Reduced FOV spinal muscle DWI with single-shot interleaved multi-slice inner volume stimulated echo DW-EPI

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Introduction: Atrophy of spinal muscles is associated with degenerative disc disease, alignment disorders and eventually back pain. Diffusion-weighted (DW) MRI of skeletal muscle has been proposed as a sensitive marker of denervation-induced muscle atrophy [1]. However, DW-MRI of spinal muscles remains challenging due to the muscle short T_2 and the sensitivity of single-shot EPI to off-resonance effects. Stimulated-echo preparation has been used to overcome the SNR limitations in muscle DW EPI (enabling eddy current compensation without additional TE increase [2]) and has been recently combined with parallel imaging [3]. However, the use of phased array coils to increase the phase encoding bandwidth depends on the sensitivity profiles of the receiver coils and is not in general feasible in spine DWI. Reducing the FOV in the phase encoding direction is another way to increase the spatial resolution of localized muscle DWI scans without lengthening the readout with the additional benefit of excluding the artifact prone regions of the FOV. There have been a number of techniques proposed to reduce the FOV in spin-echo prepared DW-EPI of white matter regions, including outer volume suppression [4] and 2D RF excitation [5]. Outer volume suppression is limited by the performance of the regional saturation pulses and 2D RF excitation can increase the echo time. Multi-slice inner volume imaging has been also achieved in twice-refocused spin-echo (TRSE) acquisitions, by making the two refocusing pulses selective in the phase encoding direction [6]. The latter approach can provide good inner volume excitation profiles with modest decrease in SNR for interleaved multi-slice acquisitions, but it has been studied only in the context of spin-echo preparation [6]. Goal of the present work is the development of a DW stimulated echo sequence with interleaved multi-slice inner volume imaging to improve the resolution of spinal muscle DWI.

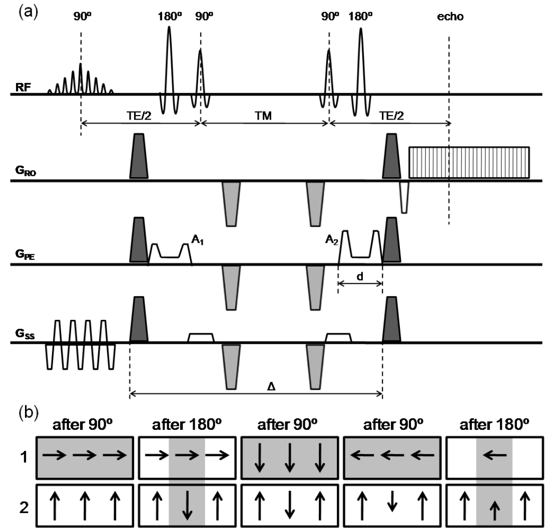

Fig. 1: (a) Schematic of pulse sequence diagram (diffusion gradients are in black and eddy current compensating gradients are in gray), (b) evolution of magnetization while imaging slice 1 in an interleaved acquisition of 2 slices.

Materials & Methods: Pulse sequence description: Refocusing pulses selective in the phase encoding direction are added before the second 90º pulse and after the third 90º pulse of a stimulated echo prepared DW-EPI sequence with eddy current compensation [2] (Fig 1a). Fig. 1b shows the magnetization evolution while imaging slice 1 in an interleaved acquisition of 2 slices. By setting the area of crushers around the refocusing pulses (A_1 and A_2) not equal, the magnetization within slice 1 outside the inner volume of interest is dephased and the desired inner volume excitation is achieved. The first 90º pulse is a fat suppressive spatial spectral excitation pulse.

In vivo measurements: A head-neck-spine array coil was used to scan the lumbar spine muscles of one healthy subject on a 3 T full-body GE scanner. DWI measurements were performed using the reduced-FOV sequence of Fig. 1a with the following parameters: TR/TE=8000/40 ms, FOV=32x9 cm^2, 4 slices with 12 mm thickness, 128x40 matrix size, 8 overscans, δ/Δ=5/170 ms, 3 directions, N_{ex}=16, b=500 s/mm^2 with as scan time of 8 min and 32 s. The same region was also scanned with the full-FOV stimulated echo sequence [2] with the same parameters except for: TE=31 ms, FOV=32x32 cm^2, 128x128 matrix size. A T_2-weighted FSE scan using IDEAL for fat suppression was also acquired for anatomical reference.

