Correction of Artifacts Caused by Transient Eddy Currents In Simultaneous Multi-Slice dMRI

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TARGET AUDIENCE – Researchers using Simultaneous-Multi-Slice (SMS) diffusion-weighted MRI (dMRI).

PURPOSE – In SMS[1] EPI dMRI acquisitions, middle slices are inevitably acquired at the beginning of each diffusion-encoded volume, making SMS more sensitive to artifacts due to transient eddy currents than conventional dMRI. In conventional dMRI, slices affected by transient eddy currents are often in areas that can be ignored such as the neck or above the brain. In SMS, however, most of the simultaneously excited slices are in the middle of the brain and transient eddy currents (Fig 1, grey region) cause slices in the first few excitations to have different geometric distortions than slices in later excitations acquired when eddy currents are in steady state. This can cause problems for eddy current correction methods[2]. The purpose of this work is to identify the artifact, propose a solution, and demonstrate the efficacy of the solution.

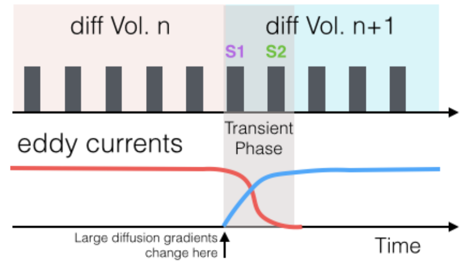

Fig. 1 – Schematic of the SMS dMRI acquisition showing the period of transient eddy currents (grey) following the change from diffusion-encoding direction n (pink) to direction n+1 (blue). The first 2 slice groups are affected (S1 and S2).

METHODS – *MRI:* dMRI was performed on a phantom and on 40 subjects (as part of a separate study) with a single-shot, single-refocused spin echo EPI sequence (CMRR multi-band C2P) [TR/TE = 4072/81.5 ms, 1.8 mm isotropic resolution over the whole brain and SMS/multi-band factor of 3 (MB=3)[5] without in-plane acceleration] on a 3T Skyra scanner (Siemens, Germany) with a 32ch head coil. Paired acquisitions with reversed phase encoding in the LR/RL direction were acquired, each with 64 matched diffusion-encoding directions (b=1200 s/mm2) and 5 un-weighted (b=0) scans. The total scan time for each acquisition was ~5 min. The phantom experiment examined the dependence of the artifact on gradient direction in the unweighted (b=0) images, looking at only the effect of eddy currents from the previous diffusion-encoding volume (Fig 1, red line). A series of unweighted images was acquired with diffusion-weighted volumes interspersed, one along each principal direction (Fig 2 X,Y,Z) and one with all three averaged (Fig 2 (X+Y+Z)/3).

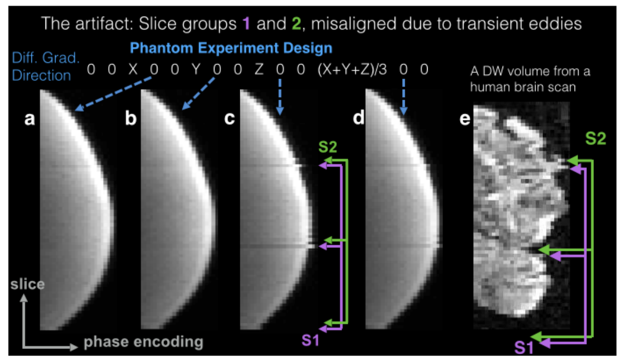

Fig. 2 – (a-d) Unweighted (b=0) images in a phantom showing the artifact's dependence on the diffusion-encoding that precedes it. On our gradient set the z-gradient produces the most pronounced artifact on the next volume (c). This is due to eddy currents from the previous volume's diffusion gradients (Fig 1, red line). The artifact appears similar in the DW image acquired in a human brain (e).

