Bipolar single spin echo: diffusion encoding with concomitant field and eddy current correction

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Introduction: Diffusion weighted (DW) imaging and diffusion tensor imaging (DTI) are important clinical and research sequences. With the proliferation of multi-site and large cohort studies, accurate and robust diffusion imaging is necessary to ensure correct and reproducible results. Diffusion encoding is typically performed with a dual spin echo sequence to minimize eddy current distortions [1]. This sequence was recently identified as being susceptible to a spatially varying bias in the estimated diffusion coefficients due to concomitant gradient fields [2, 3]. The Stejskal-Tanner single spin echo approach is immune to such errors, but can be prone to significant eddy current distortions. Here we present an encoding scheme based on a single refocusing pulse that is immune to concomitant field errors while providing some eddy current compensation.

Theory: Extending the work of Alexander [4], we propose a diffusion-encoding scheme to avoid concomitant field errors and partially null eddy currents by using a shorter negative gradient lobe, Figure 1.

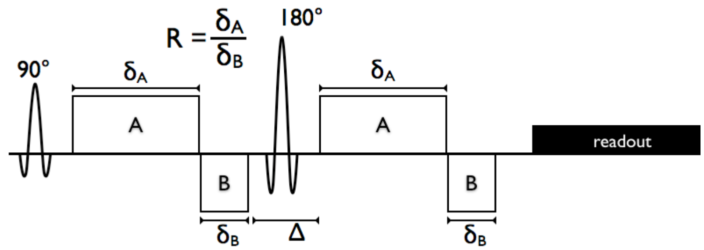

Figure 1: RF pulse and diffusion gradient lobes for the modified bipolar diffusion-encoding with concomitant field correction and eddy current attenuation. Symmetric gradient lobes about the refocusing pulse prevent net phase accrual from concomitant fields while unbalanced bipolar gradients (defined by the ratio $R = \delta_A/\delta_B$) reduce eddy currents prior to the refocusing pulse *and* image readout (single shot EPI).

Residual phase errors due to concomitant fields can be completely avoided with identical gradient lobes on each side of the refocusing pulse. Eddy currents can be minimized with bipolar gradient lobes [4]. The relative eddy current amplitude (A_e/A_0) immediately after the first 'B' lobe is given by:

$$A_e/A_o = 1 - 2e^{-\delta_B/\tau} + e^{-(\delta_A+\delta_B)/\tau}$$

Eddy currents with time constant τ can be nulled with appropriate selection of δ_A and δ_B. Neglecting ramp times, the b-value is given by:

$$b = \gamma^2 G^2 \left(\frac{2}{3}\delta_A^3 + (\delta_A - \delta_B)^2\Delta + \frac{2}{3}\delta_B^3\right)$$

Results: Figure 2 shows mean DW images (b=1000 s/mm^2) from a GE 3T MR750 using Stejskal-Tanner (TE=60ms), dual spin echo (TE=78ms), and the proposed bipolar single spin echo (R=3, TE=73ms) encoding schemes. With the proposed bipolar scheme, eddy current distortions are visibly reduced relative to the Stejskal-Tanner method; errors due to concomitant fields are not present in the proposed scheme, but are in the dual spin echo (although they are not readily seen on the DW image) [2, 3]. Relative eddy current amplitudes for various ratios (R) of lobes A to B are shown in Figure 3, along with the eddy current amplitudes for the Stejskal-Tanner and dual spin echo encoding schemes. Eddy currents with time constants between 10–40 ms are substantially attenuated with lobe ratios between 1.5 and 3.0.

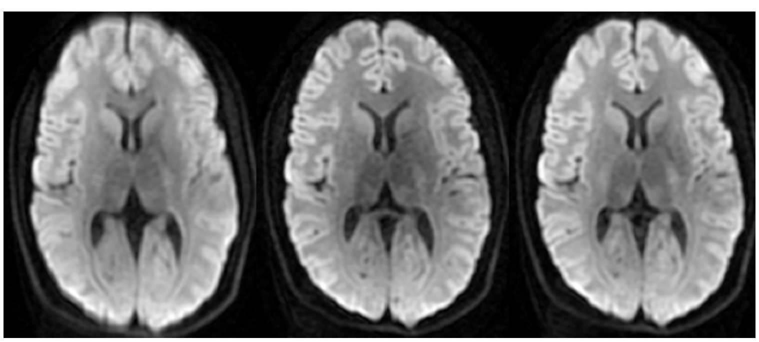

Figure 2: Mean DW images acquired 12 cm off-isocenter (to emphasize eddy currents) with the Stejskal-Tanner (left), the dual spin echo (centre), and the bi-polar single spin echo (right).

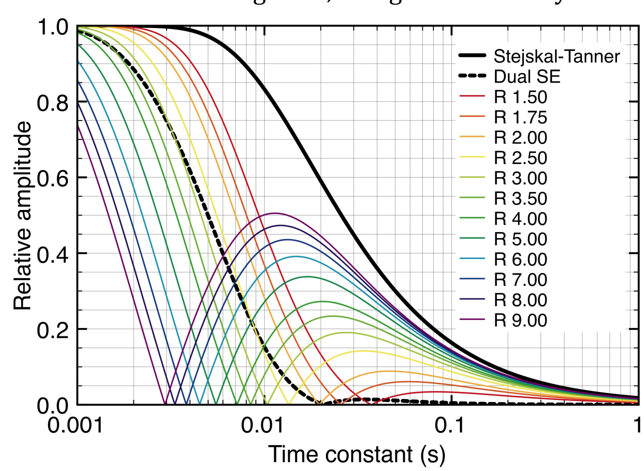

Figure 3: Simulated relative eddy current amplitudes for various R values over a range of time constants. Eddy currents for the Stejskal-Tanner and dual spin echo are also shown.

Conclusion: The proposed bi-polar single spin echo encoding scheme offers some advantages over the dual spin echo: reduced sensitivity to B_1^+ variations, lower RF power, and insensitivity to concomitant field effects. The bi-polar single spin echo is also less sensitive to eddy current distortions than Stejskal-Tanner. Its main disadvantage is that decreasing R necessitates increased echo times; however, typical values of R (i.e., ~3) result in echo times that are comparable to the dual spin echo.

References: [1] Reese TG *et al.* MRM 2003. [2] Meier C *et al.* MRM 2008. [3] Baron CA *et al.* MRM 2012. [4] Alexander A *et al.* MRM 1997.