Characterization and Correction of Eddy-Current Artifacts in Unipolar and Bipolar Diffusion Sequences using a Field-Monitoring Approach: Application to Renal Diffusion Tensor Imaging (DTI)

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Background: Time-varying eddy currents lead to field deviations and image distortions in EPI scans [1]. In diffusion imaging, artifacts are made worse by long readout durations and strong diffusion-sensitizing gradients preceding the readout. Distortions vary between different gradient directions and result in misalignment artifacts, particularly in diffusion tensor imaging (DTI). It has been shown that time-varying higher-order spatial phase offsets during the readout cannot be ignored [2-4], and can be measured using a field camera with NMR probes [5-6]. Replacing the unipolar pulses of the Stejskal-Tanner [7] sequence with velocity-compensated bipolar pulses has been shown to offer insensitivity to bulk motion [8,9].

Purpose: Using a field camera consisting of an array of 16 NMR probes [5-6], the purpose is to correct for eddy-current-induced misregistration artifacts in two (unipolar and bipolar) diffusion sequences for the application of renal DTI.

Methods: Using a dynamic field camera [5-6] (Skope Magnetic Resonance Technologies, Zurich, Switzerland), the phase offsets are measured and images are subsequently aligned from different diffusion directions for two sequences shown in Fig 1a. Additional scans were performed with the field camera with the same diffusion and readout gradients played out. Images were reconstructed with and without phase information (up to 3rd spatial order) from the field-monitoring scan, by direct conjugate phase reconstruction without gridding (i.e., E^H algorithm in [4]). Scans were performed on a 3T Philips Achieva TX system (Philips Healthcare, Best, The Netherlands). Parts of the data processing pipeline were performed with the help of GyroTools Ltd, Zurich, Switzerland. ***Phantom experiment:*** The approach was verified in a phantom where plastic structures were embedded throughout a gelatin phantom to probe various spatial locations. Imaged with: 8 channels, FOV = 230×103 mm^2, b = 500 s/mm^2, TE (uni, bipolar) = 40, 60 ms, TR = 1 s, 6 diffusion directions, avg=3. ***In vivo experiment:*** Both kidneys in a healthy volunteer were simultaneously imaged with parameters: FOV = 230x127 mm^2, b = 350 s/mm^2, 8 channels, TE(uni,bipolar) = 39, 58 ms, TR = 1 s, 15 diffusion directions, avg=8, 5 mm slice thickness, 116x116 matrix, $BW_{PE,SI}$=22.2Hz, G_{max}=60mT/m, $slew_{max}$=100T/m/s. Effects of respiratory motion were minimized with a series of breath-held scans within a 4 mm gating window using a pencil-beam navigator.

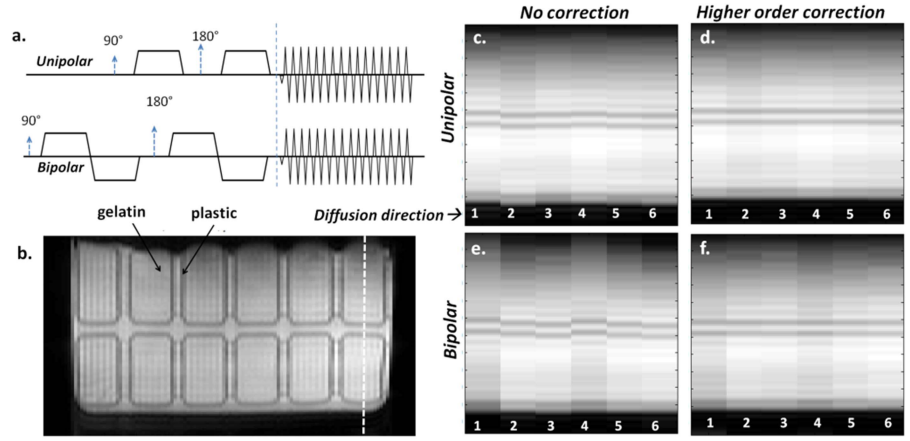
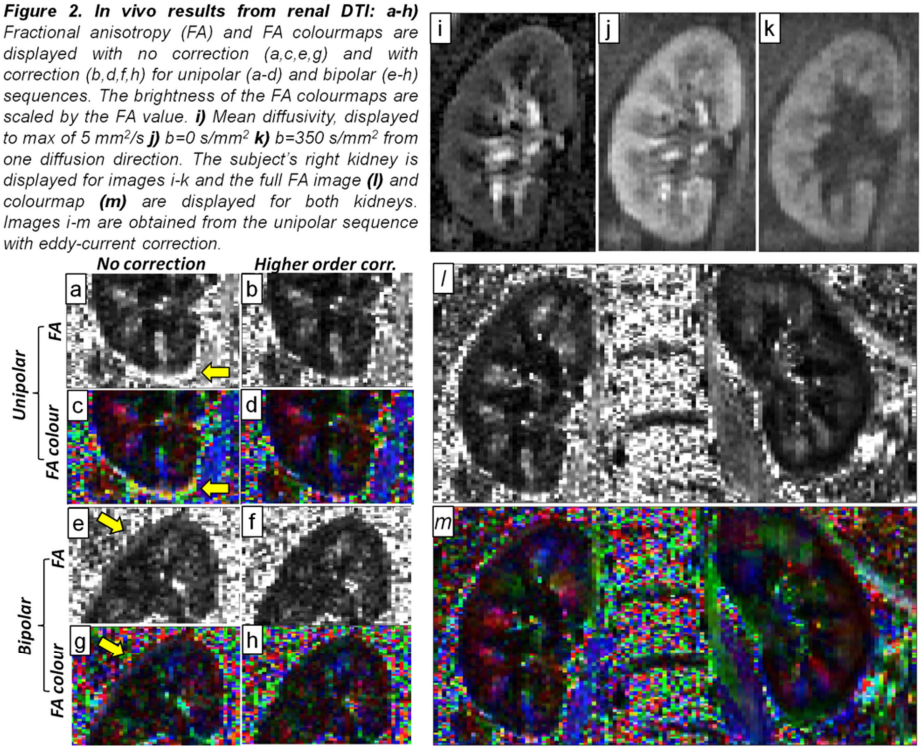