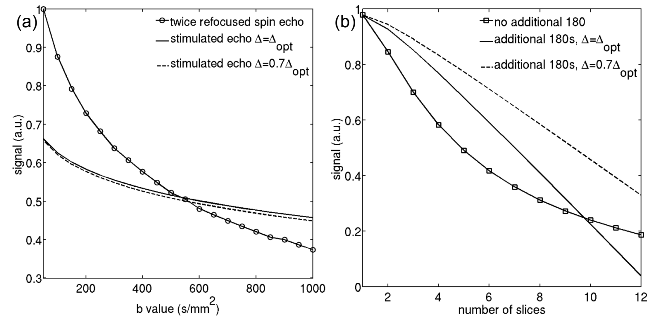

Fig. 2: Sequence tradeoffs: (a) comparison of relaxation induced signal loss between single-slice inner volume acquisitions with the twice refocused spin-echo and the proposed stimulated echo as function of b value, and (b) variation of longitudinal magnetization versus the number of interleaved slices for an inner volume stimulated echo prepared sequence and b=0.

Results & Discussion: Sequence tradeoffs: The addition of the two refocusing pulses increases the echo time by 2d where d is the duration of the added refocusing pulse with the accompagnying crushers. The T_2 and T_1 relaxation-induced signal loss of the proposed sequence is compared with the relaxation induced signal loss of the inner volume TRSE sequence [6]. The proposed sequence leads to higher SNR than the inner volume TRSE for b>500 s/mm^2 (Fig. 2a). Another important aspect of sequences with excitation/refocusing slabs in the phase encoding direction is the characterization of the T_1-induced longitudinal magnetization loss in multi-slice acquisitions [7,8]. The magnetization within the inner volume and outside the imaging slice experiences two 180º pulses separated by TM+2d. Since the SNR-optimal stimulated echo diffusion timing requires long TM [2], the proposed sequence when performing at optimal diffusion time Δ_{opt} enables multi-slice interleaved acquisition but with a considerable SNR loss (Fig. 2b). However, if the stimulated echo diffusion timing is modified such that the diffusion time Δ is 30% lower than the optimal diffusion time Δ_{opt}, a considerable increase of the longitudinal magnetization can be achieved for multi-slice interleaved acquisition (Fig. 2b) without significant loss of the transverse magnetization (Fig. 2a).

In vivo results: Fig. 3 shows the cropped full-FOV and reduced-FOV lumbar spine muscle DWI results (voxel size is 2.5x2.5x12 mm^3). Muscle contours have been drawn based on the T_2-weighted FSE. The full-FOV EPI data suffer from significant geometric distortions, showing as compression of the erectus muscle anatomy in the A/P direction (arrow 1). The full-FOV data suffer also from fat-induced chemical shift artifacts that bias ADC (arrow 2). When comparing the reduced-FOV data with the full–FOV data, there is an expected SNR loss due to the reduction of the readout duration. However, the geometric distortions and the displacement of the chemical shift artifact are significantly reduced using the reduced-FOV acquisition (arrows 1 and 2).

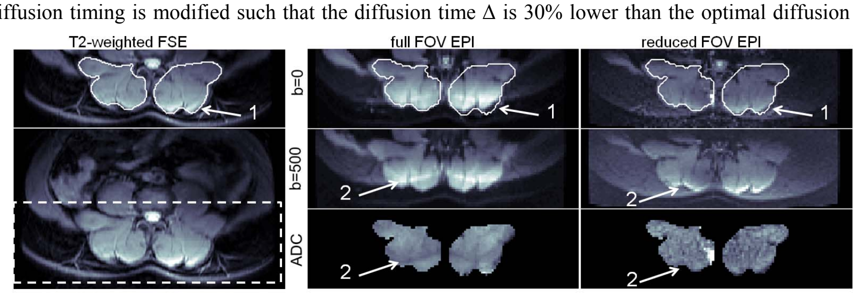

Fig. 3: *In vivo* lumbar spine muscles results. The dashed box shows the inner volume FOV.

Conclusion: A reduced-FOV DW-EPI approach, combing stimulated echo preparation with inner volume multi-slice imaging is developed for immune to off-resonance effects DWI of spinal muscles. Future work could include application of this sequence for high resolution DWI in other short T_2 tissues of the spine (marrow, disc).

References: [1] Zhang et al, Exp Neurol 212:448, 2008, [2] Steidle et al, MRM. 55:541, 2006, [3] Karampinos et al, ISMRM 2010, p. 880, [4] Wilm et al, MRM 57:625, 2007, [5] Saritas et al, MRM 60:468, 2008, [6] Dowell et al, JMRI 29:454, 2009, [7] Jeong et al, MRM 54:1575, 2005, [8] Kim et al, JMRI 30: 1068, 2009.

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