Bipolar Diffusion Encoding with Implicit Spoiling of Undesired Coherence Pathways

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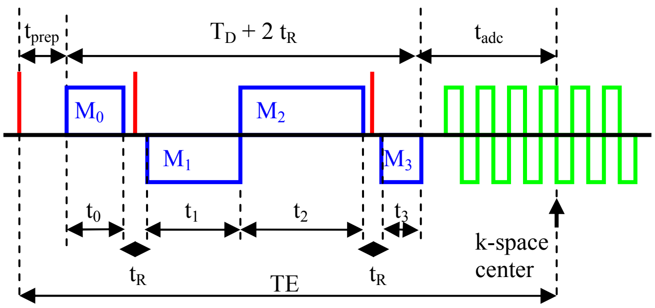

Fig 1: Schematic illustration of a DW ss-EPI sequence using the new bipolar scheme, consisting of diffusion-encoding gradients (blue), readout gradients (green), one excitation and two refocusing RF pulses (red). Note the absence of any spoiler gradients.

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 omitting the need for explicit spoiling and thus allowing for a marked reduction in TE with negligible impact on eddy current suppression efficiency. **Theory:** A schematic timing diagram of the new bipolar DW ss-EPI sequence is shown in Fig. 1. Assuming a constant amplitude G_D of the four diffusion-encoding gradients, MR physics demands that $t_0 + t_1 = t_2 + t_3$ (0^{th} moment refocusing) and that $t_{prep} + t_0 + t_3 + t_{adc} = t_1 + t_2$ (spin-echo condition). By additionally requiring that $TE - t_{prep} - t_{adc} - 2\ t_R = t_0 + t_1 + t_2 + t_3 \equiv T_D$ the diffusion encoding efficiency is maximized. Since t_{prep}, t_{adc}, t_R and TE are determined by the measurement protocol and sequence implementation details, respectively, these three conditions for the four parameters t_0, t_1, t_2, t_3 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 0^{th} moment larger than the required spoil moment M_{spoil} 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 $t_0 = 1/6\ (T_D - T_S)$, $t_1 = 1/6\ (2\ T_D + T_S)$, $t_2 = 1/6\ (T_D + 2\ T_S)$ and $t_3 = 1/6\ (2\ T_D - 2\ T_S)$ with $T_S = t_{prep} + t_{adc}$, signal contributions of undesired coherences are effectively suppressed if $|G_D|\ t_0 \geq M_{spoil}$. **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 mm^2, partial Fourier = 6/8, phase-encoding direction A-P, isotropic resolution 2mm^3, iPAT factor 2 (GRAPPA reconstruction), 25 slices without gap, DW with b = 1000 s/mm^2, 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.

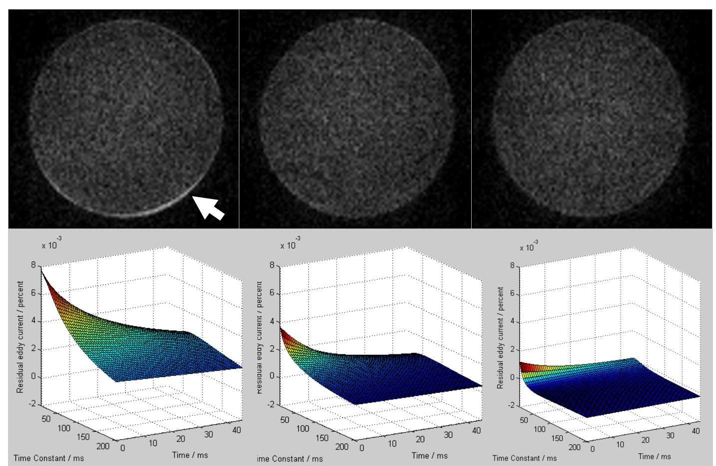

Fig 2: (top) Standard deviation maps of DW images acquired with monopolar (left), new (middle) and standard (right) bipolar diffusion encoding. Note the absence of contour artefacts indicating residual eddy currents for both bipolar schemes as compared to monopolar (white arrow). Simulation results of the residual eddy current amplitude depending on decay time constant and time within echo train (bottom).

References: [1] Heid: Proceedings ISMRM 2000 p.799, [2] Reese et al.: MRM 49:177 (2003), [3] Stejskal et al.: J.Chem.Phys. 42:288 (1965), [4] Zwanger: US Patent 7,633,291 B2, [5] Morelli et al.: Investigative Radiology 45:29 (2010) **Acknowledgement:** The author acknowledges helpful discussions with D. Porter.