Orthogonally combined motion- and diffusion-sensitized driven equilibrium (OC-MDSDE) preparation for improved vessel signal suppression in 3D TSE imaging of peripheral nerves

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Target audience: Scientists working in slow flow suppression and clinical researchers interested in peripheral nerve imaging.

Purpose: 3D neurographic sequences have been emerging for high resolution imaging of the peripheral nerves [1]. However, a persisting major challenge is the difficulty to address small-vessel contamination without disrupting the nerve signal [1], due to the similar relaxation times between blood and nerves. Previous techniques have used flow- sensitive dephasing preparation in spin echo imaging [2] or low b-value diffusion weighting in gradient echo imaging [3] to suppress vessel signal and improve the delineation of the peripheral nerves. Flow-sensitive dephasing preparation such as Motion-Sensitized Driven Equilibrium (MSDE) has been shown to help reduce the signal of larger vessels [4]. However, to reduce the signal of slowly flowing blood in small vessels (primarily veins), the first gradient moment of MSDE needs to be significantly increased, which unavoidably increases the sensitivity to motion-induced artifacts. Flow-compensated diffusion preparation is less sensitive to motion-induced phase errors and also capable of attenuating vessel signal, given the much higher diffusion coefficient of blood compared to nerve when the gradients are applied perpendicular to the nerve axis. By noting that peripheral nerves and the surrounding vessels tend to have a preferential orientation and that motion sensitivity can vary largely depending on the axis of the applied gradients, it is possible to combine motion and diffusion sensitization in orthogonal axes to take advantage of both dephasing mechanisms. In the present work, an Orthogonally Combined Motion- and Diffusion-Sensitized Driven Equilibrium (OC-MDSDE) preparation sequence for vessel-signal reduction in nerve imaging is proposed and its capability is demonstrated *in vivo* in the knee region with a 3D Turbo Spin Echo (TSE) acquisition.

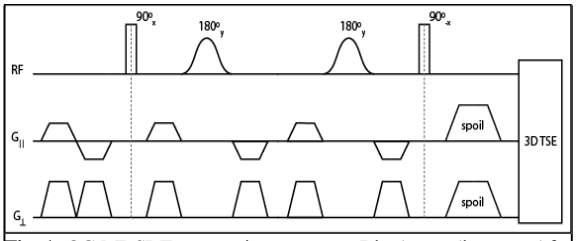

Fig. 1: OC-MDSDE preparation sequence. Bipolar gradients used for motion sensitization parallel to the nerve and unipolar gradients for diffusion sensitization perpendicular to the nerve. Gradient pairs placed prior to excitation support eddy-current correction.

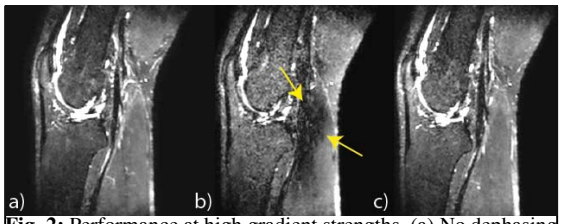

Fig. 2: Performance at high gradient strengths. (a) No dephasing gradients; (b) iMSDE with m_1 = 11740, b = 170; (c) DSDE with m_1 = 0, b = 170. m_1 and b values in mTms^2/m and s/mm^2. DSDE shows reduced motion-induced artifacts (yellow arrows).

Methods: <u>OC-MDSDE sequence:</u> Improved MSDE (iMSDE) [5] was implemented on the gradient axis parallel to the nerve while flow-compensated Diffusion-Sensitized Driven Equilibrium (DSDE) was applied perpendicular to the nerve with the objective of minimizing both motion-induced artifacts as well as diffusion-induced attenuation of the nerve signal (Fig. 1). On both axes two refocusing pulses were employed to reduce sensitivity to transmit B_1 effects [5] and additional gradient pairs were placed before the excitation pulse for eddy-current correction [6,7]. Residual transverse magnetization was spoiled after tip-up and readout was performed using 3D TSE. For the direction parallel to the nerve (iMSDE preparation), moderate gradient strengths were used to generate a first gradient moment (m_1) sufficiently large to reduce vessel signal while simultaneously having a small b-value contribution and thus negligible diffusion attenuation to the nerve signal. For the direction perpendicular to the nerve (DSDE preparation), diffusion-sensitizing gradient strengths were roughly five times higher to lessen fluid and vessel signal while inducing again minimal diffusion attenuation to the nerve signal.

