Comprehensive Geometric Distortion Correction for Diffusion Tensor Imaging at Ultra-High Field

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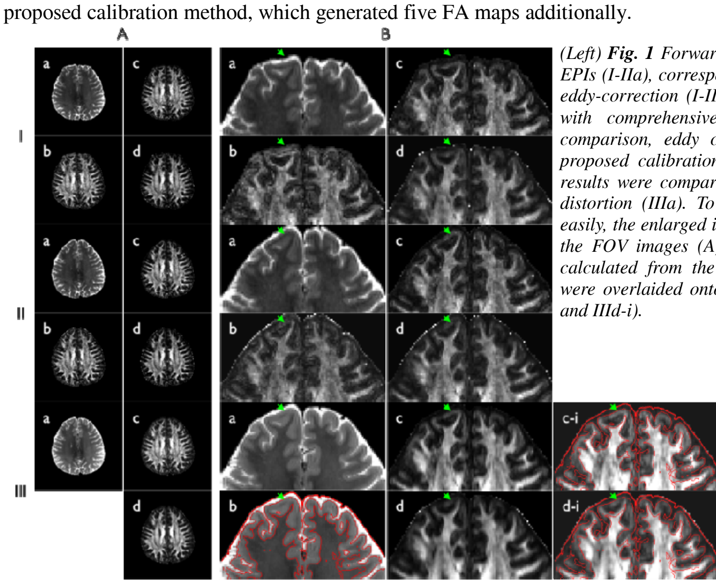
INTRODUCTION A well-known problem in echo-planar imaging (EPI) is geometric distortion due to B_0 field inhomogeneities induced by susceptibility effects in the object. In diffusion weighted EPIs (DW-EPI) used for diffusion tensor imaging (DTI) studies, in addition, the distortions vary due to eddy-currents from direction-dependent diffusion gradients. Although an extended point spread function (PSF) method with a reversed gradient approach [1] can correct susceptibility-induced distortions very accurately, the image-based eddy-current distortion correction performed by FSL [2] is still suboptimal. To improve the correction fidelity, a very fast PSF-based eddy-current calibration method is presented in this study.

METHODS PSF-based eddy-current calibration: In PSF mapping, the PSF image $I(y,s)$ is obtained by multiplying proton density $\rho(s)$ with the PSF $H(y,s)$, a single delta function approximation of the PSF leads to [3]: $I(y,s)=\rho(s)H(y,s)\approx\rho(s)\delta(s+\Delta(s)-y)$ (1), where δ is the Dirac delta function, and s and y correspond to the spin-warp (non-distorted) and EPI (distorted) phase-encoding (PE) coordinates, respectively. The distortion term $\Delta(s)$ represents deviations of the PSFs from the diagonal line along the y-direction in the s-axis. If PSF mapping is performed with diffusion gradients, the total distortion term $\Delta(s)$ becomes a combination of susceptibility $\Delta(s)_{suscep}$ and eddy-current induced geometric distortions $\Delta(s)_{eddy}$: $\Delta(s)=\Delta(s)_{suscep}+\Delta(s)_{eddy}$ (2). Therefore, subtraction between two distortion maps calculated from PSF data with and without diffusion gradient yields only the eddy-current induced distortion (or eddy) map. Since the eddy-currents induced by the DW gradients remain very stable, even over a long time periods, the eddy mapping can be performed once or twice per year [4].

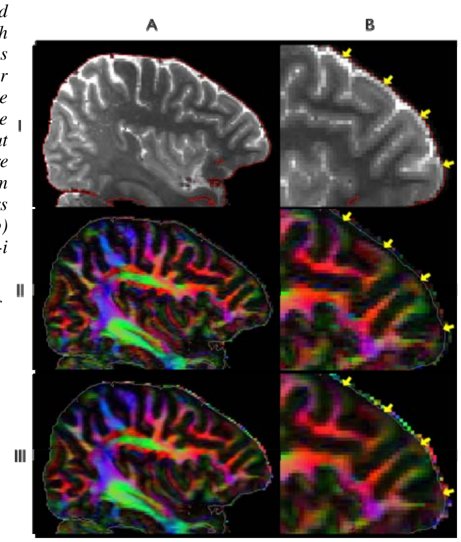
Experiments: All scans were performed on a 7T scanner (Siemens Healthcare, Erlangen, Germany) using a 32 channel coil (Nova Medical, Wilmington MA, USA). (I) For *in-vivo* DTI experiment, a PSF dataset with forward phase-encoding (PE) and pairs of diffusion weighted EPIs (DW-EPI) with forward (F) and reverse (R) PE polarities were acquired. The imaging protocols were: 80 axial slices, slice thickness=1.2 mm, TR/TE=5910/56 ms, BW=1544 Hz/pixel, FOV=224 mm^2, matrix size=180^2, partial Fourier=6/8, grappa factor=3 and the number of diffusion directions for DW-EPI was 30 (b-value=1000 s/mm^2). (II) For eddy-currents calibration, a home-made silicon oil (cylinder shape) phantom was used. Due to the homogeneous magnetic field in this phantom, highly accelerated PSF mapping is possible using a reduced field of view (rFOV) in the PSF dimension [3]. Each forward phase-encoded PSF scan was performed with a rFOV factor of 10 (corresponding to 18 measurements for each direction) and the total calibration time for 31 PSF scans (one with b-value=0 s/mm^2 and 30 with b-value=1000 s/mm^2) was about 30 minutes (18 meas.(each scan)$\times$2 sec.(TR)$\times$31 PSF scans + preparation time). The imaging protocols were identical to the *in-vivo* experiment except for TR/TE = 2000/56ms, 20 axial slices, and slice thickness=4.8 mm. TR and slice number were reduced to minimize the calibration time and slice thickness was increased to keep the same FOV along the slice direction as *in-vivo* experiments and to increase signal to noise ratio (SNR). Since the eddy-current induced distortions vary smoothly along the slice direction, bilinear interpolation was applied to generate the full eddy maps covering the entire slice range of the *in-vivo* experiment.

