Diffusion-Prepared Single-Shot Fast Spin-echo Imaging and the Effects of Eddy Currents: Preliminary Investigation

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Introduction: Single-shot (SS) diffusion-weighted (DW) echo planar imaging (EPI) is characterized by relatively high resolution and good SNR. However, the low bandwidth in the phase-encode direction makes SS-DW-EPI extremely sensitive to off-resonance. The idea of using SS-FSE (fast spin-echo) to image diffusion-encoded magnetization has led to the development of non–CPMG (Carr-Purcell-Meiboom-Gill) acquisition strategies [1-3] and diffusion preparations that return the diffusion-encoded magnetization to the longitudinal axis before the imaging pulse sequence is played [4,5]. High gradient amplitudes and slew rates used to generate high b-values within acceptable echo times produce eddy currents that can translate into spatially non-uniform phase shifts at the time of magnetization tip-up. These phase shifts are converted into unwanted modulation of the longitudinal magnetization, ultimately resulting in signal loss and banding. The aim of this work was to show the improved eddy current properties of a twice-refocused diffusion preparation motivated by previous work by Reese et al. [6] when compared to other previously reported preparations and to demonstrate the feasibility of diffusion-prepared (DP) SS-FSE.

Methods: The three diffusion-encoding schemes in Fig.1a-c were implemented as a non-selective diffusion-preparation module. The bipolar (Fig. 1b) and twice-refocused (Fig. 1c) diffusion-encoding schemes [6], unlike the monopolar scheme (Fig. 1a), provide partial eddy-current cancellation. Composite pulses were used for both the refocusing (90_x-180_y-90_x) and tip-up (270_x -(-360_x)) pulses to improve robustness to B_0 and B_1 inhomogeneity [7]. DP-SS-FSE images (FOV = 20cm, slice thickness = 10mm, NEX = 0.5, TR = 1s, BW = ±83kHz) of a phantom were compared to conventional SS dual spin-echo DW-EPI images (FOV = 20cm, slice thickness = 10mm, NEX = 1, TR = 1s, BW = ±167kHz). Evaluation of the effect of eddy currents for the diffusion preparation sequence was evaluated by integrating the three diffusion-encoding schemes in Fig.1a-c into a spin-echo pulse sequence, i.e. by replacing the tip-up pulse with a readout gradient. Two sets of experiments were performed. The first experiment was aimed at visualizing the spatial distribution of phase shifts introduced by the diffusion gradients at the time of the spin-echo when diffusion gradients were played along different axes. A uniform spherical phantom (diameter = 20cm) and a single-channel quadrature head coil were used. Phase difference maps were created by subtracting the non-diffusion-weighted phase image from the phase image acquired with diffusion gradients applied along each of the three physical gradient axes. The second set of experiments was aimed at quantifying eddy-current-induced phase shifts and was performed using the body coil and a 30cm pipe filled with silicone oil (which has a low ADC) and aligned with the physical x-axis. Slice-select and phase-encode gradients were turned off, so that the only gradients were the diffusion-sensitizing gradients and the readout gradient along the length of the tube. One-dimensional Fourier transform of the raw data yielded the phase distribution in the readout direction. Comparisons between the different diffusion-encoding schemes were performed at the minimum echo time to produce a predetermined b-value. Other imaging parameters included: FOV = 30cm, slice thickness = 10mm, 128×128 matrix size, 1 excitation, TR = 1s, BW = ±15kHz. All imaging was performed at 1.5T (Signa HDx, GE Healthcare, Waukesha, WI) with a 40mT/m maximum gradient strength and a maximum slew rate of 150mT/m/ms.

