Correcting the bias in the ADC value due to local perturbation fields: a physically informed model

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Introduction: Imaging artefacts, which perturb diffusion-weighted (DW) images, can bias the estimated diffusion tensor. Important sources of imaging artefacts in DTI are eddy current fields (EC fields), gradient nonlinearities or mis-calibration of the gradient amplitude (1-6). They can be modelled by introducing the concept of a local perturbation field (LPF). An LPF affects data differently during the course of the DTI sequence (Fig. 1): Perturbations during the *readout period* cause well known diffusion-gradient-dependent image distortions (1), which are addressed by various methods (see (2) for a summary). Perturbations during the *diffusion weighting period* lead to a mismatch between the effective $\boldsymbol{g}^{\mathrm{eff}}$ and the theoretically assumed diffusion gradients $\boldsymbol{g}^{\mathrm{thr}}$, altering the b-value and thus the DW signal. Bammer et al. proposed a retrospective correction method that accounts for *parallel* and *perpendicular* LPF gradients (4). However, their method account solely for gradient nonlinearities and vendor-specific information is necessary to calculate the perturbation field. Another correction method, which can be applied to any sequence or scanner, was suggested by Nagy et al. (5,6). They measured the apparent diffusion coefficient (ADC) of a water phantom to estimate a scaling factor (5) or a scaling field (6) to correct for the deviation of the read, phase and slice diffusion gradient. However, the method of Nagy et al. did not account for perpendicular LPF gradients. In this study, we used first order perturbation theory (7) to introduce a physically informed model that combines the advantages of both studies. We applied the model to phantom and human DTI data acquired on two different scanners.

Model: The DW signal that is measured by applying a diffusion gradient in the *i*th direction is given by Eq. [1] in Eq.-Fig.. To estimate the matrix $\boldsymbol{\Sigma}(\boldsymbol{r})$ of the LPF in first order, we measured the diffusion coefficient D_{W} in an isotropic water phantom (see Eq.-Fig., Eq. [3], where the elements of the symmetric matrix $\mathbf{A}(\boldsymbol{r})$ are quadratic functions of the elements of the perturbation matrix $\boldsymbol{\Sigma}(\boldsymbol{r})$). Estimating $\boldsymbol{\Sigma}(\boldsymbol{r})$ was divided into two stages: In the first step, we used the diffusion-tensor formalism to estimate $\mathbf{A}(\boldsymbol{r})$ on a voxel-by-voxel basis. In the second step, we estimated $\boldsymbol{\Sigma}(\boldsymbol{r})$ from $\mathbf{A}(\boldsymbol{r})$ using a linear approximation in the perturbation matrix elements that was constrained to second-order spatial dependency. We assessed face validity of the model by simulations with realistic noise models (not shown).

<u>Eq.-Fig.:</u> Diffusion signal:

$$\ln\left(\frac{S_0}{S_i}\right) = b\, {\boldsymbol{g}^{\mathrm{eff}}_i}^{\mathrm{T}}\, \mathrm{D}(\boldsymbol{r})\, \boldsymbol{g}^{\mathrm{eff}}_i = b\, {\boldsymbol{g}^{\mathrm{thr}}_i}^{\mathrm{T}}\, \mathrm{D}'(\boldsymbol{r})\, \boldsymbol{g}^{\mathrm{thr}}_i \quad (1)$$

with

$$\boldsymbol{g}^{\mathrm{eff}}(\boldsymbol{r},t) = (\mathrm{I}_3 - \Sigma(\boldsymbol{r}))\, \boldsymbol{g}^{\mathrm{thr}}(t) = \mathrm{M}(\boldsymbol{r})\, \boldsymbol{g}^{\mathrm{thr}}(t)$$

and the perturbed diffusion tensor

$$\mathrm{D}(\boldsymbol{r})' = \mathrm{M}(\boldsymbol{r})^{\mathrm{T}}\mathrm{D}(\boldsymbol{r})\mathrm{M}(\boldsymbol{r}) \quad (2)$$

Isotropic diffusion:

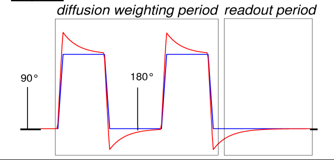
$$\ln\left(\frac{S_0}{S_i}\right) = b\, D_w\, {\boldsymbol{g}^{\mathrm{thr}}_i}^{\mathrm{T}} \underbrace{\mathrm{M}(\boldsymbol{r})^{\mathrm{T}}\, \mathrm{M}(\boldsymbol{r})}_{=\mathbf{A}(\boldsymbol{r})} \boldsymbol{g}^{\mathrm{thr}}_i \quad (3)$$

