Effects of diffusion on high resolution quantitative T2 MRI

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Target Audience: Those interested in understanding and reducing the effects of diffusion on high resolution imaging.

Purpose: The imaging and spoiler gradients in any pulse sequence act as diffusion sensitizing gradients. In most clinical applications the resolution is low enough that the effect of diffusion is negligible. The large gradients required by high resolution imaging (1.0mm x 1.0mm voxels or smaller) can cause a significant loss of SNR due to diffusion. In the case of multi-echo quantitative T2 (qT2) the diffusion effect increases with each echo, distorting the T2 decay curve and decreasing the apparent T2. The purpose of this work was to discover the resolution at which the effects on T2 become non-negligeable, and to reduce the problem by implementing a qT2 sequence with fully refocused readout gradients, similar to that used in NMR microscopy[1].

Methods: All MR experiments were conducted on a 7T Bruker BioSpin MR scanner using a 3cm solenoid coil. Spinal cord samples were obtained from a male Sprague Dawley rat. qT2 measurements used slice selective excitation, and composite $(90_x180_y90_x)$ refocusing pulses. TE 6ms, TR 3s, 128 echoes, $0.12 \times 0.12mm^2$ voxels, 1.0mm slice thickness, equally sized spoiler gradients 1.14 ms at 468 mT/m resulting in a b value of $15s/mm^2$ per echo. Images were acquired both perpendicular and parallel to the spinal cord. Analysis was done using a non-negative least squares algorithm. Phantoms consisted of $MnCl_2$ doped water, imaged using TE 10ms, TR 3s, 128 echoes, 4mm slice thickness, and $0.1 \times 0.1mm^2$, $0.25 \times 0.25mm^2$, and $0.5 \times 0.5mm^2$ in plane resolution with both the original and fully-refocused readout sequences. Both equally sized, and linearly decreasing spoiler gradient schemes were used, where $b=10s/mm^2$ for the initial spoiler, decreasing by 1/200 per echo in the decreasing spoiler scheme.

Results:
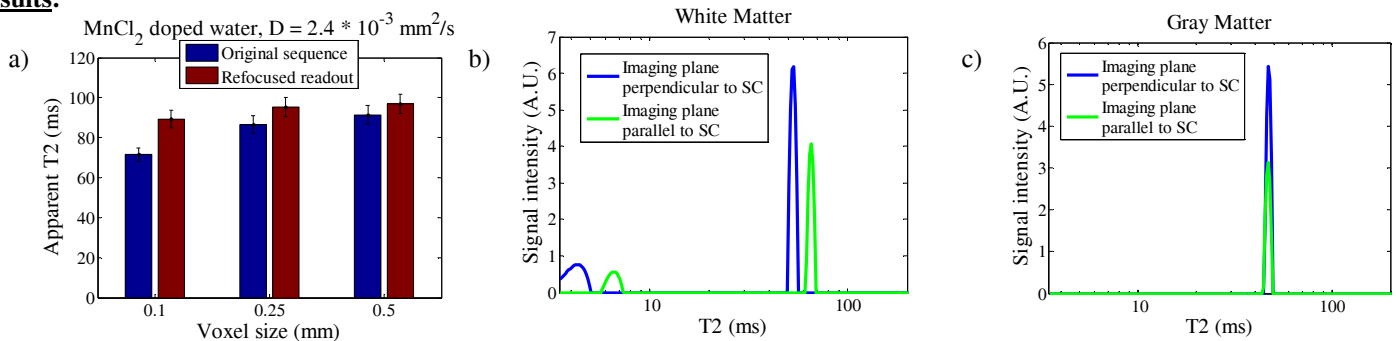
In an $MnCl_2$ doped water phantom, decreasing voxel size resulted in decreased apparent T2, this effect was reduced by using fully refocused readout gradients (a). Measured T2 values in white matter depended on the orientation of the imaging plane (b). Orientation did not affect the gray matter T2 values (c). Measuring the $MnCl_2$ doped water phantom with a decreasing spoiler gradient scheme, bi-exponential decay curves with a short T2 component comparable to those seen in white matter were noted in 11% of voxels.

Discussion: Measured T2 decreases with voxel size, and this effect becomes noticeable as voxel size decreases below $0.5 \times 0.5mm^2$. Fully refocused imaging gradients mitigate the problem, resulting in measured T2 values within 5% of actual T2 at a resolution of $0.05 \times 0.05mm^2$. Imaging slice orientation affected measured T2 only in anisotropic tissue in the presence of overly large spoiler gradients. If equally sized spoiler gradients are used to bracket each refocusing pulse, the diffusion contribution is linear with echo number and the effects of diffusion can be corrected for with a simple equation:

$$\frac{1}{T2_{app}} = \frac{1}{T2} + \frac{bD}{TE}$$, where T2 is the actual T2, $T2_{app}$ the apparent T2, D the apparent diffusion coefficient and TE the echo time.

Decreasing spoiler gradients schemes, as recommended by Poon & Henkelman[2], result in non- linear diffusion effects and a decay curve which is no longer a sum of exponentials. This invalidates the model typically used for analysis, resulting in an overestimation of myelin water fraction and precluding simple correction. A similar effect is seen when non-linear echo time spacing is used[3].

Conclusion: Diffusion due to readout gradients begins to have a noticeable effect on qT2 when voxel size decreases below $0.5 \times 0.5mm^2$. The use of fully refocused gradients reduces this threshold to $0.05 \times 0.05mm^2$. Anisotropic diffusion results in orientation dependent measures of T2. Equally sized spoiler gradient schemes can be corrected for mathematically. Decreasing spoiler gradient schemes, required for slice selective refocusing pulses, affect qT2 non-linearly and can result in an overestimation of myelin water fraction. Gradient strengths required to affect measured T2 are very large, however they are achievable using the latest technology.

References: 1. Hsu EW, Schoeniger JS, Bowtell R, et al. A modified imaging sequence for accurate T2 measurement using NMR microscopy. J Magn Reson B. 1995;109:66-69.

2. Poon CS, Henkelman RM. Practical T2 quantitation for clinical applications. J Magn Reson Imaging. 1992;2(5):541-53.

3. Does MD, Gore JC. Complications of nonlinear echo time spacing for measurement of T2. NMR Biomed. 2000;13(1):1-7.