Diffusion gradient correction in Diffusion Kurtosis Imaging

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Introduction

Diffusion Tensor Imaging (DTI) (1) is an important MRI technique that can quantify Gaussian water diffusion in vivo. It suffers from a number of artifacts due to its very demanding imaging sequence. A major source of artifacts is patient motion during image acquisition. Typically, it is compensated by image registration in post-processing. However, even if a perfect image registration is achieved, a problem in DTI still exists because of inconsistence between the gradient directions and the reoriented diffusion-weighted images (2). Diffusion Kurtosis Imaging (DKI) (3), an extension of DTI, is more sensitive to this fundamental problem, for the reason that multiple b values and high angular resolution are required. To address this problem, we incorporate the coordinate space transformation of gradient directions after image realignment. These corrections successfully lead to significantly improved Mean Kurtosis (MK) maps.

Algorithm

The diffusion-weighted signal S_n in DKI model (3) is:

$$\mathrm{S_n} = S_0 \exp\left(-bD_n + \frac{1}{6}b^2 D_n^2 K_n\right) + \eta$$

where n indexes the gradient direction, D_n is directional diffusivity, K_n is directional kurtosis, and η is background noise with constant variance σ^2. Note that fitting this equation for each single direction requires exact the same gradient direction regarding to patient's orientation for all the b values. The requirement can be removed by writing the signal in its tensor expression:

$$\ln(\mathrm{S_n}) = \ln(S_0) - \mathrm{b}\sum_{i=1}^{3}\sum_{j=1}^{3}\mathrm{n_i n_j D_{ij}} + \frac{1}{6}\mathrm{b}^2\sum_{i=1}^{3}\sum_{j=1}^{3}\sum_{k=1}^{3}\sum_{l=1}^{3}\mathrm{n_i n_j n_k n_l W_{ijkl}}\left(\frac{1}{3}\sum_{m=1}^{3}\mathrm{D_{mm}}\right)^2 + \varepsilon$$

where n_i is the component of gradient direction n. Similar to the B-matrix defined in DTI, a B_K-matrix can be defined for each diffusion-weighted volume :

$$\mathbf{B_K^n} = [1, -\mathrm{bn_i n_j}, \frac{1}{6}\mathrm{b^2 n_i n_j n_k n_l}]$$

The B_K-matrix is calculated in source space V at first. After image realignment, it is rotated into reference space V' that $\mathbf{B_K^{n}}' = \boldsymbol{R}\mathbf{B_K^n}$, where $\boldsymbol{R}$ is a rotation operator defined by the pitch (x-axis rotation), roll (y-axis rotation), and yaw (z-axis rotation) estimated from the previous image registration.

Experiments

A healthy volunteer was scanned on a Philips 3T Achieva MRI scanner (Philips Healthcare, Best, The Netherlands) under an approved Institution Review Board (IRB) protocol. A standard DTI sequence was used for its clear definition of diffusion time. One DKI experiment consisted of four 32-directions DTI scans with b values of 500, 1000, 1500, and 2000 s/mm^2. For each scan, one b0 volume and thirty-two diffusion-weighted volumes were acquired. The other imaging parameters were: TE = 85 ms, TR = 3312 ms, FOV = 224 x 224 mm2, voxel size = 1.5 x 1.5 x 1.5 mm3, 20 axial slices, SENSE factor 2, NSA = 2. The volunteer stayed still in the first experiment (the reference experiment). In the second experiment, the volunteer was asked to perform an in-plane rotation before the last scan of b = 500 s/mm^2 and maintain the position until the scan is completed. The data was then processed by a MATLAB script constituted of MATLAB toolboxes, SPM8, and FSL commends. Also the gradient correction algorithm was validated with FSL.

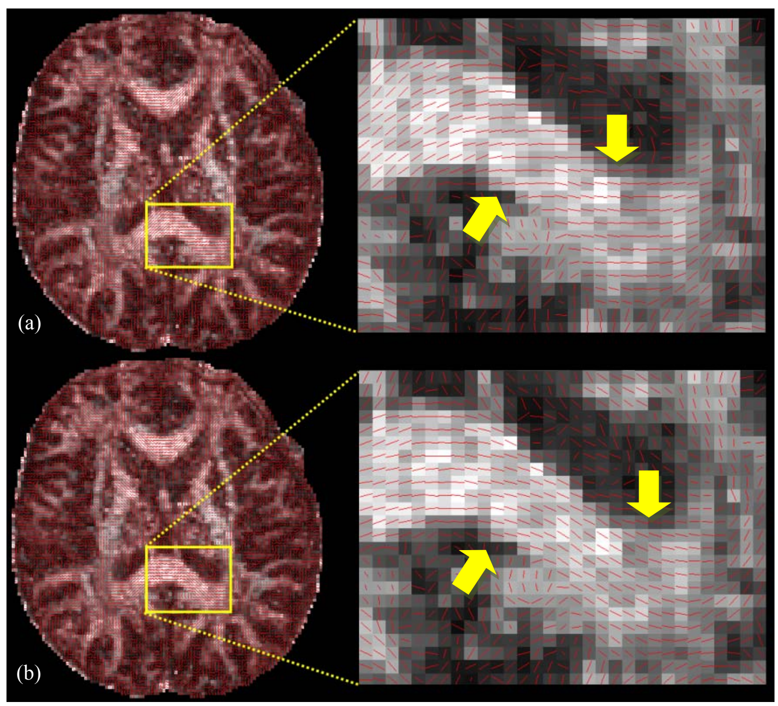

Fig. 1: The principle diffusion direction overlay with FA map in the b500 scan acquired during motion: (a) without gradient correction; (b) with gradient correction

Results and Conclusion

The largest estimated motion was yaw = 22°. Without gradient correction (Fig. 1 (a)), the principle directions cross the fiber structure in the corpus callosum as highlighted by the arrow. With gradient correction (Fig. 1 (b)), the directions are now correctly following the anatomical structure. As shown in Fig. 2, the structure destroyed in (a) is mostly recovered in (b). The residual negative kurtosis is most likely caused by poor image registration. The results demonstrate the benefit of reorientation of B_K-matrix and significant improvement of robustness and reproducibility of MK using our DKI system.

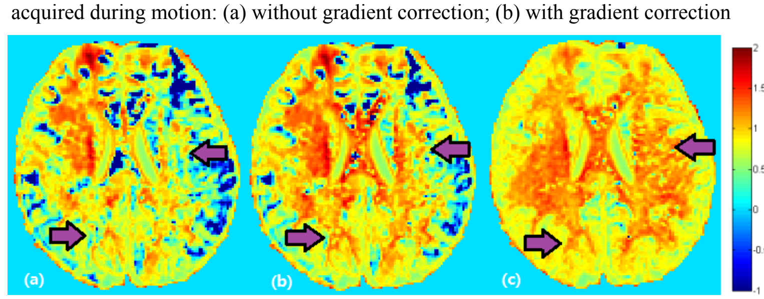

Fig. 2: The MK maps of the same slice: (a) without gradient correction; (b) with gradient correction; (c) the reference experiment

References

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