Optimized twice-refocused adiabatic spin echo sequence for diffusion weighted imaging of humans at 7T

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Introduction: There is a need for a robust diffusion weighted imaging (DWI) pulse sequence for human imaging at 7T. DWI at higher field strengths benefits from increased signal-to-noise ratio (SNR) but suffers from B_1-inhomogeneity and reduced T_2 value of tissue causing signal reduction. A twice-refocused spin echo (TRSE) DWI sequence is typically used in clinical scans for reduced eddy current distortions [1]. However, the use of two 180° RF pulses renders the sequence very susceptible to B_1-inhomogeneity. Using a twice-refocused adiabatic spin echo (TRASE) sequence has been previously proposed and shown to improve image homogeneity in phantoms at 3T [2]. We have developed a version of the TRASE DWI sequence which utilizes optimized adiabatic 180° pulses generated using the adiabatic SLR algorithm for pulse design [3]. A twice refocused sequence is well suited to the use of adiabatic pulses because the second identical 180° pulse perfectly refocuses quadratic phase induced by the first one, leaving no net phase in the final echo. This is important because quadratic phase across the final slice would result in signal loss. The adiabatic SLR pulses were optimized to minimize pulse duration (so as to minimize TE) and minimize peak B_1 at adiabatic threshold. Adiabatic pulses have shown benefit for DWI of animals and phantoms at higher fields [4-6]. Here we show results in humans at 7T using optimized adiabatic SLR pulses to maximize B_1-immunity in the TRASE DWI sequence.

Method: Our first step was to design an adiabatic SLR 180° pulse to replace the 180° pulses in the TRASE DWI sequence. We used the adiabatic SLR algorithm [3] to generate 180° pulses with the following parameters: 6 ms duration, 1.4 kHz BW and 11 μT peak B_1 at adiabatic threshold. Quadratic phase was applied to spread RF energy as uniformly as possible over the pulse duration and reduce peak B_1. Lower peak RF amplitude allows for a greater range of B_1 immunity before the hardware limit for the RF coil/amplifier combination is reached. The final TRASE EPI DWI sequence is shown in Fig. 1. The brains of 4 healthy volunteers were scanned with a product TRSE sequence and our TRASE sequence. Sequence parameters were: 45 slices, 3mm slice thickness, 128x128 grid, 24 cm FOV, TE/TR=83.8ms/5.5s and scan time=2:56 s for the product TRSE and TE/TR=94.8/6.5s and scan time=3:28 s for TRASE. The slightly longer TE/TR for the TRASE sequence was necessary to accommodate the longer RF pulses and crushers associated with larger slice select gradients. The same b value of 1000 s/mm^2 was used for both sequences. Chemical saturation was used for fat suppression. We acquired full DTI data sets with 32 diffusion encoded directions. B_1 maps were also obtained using adiabatic Bloch Siegert B_1+ mapping [7].

