Quantitative Analysis of q-space MRI Data: Theoretical and Experimental Validation

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Introduction

Diffusion Tensor Imaging (DTI [1]) cannot resolve crossing fibers [2], and other methods such as Diffusion Spectrum Imaging (DSI [2]), CHARMED [3], q-ball imaging (QBI [4]) and high angular resolution diffusion imaging (HARDI [5]) have been developed to remedy this problem. These approaches are all based on the extensive sampling of the echo attenuation in *q*-space, for many orientations and one (DTI, QBI, HARDI) or several (DSI, CHARMED) *q* values. In an attempt to lessen the burden on the acquisition phase, we propose a quantitative analysis of *q*-space MRI data (QUAQ) that merges *q*-space MRI with the physics of the diffusion process. The simplistic assumption of unrestricted anisotropic diffusion inside fibers leads to the decomposition of the signal in *q*-space into multi-Gaussian functions (MDTI). Conversely, QUAQ stems from a physically correct model of diffusion inside a network of cylindrical fibers, and constitutes the first attempt to quantitatively estimate the characteristics of the problem (diffusion constants and fiber orientations) using less input data that existing DWMRI methods require (~500 measurements in [2]).

Methods

Based on [6], an analytical formula is derived for the echo attenuation for m cylindrical fibers of radius a_m filled with a liquid with longitudinal and transverse diffusivities $D_{//}$ and $D_{\perp}$, assuming short pulsed gradients (gradient duration δ << diffusion time Δ). This formula depends on the experimental parameters (δ, Δ, diffusion gradient strength and orientation: g and θ) and the physical parameters (a_m, $D_{//}$, $D_{\perp}$, fiber orientation θ_m and volume fraction f_m). A Levenberg-Marquardt algorithm is used to fit the echo attenuation data to the analytical formula via nonlinear least-squares minimization. Assuming that a judicial choice for the axon diameter a_m can be made from prior histological knowledge, we choose $D_{//}$, $D_{\perp}$, f_m and θ_m as the fitting parameters. Our proposed method is first tested numerically and compared to DTI for single fibers and MDTI for two crossing fibers. The influence of the sampling density in *q*-space, noise in the input data and the use of data averaging to mitigate the noise level are investigated. Uncertainty is introduced in the synthetic data in the form of rectified Gaussian noise. Experimental validation of our methodology is provided via a 2×2×1 cm^3 phantom consisting of perpendicular bundles of microchannels with a_m = 50 μm (Cole-Parmer Instrument Co., Vernon Hills, IL, USA), filled with water ($D_{//} = D_{\perp} = 1.2\ 10^{-9}\ m^2/s$ at 12°C). MRI experiments were conducted using a Varian 14.1T NMR imager with gradient capabilities of up to 100 G/cm. A pulsed-field gradient stimulated-echo sequence is used with the following experimental parameters: FOV = 2.5×2.5 cm^2, 1 cm slice thickness, TR/TE = 1500/14 ms, 16×16 matrix size, δ = 5 ms, Δ = 250 ms, g up to 5 G/cm (q_{max} = 106.5 cm^{-1}). A high-resolution spin-echo image (Fig. 1) provides the validation of the QUAQ (Fig. 2) and MDTI (Fig. 3) reconstructions.

Results and discussion

Numerical results indicate that QUAQ recovers all the physical parameters for the same number of data points typically acquired for DTI (N_o = 15 orientations and N_g = 2 q values) while MDTI performs quite well for $D_{//}$ and θ_l, but underestimates $D_{\perp}$. Application of QUAQ and MDTI to MRI data is illustrated in Fig. 2 and 3. The geometry of the crossing-fiber phantom is recovered by both methods using 30 data points in *q*-space (N_o = 15, N_g = 2, N_t = 6 averages). The influence of the experimental parameters (N_t, N_g, N_o) is as follows. N_t is used to obtain a SNR sufficiently large to yield exploitable results (eg. N_t = 8 in [5]). Both the number N_g and the distribution of q values are important. While N_g > 1 is necessary for QUAQ by construction, larger q (or g) values should be sampled to the limit that the SNR remains high enough. The number of orientations N_o needs to be sufficiently large to determine the orientation of the fibers accurately, however since the variation of the normalized echo attenuation on a sphere at q constant is more pronounced for large q values, N_o does not need to be excessively large provided data is collected for q large. We have shown here that a total of 31 q values are sufficient to recover the fiber bundle geometry, to be compared with 127 for HARDI [5], 253 for QBI [4], 496 used for CHARMED [3], and 515 used for DSI [2].

References

[1] Basser PJ, Jones DK, NMR Biomed 2002;15:456-467. [2] Lin C et al, NeuroImage 2003;19:482-495. [3] Assaf Y et al, Magn Reson Med 2004;52:965-978. [4] Tuch DS, Magn Reson Med 2004;52:1358-1372. [5] Tu ch DS et al, Magn Reson Med 2002;48:577-582. [6] Callaghan PT, J Magn Reson Series A 1995;113:53-59.

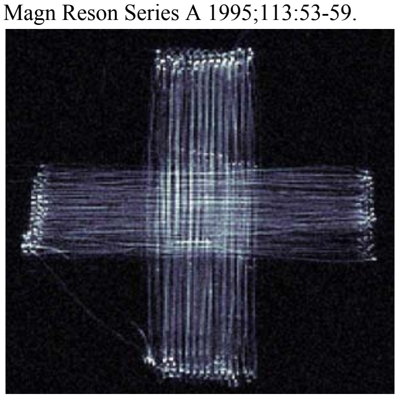

Figure 1. High-resolution spin-echo image of the experimental phantom.

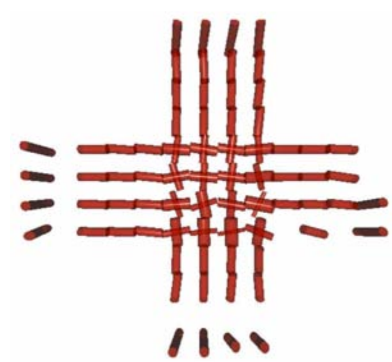

Figure 2. QUAQ reconstruction of the experimental fiber network.

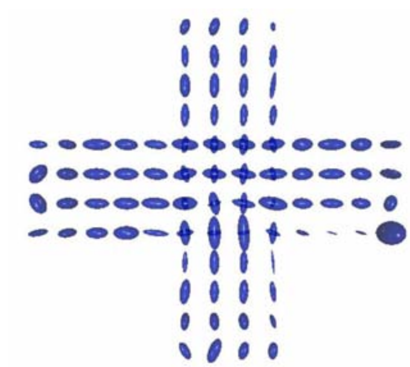

Figure 3. MDTI reconstruction of the experimental fiber network.