High-resolution skeletal muscle single-shot DW-EPI with optimized stimulated-echo preparation and SENSE

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Introduction: High resolution skeletal muscle DTI is necessary in order to resolve muscles with small cross section and to delineate the fiber architecture in the boundaries between different muscles (aponeuroses) [1, 2]. High-resolution muscle single-shot (s-sh) DW-EPI is limited by the short muscle T_2/T_1 ratio and the associated long gradient EPI readouts. The short muscle T_2/T_1 ratio results in low SNR [3] and the long gradient readouts induce distortions due to off resonance effects and T_2*-blurring due to the muscle short T_2* [4]. Stimulated-echo preparation has been used to overcome the SNR limitations in muscle DW-EPI, enabling eddy current compensation without additional TE increase [5]. Parallel imaging has been used to decrease B_o and susceptibility-induced distortions and T_2* blurring and the SNR efficiency of SENSE has been optimized in s-sh spin-echo DW-EPI [6, 7]. In the present work, it is proposed to combine eddy-current compensated stimulated echo preparation with SENSE to increase the spatial resolution of skeletal muscle s-sh DW-EPI. The eddy-current compensated stimulated echo preparation timing and the SENSE reduction factor are optimized, taking into account SNR and T_2* blurring effects.

Materials and Methods: Pulse sequence: The schematic of a diffusion-weighted stimulated echo EPI sequence is shown in Fig. 1. The left dephasing diffusion gradient is positioned so that the time separation Δ between the diffusion gradients is maximized. Additional gradients are added during the mixing time TM to compensate for eddy currents without prolonging TE, as it was proposed by Steidle et al [5]. Fat suppression is performed using a spatial spectral excitation pulse and SENSE is used to reduce t_{acq} and TE.

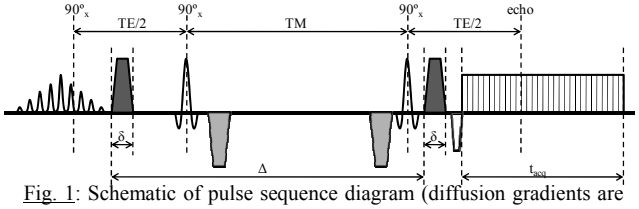

Fig. 1: Schematic of pulse sequence diagram (diffusion gradients are in black and eddy current compensating gradients are in gray).

SNR and resolution analysis: The SNR is simulated as a function of the SENSE reduction factor R and the diffusion time Δ. For given b-value, matrix size, and partial Fourier factor (pF), the analysis takes into account SNR loss due to T_2 relaxation over the echo time TE [5], T_1 relaxation over the mixing time TM [5], the mean geometry factor over the entire FOV for a particular coil geometry [6] and the reduced data acquisition window (by $R^{1/2}$) [6]. The point spread function (PSF) along the phase encoding direction is also simulated as a function of R, taking into account T_2* blurring. The full-width half maximum of the point spread function (PSF) is used as a metric of the effective resolution.

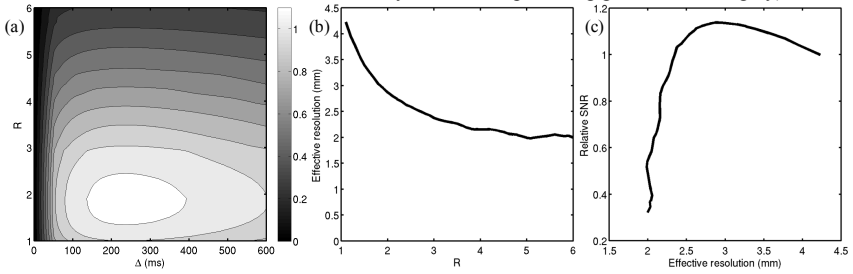

Fig. 2: (a) Variation of relative SNR with reduction factor and diffusion time, (b) variation of the effective resolution with reduction factor, and (c) trade-off between SNR and effective resolution.

In vivo measurements: An eight-channel lower extremity coil (Invivo, USA) was used to scan the calf muscle of two subjects on a 3 T full-body GE scanner. In subject A the coil was positioned in the middle calf region and in subject B the coil was positioned more superior, close to the knee. Geometry factor maps were measured from noise maps computed in both subjects using 2D gradient echo images. DTI measurements were performed using the sequence of Fig. 1 with the following parameters: TR/TE=2000/35 ms, FOV=20x20 cm^2, 6 slices with 10 mm thickness, pF=0.625, δ/Δ=6.5/170 ms, 30 directions, N_{ex}=6, b=540 s/mm^2. Two different acquisition matrices were used to compare the effect of spatial resolution, with different SNR but the same readout duration [8]: 64x64 (R=1, echo spacing (esp)=656 μs, echo train length (etl)=40) and 128x128 (R=2.86, esp=928 μs, etl=28). The scan for every acquisition was 6 min and 20 s.

