk size. Additionally, note also that signal amplitude becomes relatively limited in the sub-100μs range, especially for smaller disks.

Since $H(k_r)$ depends on *slew* and G_{max}, we also simulated the effects of varying these gradient parameters. The resulting T2 contrast curves are given in Figure 3. In general, increasing G_{max} leads to less T2 decay (due to faster readout durations). However, this trend is limited by ramp sampling and the gradient slew rate, and there is an upper limit beyond which further increases in G_{max} will not affect the T2 contrast curve. For slew rates of 70 mT/m/ms and 200 mT/m/ms, this limit occurs at G_{max} ~ 5mT/m and ~ 10mT/m, respectively. For a hypothetical slew rate of 1000 mT/m/ms (not clinically applicable), this limit occurs at G_{max} ~ 40mT/m.

Preliminary experimental validation of the numerical simulation results were performed using cylindrical $MnCl_2$ solution phantoms imaged with 2D UTE sequences containing nonselective 24μs hard pulse excitations to create a projection image through the cylindrical axis. Figure 4 contains signal amplitudes from cylindrical phantoms of multiple T2's and two different radii. Figure 5 contains signal amplitudes from phantoms of the same radii but different T2's, and scanned at different G_{max} values. These measurements demonstrate good agreement with the theoretical T2 contrast curves determined by numerical simulations.

Conclusions: T2 contrast in UTE imaging does not simply follow $e^{-TE/T2}$. Additional T2 contrast is generated by decay during excitation [3], as well as by T2 decay during radial readout as presented above. An interesting feature of T2 contrast due to decay during readout is the dependence on object size, larger objects with more central k-space signals experience less T2 decay during readout since UTE employs a radial center-out k-space trajectory. Additionally, there is dependence on gradient parameters such that increasing values of G_{max} lead to increased signal amplitudes, but only until the gradient slew rate becomes limiting. Overall, T2 decay during radial readout is an important source of T2 contrast in UTE imaging, with significant dependencies on object size, as well as the gradient parameters.

References: [1] Haacke, et.al. Magnetic Resonance Imaging (1999); [2] Rahmer, et. al. MRM. 55:1075–1082 (2006); [3] Carl, et. al. ISMRM p.2581 (2009).
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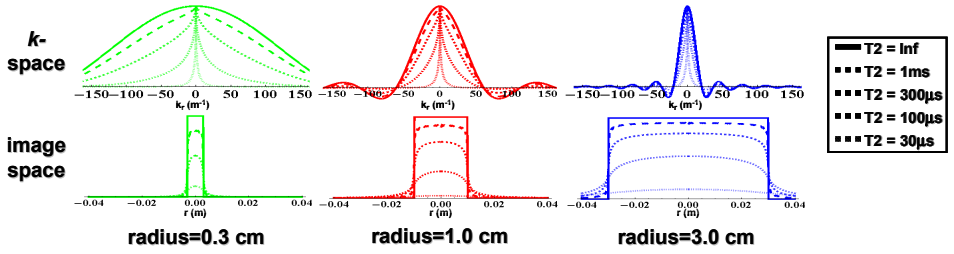

Fig 1 Radial representations of 2D k-space signals and corresponding images for disks of radii 0.3cm, 1.0cm, and 3.0 cm at multiple T2s. The k-space and image space plots correspond to $H(k_r)\cdot\Pi(k_r/2k_{\max})\cdot S(k_r)$ and $S(r)$, respectively, from Equation 2. Other parameters: G_{max} = 40mT/m, *slew* = 70 mT/m/ms, and k_{max} = 1300. Note the k-space signal is only partially displayed to emphasize the effects in k-space center.

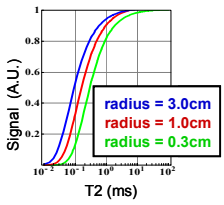

Figure 2 – T2 contrast curves of center pixel signal amplitude versus $\log_{10}$[T2] of the disks in Figure 1.

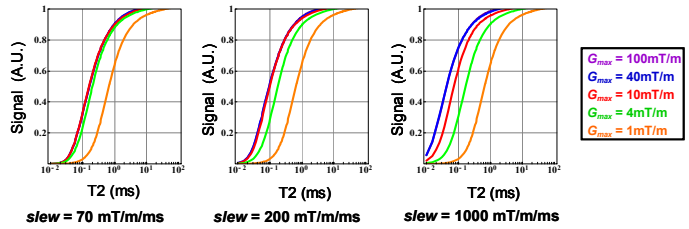

Fig 3 – T2 contrast curves with varying G_{max} and *slew*, with k_{max} = 1300 and radius=1.0cm. 1000 mT/m/ms is not a clinically applicable slew rate, but is included for theoretical considerations. Note that the G_{max}=10, 40 and 100 mT/m curves overlie one another in the *slew* = 70 and 200 mT/m/ms plots, as do the G_{max}= 40 and 100 mT/m curves in the *slew* = 1000 mT/m/ms plot.

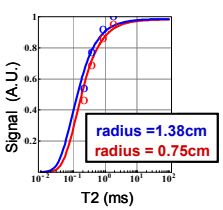

Fig 4 – Signal amplitudes of $MnCl_2$ phantoms with T2s 231, 398, 870, 1900μs and radii 0.75cm and 1.38cm, compared to T2 contrast curves from simulation.

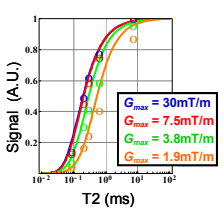

Fig 5 – Signal amplitudes of $MnCl_2$ phantoms with T2s 87us, 208us, 304us, 660us, and 7.7ms at varying G_{max}, compared to T2 contrast curves from simulation.