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:

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

where $n$ indexes the gradient direction, $D_n$ is directional diffusivity, $K_n$ is directional kurtosis, and $\eta$ is background noise with constant variance $\sigma^2$. 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:

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

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:

$$B_k = [1, -b n_i, \frac{1}{6} b^2 n_i n_j n_k n_l]$$

The $B_k$-matrix is calculated in source space $V$ at first. After image realignment, it is rotated into reference space $V'$ that $B_k' = RB_k$, where $R$ 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 Institutional 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/mm². For each scan, one $b_0$ 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/mm². 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.

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.

References