QUANTITATIVE ANALYSIS OF Q-SPACE DATA: THEORETICAL AND EXPERIMENTAL VALIDATION

L. Guy Raguin1 (raguin@uiuc.edu), D. Hernando2, D. C. Karampinos1, L. Ciobanu2, Z.-P. Liang2, J. G. Georgiadis1

1Department of Mechanical Engineering, 2Department of Electrical & Computer Engineering
3Biomedical Imaging Center, Beckman Institute for Advanced Science and Technology, University of Illinois at Urbana-Champaign, Urbana, IL

Introduction:
Diffusion Tensor Imaging (DTI) [1] cannot resolve crossing fibers [2]. 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 overcome 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 reduce the acquisition time, we propose a quantitative analysis of q-space MRI data (QUAQ) that merges q-space MRI with the physics of the diffusion process, and a simplified version (SQUAQ) that requires fewer parameters than DTI.

Methods:
An analytical formula is derived from [6] for the echo attenuation E obtained by Diffusion-Weighted MRI (DWMRI) for m cylindrical fibers of radius am filled with a liquid with self-diffusion D, assuming short pulsed gradients (gradient duration δ ≪ diffusion time Δ), which depends on the experimental (Lq) and physical parameters (am, D, fiber orientation angles, and fraction fam). The echo attenuation data is fitted via nonlinear least-squares minimization (Levenberg-Marquardt). Assuming a spherical choice for the axon diameter am, the self-diffusion D and the fiber orientation angles can be made from iterations or prior histological knowledge, we choose f = am, D, and ψm as the fitting parameters. An alternate method (SQUAQ) is tested: by assuming unrestricted anisotropic diffusion and imposing isotropy in the plane transverse to the fiber orientation, the echo attenuation takes the form of a Gaussian function with a diffusion tensor with only four parameters (instead of six for DTI).

Numerical Validation
Numerical noise is introduced in the simulated data in the form of rectified Gaussian noise [7]. Numerical results (see Table 1 and Fig. A) indicate that QUAQ and SQUAQ recover all the physical parameters for 60 data points (Nq = 30 orientations and Nq = 2 q-values) up to 10%-20% noise (SNR above 5-10). Fiber sizes are 5 μm with one fiber contributing to 40% of the signal, Δ/Δ = 5/60 ms and q = 277, 404 cm⁻¹.

Results for Fiber-Crossing Phantom:
A 2D x-y-z fibre-crossing phantom consisting of perpendicular bundles of microchannels with am = 50 μm (Cole-Parmer, Vernon Hills, IL), filled with water (D = D//= Dzz = 1.2 x 10⁻⁹ m²/s at 12°C) is imaged using a pulsed-field gradient stimulated-echo sequence with the following experimental parameters: δ/Δ = 5/250 ms, g up to 5 G/cm (qmax = 106.5 cm⁻¹) at low resolution with Nex = 6, see Fig. B(2). A high-resolution spin-echo image (Fig. B(1)) provides the validation of the QUAQ and SQUAQ reconstructions (Fig. C). The geometry of the fiber-crossing phantom is recovered by both methods using 30 data points in q-space.

Conclusions:
QUAQ stems from a physically correct model of diffusion inside a network of cylindrical fibers, and attempts to quantitatively estimate the characteristics of the problem (diffusion constants and fiber orientations) using less input data that existing DWMRI methods require. We have shown here that a total of 31 q-values are sufficient to recover the fiber-crossing phantom geometry and 90 for the section of human pons, to be ... version SQUAQ performs well. The addition of an extra-axonal compartment into QUAQ has been successfully tested.

Acknowledgments:
L. Guy Raguin, raguin@uiuc.edu, http://netfiles.uiuc.edu/raguin/www

Contact Information:
L. Guy Raguin, raguin@uiuc.edu, http://netfiles.uiuc.edu/raguin/www

References:

Table 1. Numerical validation of QUAQ and SQUAQ for two crossing fiber populations using 400 runs for statistical analysis. am is the average standard deviation for the fit of the fiber orientation angles (θx, θy, and θ2), and Δ/Δ is the variation in the sampling points. Noise is represented by its standard deviation. The results are shown for a single fiber orientation with 100 G/cm in (1) and with 250 G/cm in (2).

<table>
<thead>
<tr>
<th>Fiber Population</th>
<th>QUAQ</th>
<th>SQUAQ</th>
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<tbody>
<tr>
<td>(1)</td>
<td>(2)</td>
<td>(1)</td>
</tr>
<tr>
<td>am (μm)</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>D (m²/s)</td>
<td>1.2 x 10⁻⁹</td>
<td>1.2 x 10⁻⁹</td>
</tr>
<tr>
<td>δ/Δ (ms)</td>
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<td>5</td>
</tr>
<tr>
<td>Nex</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>SNR</td>
<td>5</td>
<td>10</td>
</tr>
</tbody>
</table>

Fig. A. Average error and uncertainty in determining the fiber orientations using QUAQ and SQUAQ with 60 q values (Nq = 30 orientations and Nq = 2 q-values).

Fig. B. Imaging of the fiber-crossing phantom (FOV 2.5 x 2.5 cm², thickness = 1 cm): (1) High-resolution spin-echo image (matrix size = 256 x 256, TR / TE = 1000 / 10 ms); (2) Non-diffusion-weighted stimulated echo (16 x 16, TR / TE = 1500 / 14 ms).

Fig. C. Fiber reconstruction for fiber-crossing phantom using (1) QUAQ, (2) SQUAQ using 90 q values (Nq = 3 q-values, Nex = 6, and q = 277, 404, 468 cm⁻¹).

Fig. D. Section of human pons: (1) digital photograph with placement inside brain; (2) high resolution spin echo image (matrix size = 256 x 256, TR / TE = 1000 / 10 ms); (3) QUAQ fiber reconstruction; and (4) QUAQ crossing fiber reconstruction overlaid on top of high resolution spin-echo image. QUAQ was used with 90 q-values (Nq = 3, Nq = 15 orientations, Nex = 6). Color scheme: x = green, y = red, z = blue.