***Figure 1. Uni/bipolar sequences and results from phantom experiment**: **a)** DW-EPI spin-echo sequences with unipolar Stejskal-Tanner and bipolar diffusion lobes. Both sequences are sampled with an EPI readout where phase deviations from eddy currents are "monitored" by a separate scan with the field camera. **b)** Gelatin phantom with plastic structures (b=0 s/mm^2). **c-f)** Signal intensity shown (at the dotted vertical line in image b) for each diffusion direction with no eddy-current correction (c,e) and correction with higher-order phase information (d,f).*

***Figure 2. In vivo results from renal DTI: a-h)** Fractional anisotropy (FA) and FA colourmaps are displayed with no correction (a,c,e,g) and with correction (b,d,f,h) for unipolar (a-d) and bipolar (e-h) sequences. The brightness of the FA colourmaps are scaled by the FA value. **i)** Mean diffusivity, displayed to max of 5 mm^2/s **j)** b=0 s/mm^2 **k)** b=350 s/mm^2 from one diffusion direction. The subject's right kidney is displayed for images i-k and the full FA image **(l)** and colourmap **(m)** are displayed for both kidneys. Images i-m are obtained from the unipolar sequence with eddy-current correction.*



Results: ***Phantom experiment:*** For the same b-value, the bipolar diffusion sequence resulted in more severe misalignments compared to the unipolar sequence, as shown by the phantom experiment (Fig 1). Fig 1c and e show object translations up to several pixels without any correction. Figures 2d and f show better alignment with correction. ***In vivo experiment:*** Fractional anisotropy maps, displayed in both grayscale and colour (red=LR, green=AP, blue=SI), show misregistration artifacts, indicated by the arrows near the edges of the kidney (Figs 2a,c,e,g). These artifacts differ depending on the sequence. Image quality is improved for both unipolar and bipolar sequences with eddy-current correction (Figs 2b,d,f,h). A set of corrected images from the unipolar sequence is shown in Figs 2i-m, including a mean-diffusivity image (Fig 2i), b=0 s/mm^2 image (Fig 2j), and a diffusion-weighted image (Fig 2k) of the right kidney. The FA and FA colourmap of both kidneys obtained with the unipolar sequence are shown in Fig *l* and m. Anisotropic diffusion in the renal pyramids of the medulla is visible, with higher FA than the surrounding renal cortex.

Discussion and Conclusions: Measuring the phase deviations using NMR probes [5-6] is a valuable approach for characterizing the time-varying nature of higher-order eddy currents. Sequences dominated by non-linear spatial phase offsets (e.g., in the unipolar case) benefit from higher-order reconstruction. This work demonstrates that eddy-current-induced misregistration artifacts can be corrected in both unipolar and bipolar diffusion sequences, and offer improvements in image quality for renal DTI.

References: [1] Jezzard P. et al. MRM 1998, 39: 801–812. [2] Boesch C et al. MRM 1991; 20:268–284. [3] van Vaals JJ and Bergman AH. JMRI 1990;90:52–70. [4] Wilm BJ et al. MRM 2011;65:1690–1701. [5] Barmet C et al. MRM 2009;62(1):269-276. [6] De Zanche N et al. MRM 2008;60:176–186. [7] Stejskal EO et al. J Chem Phys 1965; 42: 288–292. [8] Gamper U et al. MRM 2007; 57: 331–337. [9] Ozaki M. et al. JMRI 2012 (in press). **Acknowledgements:** This work is supported by UK EPSRC.