Comprehensive distortion correction: The eddy-current correction in *in-vivo* DW-EPI data was performed by the final directional eddy maps obtained as described in Ref. [3]. To correct eddy-current induced distortions in the corresponding DW-EPI with opposite PE polarity, the inverted eddy maps were used for the correction. After eddy-current correction, susceptibility-induced distortion correction followed. A pair of EPI-PSF kernels was calculated from the forward PSF reference data and applied to both DW-EPIs with opposite PE polarity [1]. Every distortion-free image was finally generated by weighted summation [1] of the two distortion-corrected images. Based on the distorted (F and R), eddy-current induced distortion-corrected (F and R), both eddy-current and susceptibility induced distortion-corrected (F and R), and combined DW-EPIs, seven fractional anisotropy (FA) maps were calculated. For comparison, FSL [2] was used for eddy-current correction instead of the proposed calibration method, which generated five FA maps additionally.



(Left) ***Fig. 1*** *Forward (I) and reverse (II) phase-encoded EPIs (I-IIa), corresponding FA maps without (I-IIb), with eddy-correction (I-IIc and I-IId) and the final FA maps with comprehensive distortion correction (III): For comparison, eddy correction was performed with the proposed calibration method (c) and FSL (d) and the results were compared with an reference image without distortion (IIIa). To verify the correction quality more easily, the enlarged images of the anterior areas (B) from the FOV images (A) were calculated and red-contours calculated from the enlarged reference image (B-IIIb) were overlaided onto the enlarged final FA maps (IIIc-i and IIId-i).*

(Right) ***Fig. 2*** *A sagittal image of the whole volume reference (I) and corresponding color-coded final FA maps with comprehensive distortion correction (II,III). Different eddy corrections schemes are demonstrated: proposed method (II); and FSL (III). FOV images (A) and the enlarged images of frontal lobes (B) are shown.*



RESULTS AND DISCUSSION Susceptibility-induced geometric distortions were easily seen in both EPIs with opposite PE polarity due to the reverse distortions (Figs. 1Ia and 1IIa). Severe errors in the corresponding forward and reverse FA maps without correction occurred due to the mismatch between DW-EPIs caused by eddy-current induced varying distortions, particularly near boundaries of anterior regions. After eddy-current correction by the proposed method, the errors in the FA map were significantly reduced and a much clearer FA map was obtained (Figs 1Ic and 1IIc). Together with susceptibility-induced distortion correction, the final combined FA map was geometrically matched very well with the reference image as shown in red-contour overlaid on FA map (Fig. 1IIIc-i). In contrast, FSL-based eddy-current correction yielded a more smoothed FA map, which resulted in some loss of spatial detail in the final FA map (see arrows in Fig. 1IIId). Due to very low FA values of cerebrospinal fluid (CSF) near boundary regions, clear gaps between the white contour line and brain tissues appear across the slice direction in the final FA map obtained by the proposed method (II) rather than FSL (III). In other words, slight geometrical mismatch between the final FA map and reference image was obtained by FSL due to suboptimal eddy-current correction (see arrows in Fig. 2).

CONCLUSION The results demonstrate that the proposed eddy-current calibration method allows a superior accuracy compared to image-based correction (FSL) although both corrections overall performed well. Since the extended PSF method corrects susceptibility-induced distortions in both EPIs with opposite PE polarity very well, the combination of the PSF-based methods allows distortion-free DW-EPIs, which enables a reliable analysis in DTI applications.

REFERENCES **[1]** MH In et al., ISMRM 2014 submitted **[2]** FSL, http://fsl.fmrib.ox.ac.uk/fsl/ **[3]** M Zeitsev et al., MRM 2004 **[4]** T-K Truong et al., Neuroimage 2011

ACKNOWLEDGEMENTS Grant support by DFG-grant (SP632-4).