Multiple Fiber Orientations Resolved by Generalized Diffusion Tensor Imaging

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Introduction

Diffusion tensor imaging (DTI) is known to be incapable of resolving complex fiber structures. This has prompted the use of more complicated models to extract the fiber orientations from the directional diffusion measurements. In a method introduced recently, the Bloch-Torrey equation is modified with the inclusion of a phenomenological diffusion term employing a Cartesian tensor of rank higher than 2 [1]. This equation is solved and the corresponding echo attenuation is quantified by a generalized Stejskal-Tanner formula given by

$$S = S_0 \exp\left(-b \sum_{i_1=1}^{3} \sum_{i_2=1}^{3} \cdots \sum_{i_r=1}^{3} D_{i_1 i_2 \ldots i_r} g_{i_1} g_{i_2} \ldots g_{i_r} \right),$$

where S_0 is the non-diffusion weighted signal, b is the b-value, $D_{i_1 i_2 \ldots i_r}$ is the rank-r diffusion tensor, and g_{i_n} is the i_n-th component of the gradient direction. Although this scheme makes it possible to estimate apparent diffusion coefficients along an arbitrary orientation, the diffusivity profiles are not readily capable of producing distinct fiber orientations since the fiber directions do not necessarily correspond to the peaks of the diffusivity profile. However, the diffusivity profiles do have some orientational information, which was shown by simulations [2].

In this work, we simulate a high angular resolution diffusion imaging (HARDI) experiment for one, two and three fiber systems and show that if the q-space signal is artificially constructed by assuming monoexponential attenuations along each direction, then the corresponding displacement probabilities can be used to find the different fiber orientations. Therefore, the well-known “crossing fibers” problem of traditional (rank-2) DTI can be resolved by clinically feasible experiments at low b-values using generalized DTI.

Methods

The magnetic resonance signal attenuation in a cylindrical geometry, when the diffusion gradient makes an angle θ with the cylinder's axis, is given in Ref. [3]. Using this expression, we have simulated HARDI, q-space and rank-2 DTI experiments using magnetic field gradients of 1500 s/mm^2 applied along 81 directions, where the cylinders were taken to have a length 5mm, radius 5μm, free diffusivity of water 2.0x10^{-3} mm^2/s, Δ=20.8ms and δ=2.4ms. Together with an image at b=0 s/mm^2, we have calculated the apparent diffusion coefficient profiles, as well as the rank-8 diffusion tensor. Since in the generalized tensor model the diffusivity along some direction $\hat{g}$ is given by

$$D(\hat{g}) = \sum_{i_1=1}^{3} \sum_{i_2=1}^{3} \cdots \sum_{i_8=1}^{3} D_{i_1 i_2 \ldots i_8} g_{i_1} g_{i_2} \cdots g_{i_8},$$

the signal attenuation along any direction can be calculated. Under the free diffusion assumption, in which case the signal will attenuate in a monoexponential fashion, the q-space spectrum is calculated. The Fourier transform of this gives the desired displacement profiles.

Results and Discussion

Simulation results are presented in Fig. 1. The equiprobability surfaces obtained from generalized DTI are consistent with the outcomes of the q-space simulations as well as the known orientations of the fibers. Diffusivity (ADC) profiles and traditional (rank-2) DTI failed to produce meaningful results. This simulation suggests that it may be possible to resolve orientational heterogeneity within the voxel by using generalized DTI and without necessarily covering all of q-space, reducing the requirements on gradient systems and imaging time.

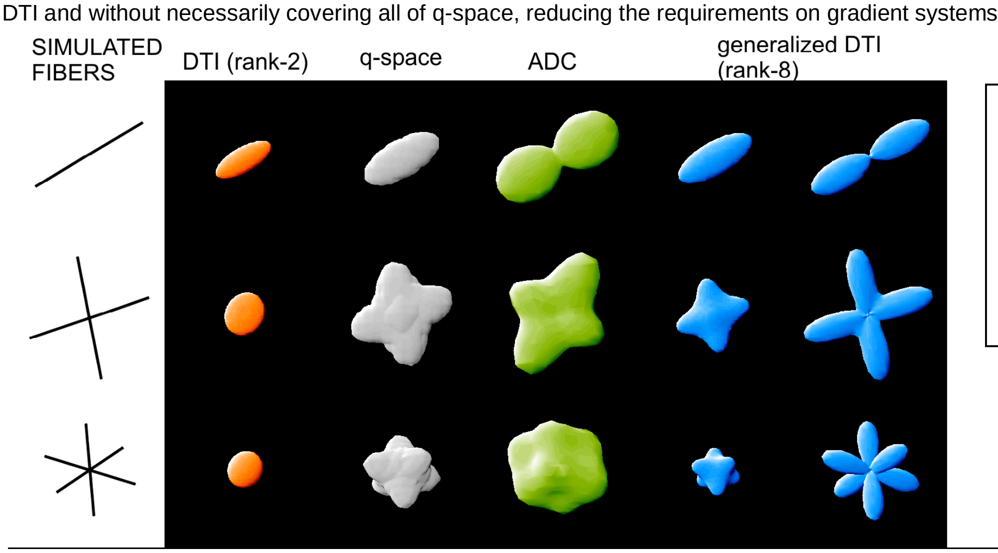

Fig. 1: On the left are the orientations of the fibers simulated. The equiprobability surfaces for traditional DTI (orange), q-space imaging (gray) and generalized DTI simulations are presented (blue). Also shown is the apparent diffusion coefficient profile (green). The second blue column is just the isosurface of the displacement probability profile after a sharpening transformation.

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