

Optimisation of T_2^* imaging for the investigation of white-matter MS lesion heterogeneity

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Introduction: White-matter (WM) MS lesions are visible on MRI scans at conventional field strength and so MR is often used to diagnose and monitor patient progression. However, the poor correlation between MR findings and patient symptoms highlights the need to advance the study of these lesions *in vivo*. In particular, there is considerable interest in the heterogeneity of WM lesions. Post-mortem studies of these lesions have shown a close spatial relationship to parenchymal blood vessels¹, but the study of this *in vivo* is limited at conventional field strength by the difficulty in demonstrating both lesions and small vessels on one MR image. However, the decrease in T_2^* at ultra-high field (7T) allows us to acquire T_2 -weighted images with enhanced susceptibility contrast and high SNR compared to conventional field strength, aiding the detection of these small blood vessels². In order to obtain an accurate picture of the relationship between vessels and lesions, it is essential to determine and implement optimum scanning parameters for the detection of these vessels. It is also important to know the minimum size of a vessel that can be detected using T_2 -weighted imaging. In this work, we simulate the susceptibility effect around a vessel at different orientations in the B_0 field. We predict optimum echo times for the detection of vessels at both 3T and 7T for T_2 -weighted magnitude and phase images, and susceptibility-weighted images (SWI)³. We calculate the size of the smallest detectable vessel at both field strengths and demonstrate the benefits of ultra-high field.

Theory: Modelling a vessel as a cylinder of infinite length with radius r_v , the change in resonant frequency for a spin inside a vessel oriented at θ° to the B_0 field can be calculated by⁴: $d\omega = (dX/2)\omega_0(\cos^2\theta - 1/3)$. For a spin outside the vessel, at a position r, ϕ from the centre of the vessel, the change in frequency will be given by: $d\omega = (dX/2)\omega_0(r_v/r)^2 \sin^2\theta \cos(2\phi)$. The total signal within a voxel containing a vessel can then be calculated by summing the contributions from all individual spins: $S_v = (S_0/N) \sum \exp(i d\omega TE) \exp(-TE/T_2)$ whereas the signal from a voxel that does not contain a vessel can be simply calculated by: $S_n = S_0 \exp(-TE/T_{2,WM})$. For a vessel to be considered detectable, we have assumed that the difference in signal caused by the vessel must be greater than twice the standard deviation of the noise. This gives a threshold of $(S_n - S_v)/S_n > 2/SNR$.

Methods: 3T scans were acquired using a Philips Acheiva 3.0 T system with a whole-body gradient set, whole-body transmit coil and 8-channel SENSE rf receive coil. Scanning at 7T was performed using a Philips Acheiva 7.0 T scanner with whole-body gradient set, head-only transmit coil and NovaMedical 16-channel SENSE rf receive coil. The study received approval from the local ethics committee and all subjects gave their informed consent. T_2^* images were acquired using a 3D gradient-echo acquisition, with flip angle 14° over a $192 \times 164 \text{ mm}^2$ FOV in 4 stacks, each with 50 slices at 7T and 32 at 3T, using a 150-ms TR. Voxel sizes were 0.8 mm isotropic at 3T and 0.5 mm isotropic at 7T as these were the minimum size to give reasonable SNR in acceptable imaging time. SNR in WM was measured at both 3T and 7T and corrected for sensitivity encoding⁵. The predicted signal in a voxel with and without a vessel was then simulated using the theory outlined above. The standard deviation of the noise in the phase images was estimated to be the inverse of the SNR in the magnitude image³. Susceptibility-weighted images were created and simulated by applying a high-pass filter to the phase information which was then raised to the power 4 before being multiplied by the magnitude image³. The contrast-to-noise ratio (CNR) between a voxel containing a vessel and a voxel containing WM only was calculated according to Haacke et al³ and the vessel was deemed to be detectable if the CNR was greater than 2. The smallest detectable vessel was calculated as a function of TE in magnitude and SWI images at 3 and 7T, taking into account vessel orientation (θ).