Results and Discussion: Figure 2 shows axial phase difference maps acquired with the monopolar (1st row), bipolar (2nd row) and twice-refocused (3rd row) diffusion-encoding schemes and diffusion gradients applied along the R/L (1st column), A/P (2nd column) and S/I (3rd column) directions, respectively (b=500s/mm^2; TE=63ms (monopolar), 99ms (bipolar) and 78ms (twice-refocused)). All three schemes resulted in negligible phase shifts when the diffusion gradients were applied in the S/I direction. The twice-refocused scheme resulted in the least eddy-current-induced phase shifts for all diffusion-sensitizing directions. In contrast, the monopolar and bipolar diffusion-encoding schemes were found to generate high order eddy currents when the diffusion gradients were applied along the readout direction (Fig.3; axial plane, readout = R/L direction, b=300s/mm^2; TE=55ms (monopolar), 85ms (bipolar) and 68ms (twice-refocused)). Fig.4a shows DP-SS-FSE axial images of a uniform phantom obtained with the twice-refocused diffusion-encoding scheme, a b value of 800s/mm^2 (TE = 117ms) and diffusion gradients applied along the R/L (top), A/P (middle) and S/I (bottom) directions. Residual phase shifts at the time of tip-up (cf. Fig.3, 3rd row) produced signal drop-out regions in the R/L and A/P diffusion images. Although this inherently limits the acquisition to S/I diffusion-weighted images, this is not a serious limitation for applications (eg. liver, breast, etc) where diffusion is isotropic. In such applications, the twice refocused preparation produces diffusion-weighted images with minimal distortion, as shown in Fig.4, where two arbitrary slices obtained with the DP-SS-FSE technique (Fig.4b) are compared to conventional SS dual spin-echo EPI (Fig.4c; b=800s/mm^2, S/I diffusion, TE = 96ms (SS-FSE) and 112ms (SS-EPI)). In conclusion, the use of eddy-current-compensated diffusion preparation sequences hold potential to avoid artifacts that occur from large eddy-current-induced phase shifts at high b-values.

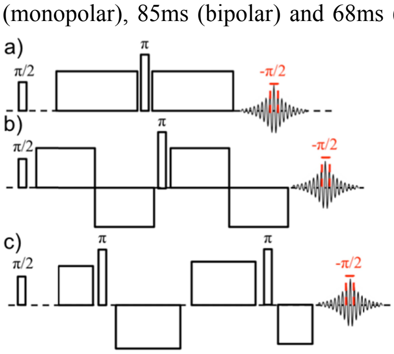

Figure 1

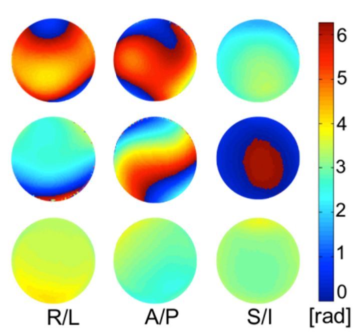

Figure 2

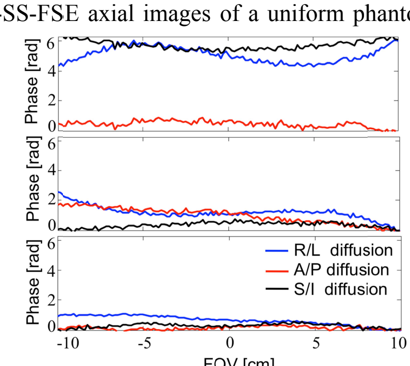

Figure 3

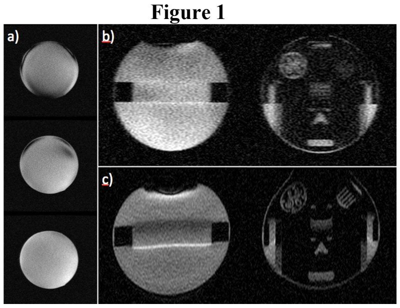

Figure 4

References: [1] MRM 2007; 58:643; [2] AJNR 2007; 28:575; [3] MRM 1997; 38:527; [4] US Patent 7,804,299, 2010; [5] US Patent 6,078,176, 2000; [6] MRM 2003; 49:177; [7] MRM 1995; 33:689.