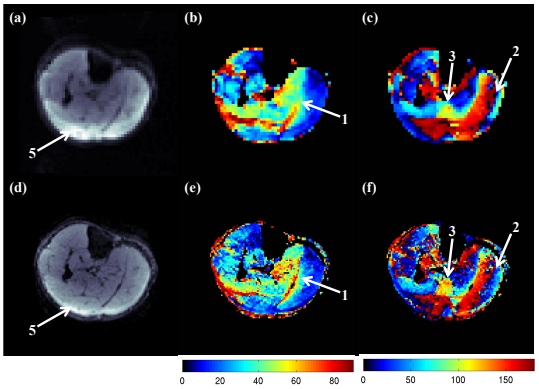

Fig. 3: Comparison of high (a-c) with low (d-f) resolution DTI results in mid calf slice of subject A: (a, d) b=0 images, (b, e) map of V_1 zenith angle, (c, f) map of V_1 azimuth angle.

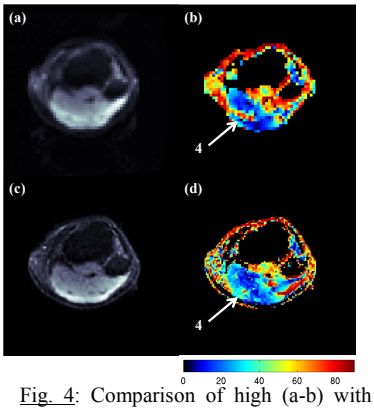

Fig. 4: Comparison of high (a-b) with low (c-d) resolution DTI results in higher calf slice of subject B: (a, c) b=0 images, (b, d) map of V_1 zenith angle,

Results and Discussion: Sequence optimization: Fig. 2 shows the iso-contour lines of relative SNR in the R-Δ plane (T_1/T_2=1500/30 ms, 128x128 matrix size, b=600 s/mm^2 and the mean geometry factor values from the *in vivo* scans). The reference SNR is the maximum SNR for R=1. As R increases, the SNR loss due to T_2 relaxation decreases (TE decreases), but the SNR loss due to reduced data sampling increases (Fig. 2a). As Δ increases, the SNR loss due to T_2 relaxation over TE decreases, but the SNR loss due to T_1 relaxation over TM increases. Maximum SNR is observed at R_{opt}=1.92 and Δ_{opt}=237 ms. However, Fig. 2a shows a moderate decrease in SNR for Δ lower than Δ_{opt} and since lower values of Δ would reduce the sensitivity to motion and allow more slices per TR, they are preferable. Regarding spatial resolution, as R increases, T_2*-induced blurring (in muscle T_2*=25 ms) is decreased (Fig. 2b). Fig. 2c shows the trade-off between SNR and effective resolution for varying R with diffusion time Δ_{opt}. An increase in R over R_{opt} (R=3) appears to improve spatial resolution (by 23%) with moderate SNR loss (by 10%) relative to maximum SNR.

In vivo results: Fig. 3 shows the DTI maps for the mid calf slice of subject A for the high (128x128) and low (64x64) in plane resolution. The primary eigenvector V_1 orientation is defined by its zenith and azimuth angles. Improved in plane spatial resolution allows the reduction of partial volume effects close to the posterior aponeurosis of the soleus (arrow 1). The bipennate nature of the medial gastrocnemius muscle and soleus is also better resolved with the higher resolution scan (arrows 2 and 3). Fig. 4 shows the DTI maps for a slice inferior to the knee in subject B. High resolution DTI reduces partial volume effects in muscles with small muscle cross-sections (arrow 4). The use of SENSE in the high resolution scan also reduces the absolute displacement of the olefinic fat chemical shift artifact [9] (arrow 5). Further work would be required to study the partial volume effect induced by the high slice thickness and the anisotropic voxel shape employed in the present work.

Conclusion: The spatial resolution of DTI is improved in an s-sh EPI acquisition with optimized stimulated echo preparation and SENSE. *In vivo* results show that high spatial resolution DTI can remove partial volume effects close to aponeuroses and in muscles with small cross sectional areas.

References: [1] Heemskerk et al, MRM. 61: 467-472, 2009, [2] Karampinos et al, ABME, in press, [3] Damon, MRM 60: 934-944, 2008, [4] Sinha et al, ISMRM 2008, p. 571, [5] Steidle et al, MRM. 55: 541-548, 2006, [6] Jaermann et al, MRM 51: 230-236, 2004, [7] Jaermann et al, MRM 55: 335-342, 2006, [8] Karampinos et al, MRM 62: 1007-1116, 2009, [9] Hernando et al, ISMRM 2009, p. 2064.