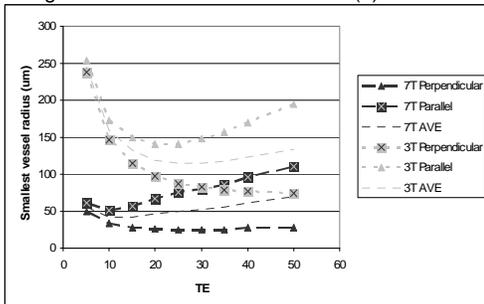


Figure 1 – Size of detectable vessels perpendicular and parallel to B_0 field in magnitude images as a function of TE

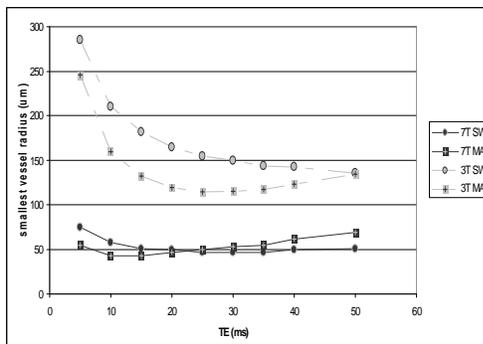


Figure 2 – Detectable vessel radii in magnitude and susceptibility-weighted images as a function of TE

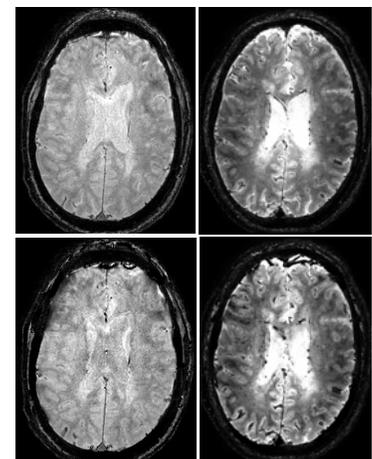


Figure 3 – modulus images at A) 3T and B) 7T and SWI at C) 3T and D) 7T

Results: Figure 1 shows the smallest vessel (radius) detectable for a given TE in magnitude T_2^* -weighted images. The simulations show the optimum echo times to be 25 ms at 3T and 15 ms at 7T. The radii of the smallest detectable vessels in the magnitude images are then predicted to be 141 and 87 μm at 3T (for $\theta = 0^\circ$ and 90° , respectively) and 56 and 28 μm at 7T. However, application of these echo times at 3T resulted in low SNR (making lesion detection difficult) and prohibitively long scan times. A TE of 20 ms was chosen in order to reduce scan time and maintain SNR. Using this TE, the smallest detectable vessels are predicted to have radii 141 and 97 μm . The TE at 7T was extended to 20 ms in order to increase the contrast between WM and lesions, giving vessel radii 67 and 26 μm . Figure 2 shows detectable vessel radii as a function of TE for magnitude and susceptibility-weighted images (average of parallel and perpendicular orientations). Figure 3 shows example magnitude and SWI images acquired on a MS patient at 3T and 7T using a 20-ms echo time.

Discussion: At 7T, vessels can be detected with areas around 7 times smaller than those detectable at 3T, using a shorter echo time. This increased sensitivity to vessels suggests that 7T may play a crucial part in the study of WM lesion heterogeneity. At very long echo times, the creation of susceptibility-weighted increases the sensitivity to small vessels. However, the detection of smaller vessels is possible in the magnitude images using shorter echo times. The size of vessels that can be detected at 7T is in the range of those associated with WM lesions in MS⁶, suggesting that this is a reliable technique for the further investigation of this relationship.

References: [1] Lucchinetti et al, Ann Neurol 2000;707-17 [2] Tallantyre et al, Neurology 2008;2076-8 [3] Haacke et al, Magn Reson Med 2004;52:612-8 [4] Sedlacik et al, Magn Reson Med 2007;58:1035-44 [5] Pruessmann KP, Magn Reson Med 1999;42:952-62 [6] Lumsden CE, Handbook of Clinical Neurology 1970

Acknowledgements: MS Society, MRC and EPSRC for program grant support.