Whole-Brain FLAIR using 3D TSE with Variable Flip Angle Readouts Optimized for 7 Tesla

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Introduction

Whole-brain FLAIR is a requirement for most routine clinical neuroimaging. Traditional techniques employ a two-dimensional inversion-recovery turbo spin echo (2D IR-TSE) pulse sequence with the inversion time (TI) chosen to null CSF signal. However, at 7 Tesla (T) and higher whole-brain FLAIR using traditional techniques has not been feasible in an acceptable scan time. The traditional FLAIR pulse sequence requires a large number of inversion and refocusing pulses which leads to a prohibitively high SAR and only a few slices can be acquired at ultra-high $\mathbf{B_0}$ [1]. Furthermore, $\mathbf{B_1}$ inhomogeneity at 7T makes robust CSF suppression very difficult to achieve with 2D techniques.

Recent work [2] demonstrated the feasibility of using 3D IR-TSE with a T_2-selective inversion pulse and a long echo train with a reduced flip angle readout (70º) to perform whole brain FLAIR at 7 Tesla for the first time. The present work seeks to extend this approach by adding a variable flip angle readout, optimized for the T_1 and T_2 values of brain tissues at 7T, to further reduce SAR and improve contrast and SNR per unit time.

Methods

Bloch simulations were performed to explore the optimal combinations of TI, TR, echo train length (ETL), and flip angle evolution to achieve robust CSF suppression, and to maintain excellent contrast between gray matter (GM) and white matter (WM) regions using typical GM ^1H_2O relaxation properties [3]. Data were acquired at 7T (MAGNETOM 7T, Siemens) using either an 8-channel phased array head coil (Rapid Biomedical) or a 24-channel phased array head coil (Nova Medical).

A T_2-selective adiabatic IR pulse was used to selectively invert CSF ^1H_2O signal. Combinations of TI and TR were tested to confirm optimal values for CSF suppression and to compare with simulations. The T_1 and T_2 values used in the Bloch simulations to optimize the variable flip angle RF pulse train were matched to typical values of gray matter at 7 T [3], using a variable flip angle train designed to yield improved SNR for long echo trains. The TE was varied to determine the best combination of T_2 contrast and minimal blurring along the phase encoding axes. Both a sagittal whole-brain 160 slice $(1mm)^3$ voxel protocol and a lower spatial resolution axial whole-brain 96 slice $(1mm)^2$x2mm voxel protocol were developed. Elliptical sampling of k-space along the phase encode axes was also added to reduce scan time. After initial testing in phantoms to confirm that the pulse sequence could operate reliably within SAR constraints for a reasonable scan time, optimization was performed with eleven subjects scanned under informed consent, including one subject with small confirmed WM lesions. Images were evaluated on the basis of low SAR, practical scan time, uniformly good CSF suppression, contrast between cortical GM and WM, and image sharpness. Image sharpness was evaluated visually along all three dimensions using multi-planar reformatting of the 3D image volume.

Results and Discussion

GM and WM ^1H_2O T_1 values increase significantly with $\mathbf{B_0}$, while CSF ^1H_2O T_1 does not [3]. Thus, the TI required to null CSF signal is independent of $\mathbf{B_0}$, and the recovery from inversion of WM/GM signals at 7T is substantially reduced compared to acquisitions at lower $\mathbf{B_0}$. The use of a T_2-selective inversion pulse significantly increases the GM/WM signal recovery compared to a regular inversion pulse.

Fig. 1 shows the variable flip angle evolution scheme optimized for 7T brain tissue relaxation times for the high resolution sagittal protocol. The bend in the middle of the flip angle evolution corresponds to the center of k-space and the TE. After a rapid fall off from 180° at the beginning of the RF pulse train, the lower flip angles in the first half of the train will significantly prolong the decay and thus reduce blurring due to higher T_1 components. The flip angle at the center of the pulse train is approximately 20° representing a major reduction in RF energy compared to 180° refocusing pulses used in typical 2D TSE FLAIR, and also compared to the previously reported 70° 3D TSE readout [2].

Optimal CSF suppression was achieved with TI/TR=2350/10000ms, yielding excellent suppression over the entire brain in all subjects. A high BW=751Hz/pixel was used to reduce the echo spacing to 3.4ms which shortened the echo-train length and minimized blurring. A long TE (380ms) had a minimal affect on SNR for the flip angle train shown in Fig 1, and the long TE improved both the GM/WM contrast and reduced through-slice blurring. Elliptical k-space sampling shortened the scan time by 15-20% depending on the amount of partial Fourier acceleration used.

The optimized axial protocol with $(1mm)^2$x2mm resolution had a scan time of 6m11sec. The CSF suppression and GM/WM contrast were very good throughout the brain, and the resolution was higher than typical clinical FLAIR protocols. A comparable 2D FLAIR protocol could only acquire approximately 5 slices within the same scan time due to SAR constraints at 7 Tesla. The optimized sagittal protocol with $(1mm)^3$ resolution had a scan time of 10m14sec. Multi-planar reformatted images acquired using this protocol are shown in **Fig. 2** for a subject with confirmed WM lesions highlighted in red. In conclusion, 3T TSE with a variable flip angle readout optimized for 7 Tesla brain and a long echo train combined with T_2-selective IR and elliptical imaging provides excellent quality whole-brain FLAIR images at 7 T in a practical scan time.

References [1] Zwanenburg Eur. Rad. Oct. 3 (2009). [2] Visser, Proc. ISMRM 2009 (#2760). [3] Rooney, MRM 57:308-318 (2007).

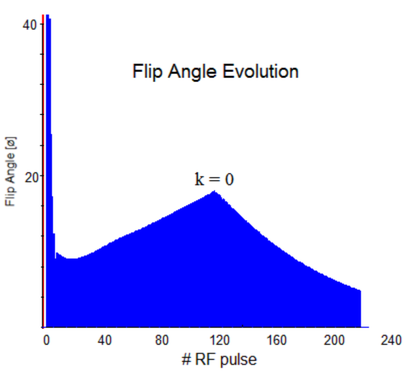

Fig 1. Variable flip angle train for T_1/T_2=1650/60ms.

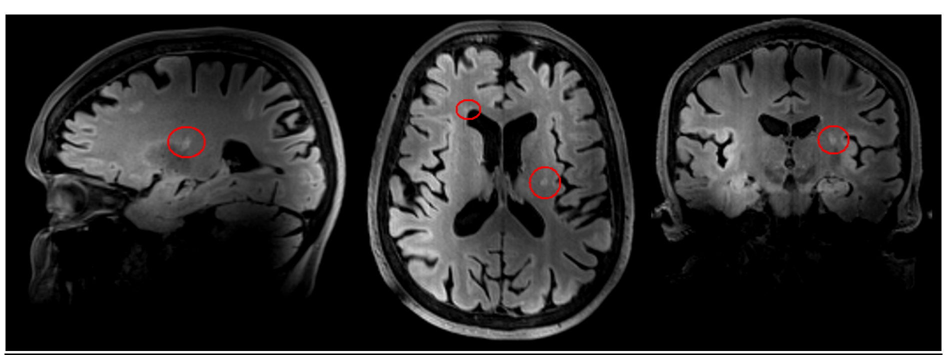

Fig 2. Multi-planar reformatted images of a subject with confirmed small white matter lesions (circled in red). 160 sagittal slices, 1mm isotropic voxels, 10m14sec scan time.