Proposed Correction: Empirically it was found that only the first two groups of slices acquired (S1 and S2) were affected by the artifact. The correction consists of re-registering the affected slices back to the rest of the volume. Since 75 slices were acquired with MB=3 and interleaved slice ordering, S1 consisted of slice 1, 26, and 51, while S2 consisted of slices 3, 28 and 53. To re-register the one slice from each group slice 51 from S1 and 53 from S2 were registered independently to the slice between them, slice 52, using FSL *flirt* constrained to shift, scale and shear along the phase-encoding direction. Transformation matrices obtained for slice 51 and 53 were applied to all slices in S1 and S2 respectively to generate an artifact-free volume.

Analysis: Processing of the diffusion-weighted data was performed 2 ways: using an in-house version of the Human Connectome Project pipeline[3] and FSL[4], (1) without the proposed correction, and (2) with the proposed correction. Standard deviation over DW volumes was computed in MATLAB. Color FA maps were computed in FSL.

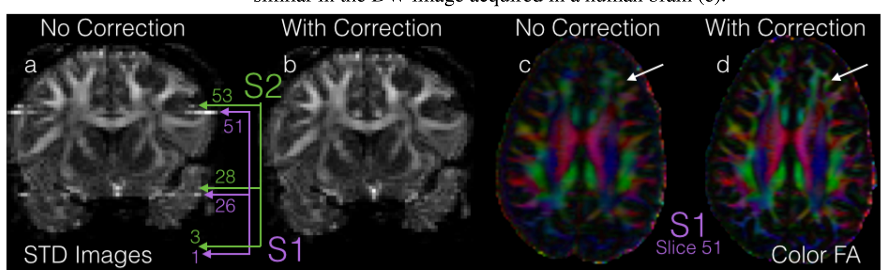

Fig. 3 – Standard deviation of DW volumes without (a) and with correction (b) showing the artifact in the affected slices groups (b, arrows). Axial color FA images show the consequence of the artifact uncorrected (c) and how correction (d) improves blurring caused by the artifact (c,d arrows)

RESULTS– The phantom images (Fig 2a-d) demonstrate that the artifact affects the first 2 groups of slices , that it is most prominent following diffusion-encoding along the Z direction (Fig 2c), and scales with magnitude of the z-component (Fig 2c,d). Adding a delay to each TR removed the artifact from b=0 images but did not remove it from DW images indicating that it is caused by transient eddy currents from the current volume (Fig 1, blue line) as well as from the previous volume (Fig 1, red line). The same artifact is present in the image acquired in the human subject (Fig 2e, arrows). The consequence of not correcting the artifact can be seen in the color FA images of slice 51 from S1 (Fig 3), The uncorrected volume has clear blurring due to uncorrected eddy currents (Fig 3a) while the corrected volume does not (Fig 3b). The correction performed robustly on dMRI data from all 40 subjects (data not shown).

DISCUSSION and CONCLUSIONS – Phantom tests indicated that the artifact was gradient-axis-specific and arose from 2 sources of eddy currents: (1) decaying eddy currents from the previous encoding volume (Fig 1 red line) and (2) eddy currents building in the current encoding volume (Fig 1 blue line). Data collected from other scanners also showed that the magnitude of the artifact depends on gradient coil model. It is conceivable a few dummy slice acquisitions at the beginning of each diffusion-encoding volume could eliminate the artifact but would prolong scan time (a few hundreds of ms in TR). The proposed correction greatly reduces the artifact without extra scan time. While the constrained affine transformation proposed here performed well for the eddy currents present in our scanner, it is possible that higher order terms need to be included. Future efforts will focus on more complete modeling of the eddy currents to accommodate a wider range of hardware. Nevertheless, with a simple, easy-to-implement correction, the artifacts were almost completely eliminated. Given the reliance of many studies on SMS-based dMRI the proposed correction is important for obtaining accurate dMRI-derived metrics.

REFERENCES – [1] Setsompop et al. MRM 2012. [2] Andersson, et al. ISMRM 2012, p2426 [3] Glasser et al., Neuroimage 2013. [4] FSL: http://fsl.fmrib.ox.ac.uk.
FUNDING – Internal Funding from the Icahn School of Medicine.