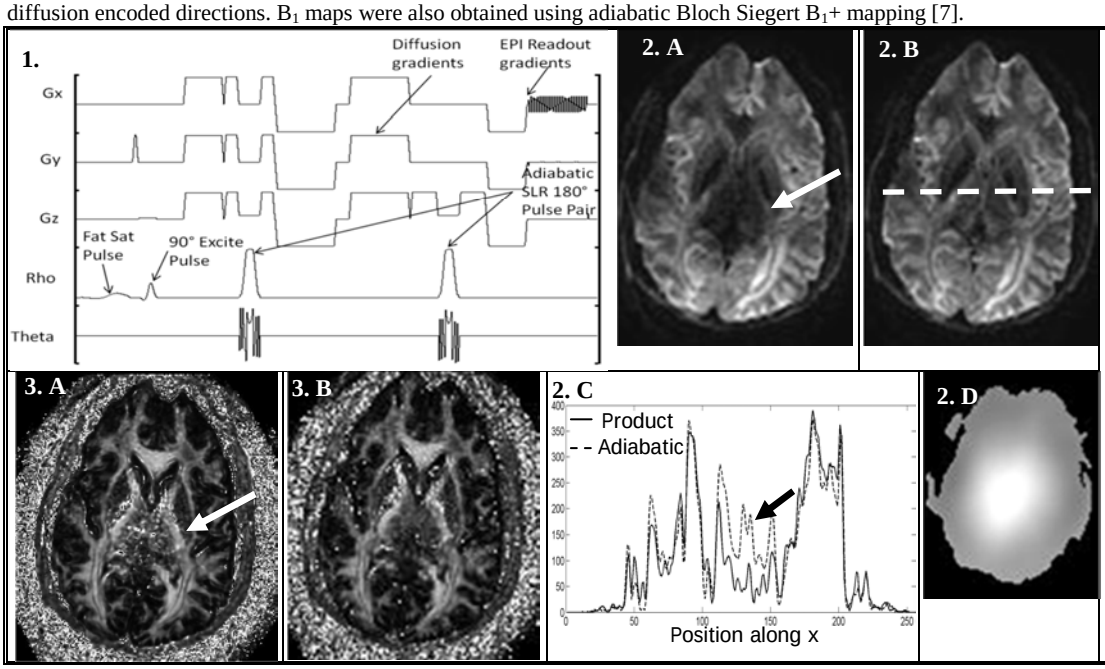

***Figure 1 (Left, above)**: RF amplitude, phase and gradient waveforms for TRASE DWI sequence with optimized adiabatic SLR pulses.*
***Figure 2 (Right)**: Diffusion weighted image along one direction for a chosen slice of the brain obtained using **(A)** the product TRSE sequence and **(B)** the proposed TRASE sequence. White arrow indicates area of signal loss due to B_1 inhomogeneity. **(C)** Cross section as indicated by the white dotted line in **(B)** across both images. Black arrow indicates signal difference at center. **(D)** B_1 map of the slice.*
***Figure 3 (Left, below)**: Fractional anisotropy maps of same slice of the brain generated from the DTI dataset obtained using **(A)** TRSE and **(B)** TRASE sequence. White arrow indicates area of increased noise in the FA map due to B_1-induced signal loss in the diffusion weighted images.*

Results: Figure 2 shows diffusion weighted images in one direction for a slice of the brain of a representative volunteer obtained using (A) product TRSE and (B) our TRASE sequence for DWI. The B_1 profile of the slice is shown in Fig. 2 D. The main area of signal loss due to a peak in the B_1 profile at the center of the brain is indicated by the white arrow in Fig. 2 A. This signal is largely recovered by the TRASE sequence as shown by Fig. 2 B. Central cross sections through these two images are shown in Fig. 2 C, demonstrating appreciable signal increase afforded by the TRASE sequence at the center of the brain. Fractional anisotropy (FA) maps were generated using all 32 directions with a custom developed DTI map plug-in on Osirix. FA maps are shown in Figs. 3 A and B for the same slice using the product TRSE and TRASE sequences, respectively. The FA map obtained by the adiabatic SLR TRASE sequence suffers from less noise and distortion when compared to the product TRSE sequence.

Discussion: *In vivo* data obtained at 7T demonstrate that the proposed TRASE sequence for DWI results in improved SNR and homogeneity for diffusion weighted images. TE is longer for the adiabatic sequence causing signal loss in short T_2 tissues. We are planning to shorten the crusher gradients and pulse duration further in order to achieve comparable TE's. More powerful gradient sets would help shorten the TE even further and enable shorter diffusion gradients for the same b values, improving overall DWI performance at 7T. The proposed TRASE sequence still outperforms the non-adiabatic TRSE sequence given the disadvantage of longer TE in regions with high B_1-inhomogeneity. Adiabatic RF pulse amplitude was set to 11 μT, even though higher amplitude could be achieved within hardware limits, allowing greater overdrive range and improved performance. However, in order to remain within SAR limits for all volunteers, the max amplitude was limited to 11 μT.

References: [1] Reese TG, et al. *MRM*. 2003;49:177-182. [2] Auerbach EJ and Ugurbil K. Proc. ISMRM, 2004. [3] Balchandani P, et al. *MRM*. 2010; 64(3): 843-851. [4] van de Looij Y, et al. *MRM*. 2011; 65:732–737. [5] Sun Z and Bartha R. *J Magn Reson*. 2007; 188(1): 35–40. [6] Skare, S, et al. Proc. ISMRM, 2007. [7] Khalighi et al., *MRM* DOI 10.1002/mrm.24507.

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