Methods: We acquired two DTI data sets from a healthy male subject with informed consent (DTI1 and DTI2). DTI1: 3T Siemens TIM Trio with a 12-ch headcoil (twice-refocusing spin echo (3,5), 61 DW images in non-collinear directions and with b = 1000 mm/s^2 and 7 images with low DW b=0 mm/s^2, matrix 96^2, 60 slices, resolution 2.3mm^3). DTI2: 3T GE Signa HDx 8-ch headcoil for signal reception (Stejskal-Tanner sequence (8), parallel imaging factor 2, 52 DW images in non-collinear directions and with b = 1200 mm/s^2, matrix 96^2(reconst. to 128^2), 60 slices, resolution: 1.9mm in-plane, 2.4mm slice). Both DTI data sets were preprocessed (corrected for motion and EC image distortions during readout (2)). Then, we used the new method to estimate the LPF and correct the diffusion tensor for the effects of LPFs during the diffusion weighting period. To assess the importance of the perpendicular LPF gradients, we performed two different corrections: 1) we used solely the diagonal elements of the perturbation matrix, which account for the parallel LPF gradients, 2) we used the entire perturbation matrix (parallel and perpendicular LPF gradients). We compared the measured FA map (FA$^{\mathrm{meas}}$) to the FA maps corrected with correction 1 (FA$^{\mathrm{cor1}}$) and 2 (FA$^{\mathrm{cor2}}$).

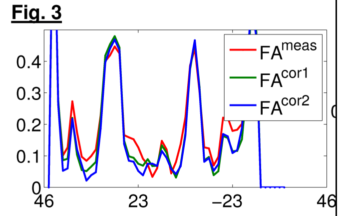
Results and Discussion: The magnitude of the amplitude range of the LPF in DTI2 (Fig. 2a) was five times higher than in DTI1 (not shown). Thus, the proposed method had almost no effect on the DTI1-based FA maps, but for the DTI2 data the improvement in FA map quality can be seen (Fig. 2). The corrected FA maps were more clearly delineated and showed stronger grey to white matter contrast (Fig. 2c-e). In particular, near to the cortex the corrected FA maps showed a reduction in FA (2f-g, and 3). This is in line with the observation of Bammer et al., who showed that the FA value of a water phantom that was subject to a strong LPF significantly decreased after correction (5). Therefore, we conclude that the quality of the FA maps was improved after correction. The improvement in FA map quality was even more evident, when both the parallel and perpendicular LPF gradients were used to correct the DTI data (Fig. 2e, 2g and 3).

Conclusion: Using water phantom DTI measurements and a physically informed model we were able to estimate LPFs and improve the quality of FA maps without requiring vendor-specific information. We showed that our method performed better if both the parallel and perpendicular LPF gradients were taken into account. FA maps are most susceptible to LPFs near to the cortex, because low FA values are more sensitive to perturbations (9) and because, generally, the cortex is furthest away from the isocentre. Thus, our method could help to improve the quality of FA maps near to the cortex. This might be important for high resolution scans at 7T or higher fields (10), where stronger diffusion gradients are required and so the LPFs are more pronounced. Our correction method might also be beneficial in tractography studies, which require precise boundaries between grey and white matter. **<u>References:</u>** [1] Haselgrove, MRM **36**, 960 ('96), [2] Mohammadi, MRM **64**, 1047 ('10), [3] Reese, MRM **49**, 177 ('03), [4] Bammer, MRM **50**, 560 ('03), [5] Nagy, MRM **58**, 763 ('07), [6] Nagy, ISMRM 17, Abstract: 849 ('09), [7] Arfken, Academic Press, San Diego (95'), [8] Stejskal, JCP **42**, 288 ('65), [9] Pierpaoli, MRM **36**, 893 ('96), [10] Heidemann, MRM **64**, 9 ('10). **Acknowledgments:** Funded by the Wellcome Trust.

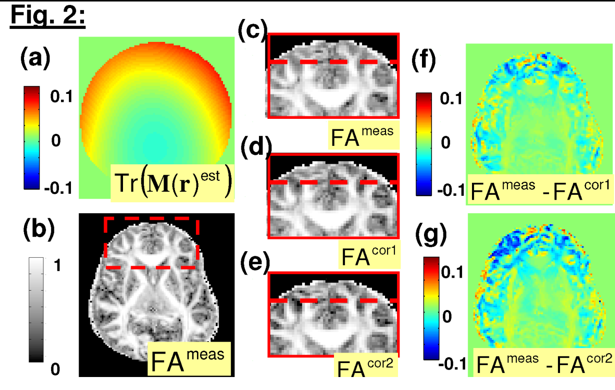
<u>Fig. 1:</u>



<u>Fig. 3</u>



<u>Fig. 2:</u>



<u>Fig. 1:</u> Stejskal-Tanner sequence (8). Difference between theoretical (blue) and effective (red) diffusion gradient is depicted for the example of EC LPFs .
<u>Fig. 2:</u> The DTI2 data set: (a) the trace of the estimated perturbation matrix (in percent), (b) the measured FA in log-scale to stress improvement in grey/white matter contrast, (c-e) highlighted region in (a) for: (c) measured FA, (d) corrected FA using correction 1, and (e) corrected FA using correction 2, (f and g) difference image between measured and corrected FA (dark blue in grey matter reflects strong correction).
<u>Fig 3:</u> Profile of FA map (cf. Fig. 2c-e, dashed line).