

# Optimisation of 7T Double-Inversion Recovery (DIR) Imaging to Improve Detection of MS Lesions *In Vivo*

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**Introduction:** DIR imaging has often been used in neuroimaging to null the signal from two chosen tissues in the brain, leaving a grey- or white-matter only image<sup>1</sup>. Grey-matter only images are particularly useful in the study of multiple sclerosis (MS) as they enhance the contrast between white-matter (WM) MS lesions and the surrounding tissue, and they have been shown to improve the detection of lesions in the grey matter (GM) at 1.5T<sup>2</sup> and 3.0T<sup>3</sup>. However, this sequence has an intrinsically low signal-to-noise ratio (SNR) due to the fact that the magnetisation in the tissue of interest has only partly recovered when the image is acquired. This limits the resolution available, suggesting that development of the sequence for use at higher field strengths would be beneficial. This involves the determination of new sets of inversion times (TIs), as longitudinal relaxation times increase with field strength. Previous attempts to do this at lower field have all used empirical methods<sup>1,4</sup>, but the initial difficulties in implementing this at 7.0T suggests the need for a more reliable, theoretical, method of calculating TIs which could then be easily transferred between field strengths. In this work, we present the theory describing the longitudinal magnetisation in a DIR sequence and show that, for two given relaxation rates, only one pair of inversion times will successfully null both required signals. Although analysis of this theory is not new<sup>1</sup>, it has not yet been used to successfully determine and implement optimum inversion times. We (i) extend the theory to account for possible variation in inversion pulse flip angle to account for the inherent RF inhomogeneity at 7T, and the fact that SAR limits prevent the use of fully adiabatic inversion; (ii) apply the theory to DIR at 3T and show that this yields an improvement over the manufacturer's preset sequence; (iii) use the theory to implement DIR at 7T and show the improved spatial resolution that this allows; (iv) demonstrate the sequence on MS patients at 7T.

**Theory:** For a GM-only image, the longitudinal magnetisation on application of the 90° pulse must be zero for both WM and CSF. The longitudinal magnetisation at the point of image acquisition can be found using the following equation:

$$M_z = M_0 \left[ 1 - \exp\left(-\frac{TI_2}{T_1}\right) \right] + M_{eq} \cos \alpha \exp\left(-\frac{TI_2}{T_1}\right) \left[ 1 - \exp\left(-\frac{TI_1}{T_1}\right) \right] + M_{eq} \cos^2 \alpha \exp\left(-\frac{TI_2}{T_1}\right) \exp\left(-\frac{TI_1}{T_1}\right)$$

where  $T_1$  is the time delay between the inversion pulses (flip angle  $\alpha$ ), and  $TI_2$  is the time between the second  $\alpha$ -pulse and the acquisition. This can be calculated assuming the flip angle is known, along with the  $T_1$ s of WM and CSF at the relevant field strength. The equilibrium magnetisation,  $M_{eq}$ , can be calculated as a proportion of  $M_0$  assuming that the longitudinal magnetisation at the end of the acquisition period is zero:

$$\frac{M_{eq}}{M_0} = 1 - \exp\left(-\frac{\tau}{T_1}\right)$$

where  $\tau$  is the time between the end of the acquisition and the repetition of the sequence, which can be reduced in order to lower scan time [N.B.  $TR = TI_1 + TI_2 + \tau + \text{length of the acquisition period}$ ].

**Methods:** Scanning was performed using a Philips Acheiva 3T MR scanner with a whole-body gradient set, 8-channel SENSE rf receive coil, and whole-body volume transmit coil, and a Philips Acheiva 7T scanner with a whole-body gradient set, 16-channel NovaMedical SENSE rf receive coil and head-only volume coil. An inversion recovery experiment was performed to measure the flip angle at 7T, which was found to vary between 140° in the frontal and occipital lobes, 160° in the centre of the head, and 108° in the temporal lobes. A full inversion was assumed at 3T. 3D DIR scans were acquired at 3T with whole-head coverage in 1.25-mm isotropic voxels, using a turbo spin-echo readout. 2D single-slice images were acquired with 1x1x2 mm<sup>3</sup> voxels. TR was varied in the range 7 – 11s and dual TI values calculated to produce a GM-only image for each TR, using the equation above, to test the theory. A 2D multi-slice GM-only image was acquired according to the manufacturer's preset procedure at the same resolution, with 38 slices. Inversion times were 3075 and 325 ms; TR = 11000 ms; TE = 100 ms; TSE factor = 26; Acquisition time 11.7 minutes. 3D images were acquired at 7T with 0.6x0.6x2.0 mm<sup>3</sup> voxels, 11.5-s TR, 680-ms TE, 100x219x164 mm<sup>3</sup> FOV, SENSE factor 4 (AP), 2 signal averages, in 6.7 minutes, and with 0.8-mm isotropic voxels over a 80-mm FOV (FH) in 10.5 minutes. 2D single-slice images were also acquired at 7T with a range of TRs so that quantitative comparisons could be made.

