Bipolar Diffusion Encoding with Implicit Spoiling of Undesired Coherence Pathways

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Introduction: High-resolution diffusion tensor imaging (DTI) requires both high SNR and good spatial alignment of images acquired with different b-values and diffusion directions. Due to its acquisition speed, diffusion-weighted (DW) single-shot EPI (ss-EPI) is still commonly used, despite the fact that strong gradient pulses used for diffusion encoding in combination with a low pixel bandwidth along the phase-encoding direction result in considerable eddy-current-induced distortions. Using bipolar (twice refocused) diffusion encoding [1] [2], eddy current distortions are effectively reduced as compared to the monopolar Stejskal-Tanner approach [3]. However, additional spoiler gradients required in order to suppress undesired stimulated echo contributions increase TE and correspondingly reduce SNR [4] [5]. Here, we are discussing a new bipolar gradient scheme marked reduction in TE with negligible impact on eddy current suppression efficiency.

Ommitting the need for explicit spoiling and thus allowing for a suppression efficiency. Theory: A schematic timing diagram of the new bipolar DW ss-EPI sequence is shown in Fig. 1. Assuming a constant amplitude G0 of the four diffusion-encoding gradients, MR physics demands that t0 + t1 = t2 + t3 (0th moment refocusing) and that tprep + t0 + t1 + tadc = t0 + t2 (spin-echo condition). By additionally requiring that TE - tprep - tadc - 2 tE0 = t0 + t1 + t2 + t3 = T0 the diffusion encoding efficiency is maximized. Since tprep, tadc, tE0 and TE are determined by the measurement protocol and sequence implementation details, respectively, these three conditions for the four parameters t0, t1, t2, t3 leave one degree of freedom. In contrast to the original approach which uses this freedom to zero eddy currents with a specific time constant, here we use it to spoil undesired coherence pathways. Besides the desired twice refocused spin-echo, the three RF pulses generate three free induction decays, three spin-echoes, a stimulated echo and an anti-stimulated echo. For each undesired coherence pathway, an inequation describing the demand for an accumulated absolute 0th moment larger than the required spoil moment Mspoil can be formulated. It turns out that a solution exists for this set of inequations that simultaneously fulfills the three basic timing conditions stated above. By using t0 = 1/6 (TD - Ts), t1 = 1/6 (2 TD + Ts), t2 = 1/6 (TD + 2 Ts) and t3 = 1/6 (2 TD - 2 Ts) with Ts = tprep + tadc, signal contributions of undesired coherences are effectively suppressed if |G0| t0 ≥ Mspoil. Methods: Phantom experiments were performed on a 1.5T whole body MR scanner (MAGNETOM Espree, Siemens Healthcare Sector, Erlangen, Germany) with a 12-element Head Matrix coil. DW images were acquired with a prototype sequence using the standard bipolar timing, the new timing discussed here and a monopolar encoding module: FOV = 256x256 mm², partial Fourier = 6/8, phase-encoding direction A-P, isotropic resolution 2mm², iPAT factor 2 (GRAPPA reconstruction), 25 slices without gap, DW with b = 1000 s/mm², 20 directions, TR = 3500ms, TE = 90ms (standard bipolar), 82ms (new bipolar) and 84ms (monopolar), respectively. Residual eddy current contributions of the diffusion encoding gradients were simulated for all variants assuming a mono-exponential decay using MatLab (The MathWorks Inc., Natick, MA). Results and Discussion: Standard deviation maps are used to assess the spatial alignment of the DW images acquired using different diffusion directions. Residual eddy current induced distortions show up as bright contours in this representation. As shown in Fig. 2a, both standard and new bipolar diffusion-encoding yield similar results, indicating comparable eddy current suppression efficiency. This observation is supported by the simulation results shown in Fig. 2b. The new timing allows reducing TE by 8ms for this protocol, accompanied by a corresponding SNR increase. Conclusion: The proposed modification of the bipolar diffusion encoding scheme allows for a markedly reduced TE and correspondingly increased SNR with negligible impact on eddy current suppression efficiency. First volunteer images confirm the expected benefit, giving prospect of improved DTI data quality.