<u>In vivo</u> <u>measurements:</u> Scans of two healthy volunteers were conducted using a 16-channel knee coil on a 3 T Philips system. Sagittal acquisitions of the lower part of the knee were carried out with 3D TSE using the following sequence parameters: FOV = 270×165×100 mm^3, acquisition voxel = 1.25×1.25×1.40 mm^3, reconstruction voxel = 0.63×0.63×0.70 mm^3, TR/TE = 2000/273 ms, TSE factor = 150, total scan duration = 2m26s. The preparation sequence was employed with a constant duration of TE_{prep} = 57 ms and with varying gradient strengths to assess motion- and diffusion-sensitization effects on vessel and nerve signals. Overall performance at relatively high gradient strengths was studied for iMSDE and DSDE separately and for the proposed OC-MSDE.

Results: When iMSDE is used, the region around the popliteal artery shows degraded image quality due to motion-induced phase errors at m_1 = 11740 mTms^2/m (Fig. 2b). In contrast, when flow-compensated DSDE is used with a similar gradient strength, this sensitivity is considerably reduced and improved image quality is observed (Fig. 2c). Figure 3 compares the performance of motion and diffusion sensitization in the suppression of vessel signal in proximity to the tibial nerve. Vessel signal that is not suppressed with motion sensitization using m_1 = 6780 mTms^2/m (Fig. 3b) is notably reduced when diffusion sensitization perpendicular to the nerve is used with a b value of 300 s/mm^2 (Fig. 3c) without notably affecting the signal of the nerve. The effect of motion sensitization parallel to the nerve in addition to diffusion sensitization perpendicular to the nerve is further illustrated in Figure 4. Residual vessel signal superimposed on the nerve observed with DSDE using b = 300 s/mm^2 (Fig. 4a) is suppressed when OC-MSDE (m_1 = 3915 mTms^2/m, b = 320 s/mm^2) is used leading to a less obstructed view of the nerve (Fig 4b).

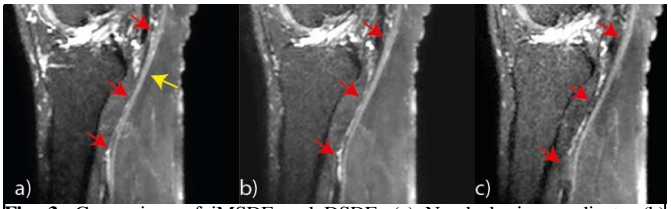

Fig. 3: Comparison of iMSDE and DSDE. (a) No dephasing gradients; (b) iMSDE in all three directions (m_1 = 6780, b = 60); (c) DSDE perpendicular to nerve (m_1 = 0, b = 300). DSDE improves delineation of the nerve (yellow arrow) by reducing vessel signal (red arrows). m_1 and b values in mTms^2/m and s/mm^2.

Discussion & Conclusion: The present results show that standard MSDE preparation at moderate m_1 values can be insufficient for reducing signal from stagnant vessel flow and that at higher m_1 values it is no longer suitable due to the appearance of motion-induced artifacts. Flow-compensated DSDE has been verified to have a much better behavior in the presence of motion and its ability to suppress vessel signal with minimal effect on the nerve has been demonstrated. Both diffusion and higher-order gradient moments [8] are responsible for the observed vessel attenuation in flow-compensated DSDE. The integration of iMSDE and flow-compensated DSDE, in separate working regimes of gradient strength and with gradient-axis selection accommodating nerve orientation, has been shown to provide improved vessel reduction while preserving nerve signal and in the particular case presented has been proven to yield a clearer depiction of the nerve. A b value of 300 s/mm^2 on a gradient axis perpendicular to the nerve has been found to partially suppress vessel signal and an m_1 value of 3915 mTms^2/m on the axis parallel to the nerve has been found to further help with vessel signal suppression without introducing significant diffusion weighting for the nerve. The proposed OC-MDSDE preparation method is therefore shown to serve as a tool for effectively reducing vessel signal in regions of slow flow while being robust against motion and readily compatible with a high-resolution readout such as 3D TSE.

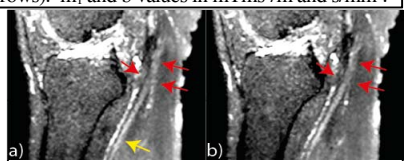

Fig. 4: Comparison of DSDE and OC-MSDE. (a) DSDE perpendicular to nerve (m_1 = 0, b = 300); (b) OC-MDSDE with motion sensitization parallel to nerve and diffusion sensitization perpendicular (m_1 = 3915, b = 320). OC-MDSDE further improves vessel suppression (red arrows) next to the nerve (yellow arrow).

References: [1] Chhabra, AJR 196:583, 2011, [2] Yoneyama, Proc. ISMRM 2011, p. 2721, [3] Chhabra, JMRI 34:962, 2011, [4] Wang, Magn Reson Med 58:973, 2007, [5] Wang, JMRI 31:1256, 2011, [6] Absil, Proc. ISMRM 2007, p. 12, [7] Obara, JMRI 40:824, 2014, [8] Liu, Proc. ISMRM 2014, p. 2532.

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