**Results:** Figure 2A shows a single-slice 3T DIR image acquired with 10.8-second TR, voxel size 1x1x2 mm<sup>3</sup>, while Fig. 2B shows the same slice acquired with a shorter TR (7.3 s). TIs were 3207 and 551 ms for (A) and 2669, 535 ms for (B). Fig 2C shows a 3D image which allows whole-head coverage with 1-mm isotropic voxels in 7.5 minutes. Fig 2D, shown for comparison, is the standard GM-only image using manufacturer-provided acquisition parameters with similar windowing to highlight residual WM signal. Figure 2E shows a DIR image acquired on a healthy volunteer at 7T with 0.6x0.6x2.0 mm<sup>3</sup> voxels. Figure 1 shows the recorded signal (arbitrary units) in GM, WM and CSF for DIR images at 7T with varying TR. Finally, figure 2F is a 7T DIR image with 0.8-mm isotropic voxels acquired on an MS patient.

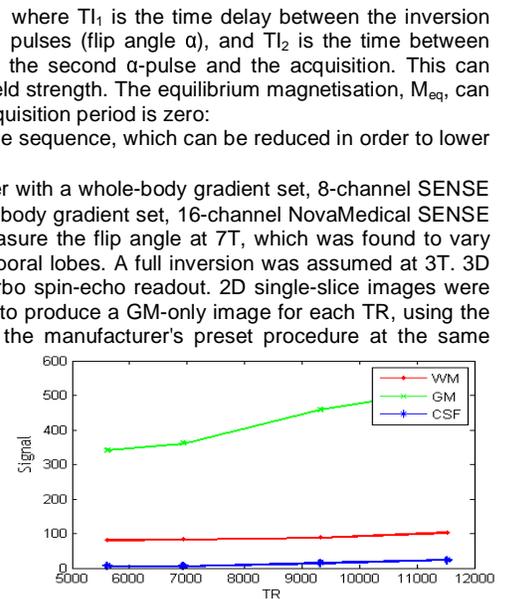


Figure 1 – Signal in WM, GM and CSF for DIR scans as a function of TR

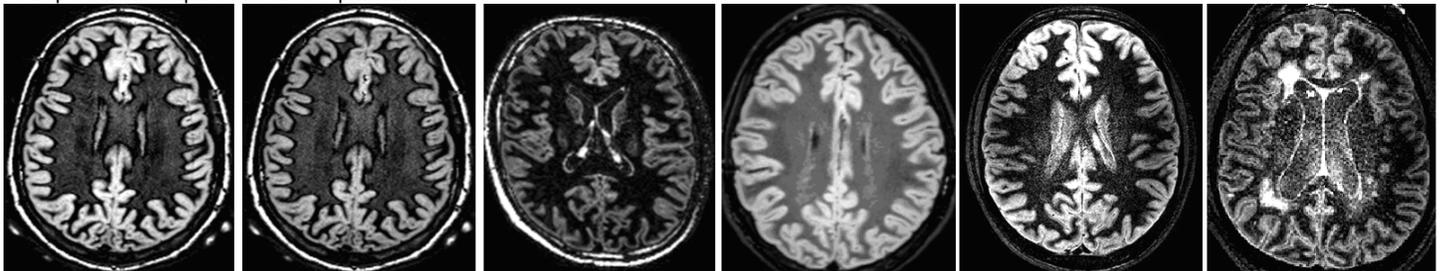


Figure 2 – DIR images acquired at 3T (A – D) and 7T (E/F)

**Discussion:** These results show that, with a knowledge of the inversion pulse flip angle (from a B1 map), simultaneous nulling of WM and CSF is achievable at both 3 and 7T. The use of the theory described to predict inversion times enables the TR to be reduced without compromising SNR or tissue suppression (Fig 1). It also yields an improvement over the manufacturer's preset procedure at 3T, and allows high-resolution images to be obtained at 7T. Such images show clearly the areas of signal abnormality associated with MS lesions, and the high resolution available at 7T should enable the detection of smaller lesions than is possible at 3T. It should also improve our ability to classify lesions in or close to grey matter. Similar theory can also be used to optimise a 3D FLAIR sequence that can be used at 7T with a range of TRs.

**References:** [1] Redpath & Smith. Brit J Radiol 1994;1258-63 [2] Geurts JJ et al. Radiology 2005;236-54 [3] Poonawalla et al. Proc Intl Soc Mag Reson Med 2007 [4] Bedell & Narayana. J Magn Reson Imag 1998;544-547 **Acknowledgments:** MS Society, MRC and EPSRC for program grant support.