Dataset-independent reconstruction of high angular resolution diffusion sampling schemes by generalized q-space imaging

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Abstract We propose a novel q-space imaging method called generalized q-space imaging (GQI), which is derived from the Fourier transform relationship between the MR signals and underlying diffusion displacement [1]. The method is characterized by being independent of the q-space sampling schemes, enabling us to use either q-ball imaging (QBI) [2] or diffusion spectrum imaging (DSI) dataset [3]. The accuracy of the proposed method is examined under the comparison with spherical harmonics based QBI and DSI.

Introduction DSI and QBI are q-space imaging methods able to resolve crossing fibers. However, DSI is limited by its specific q-space sampling scheme, while for QBI, the relation between the orientation distribution functions (ODFs) and the MR signals is only partially fulfilled. Since diffusion MR signals and the underlying diffusion displacement are related by the Fourier transform, all MR signals obtained by different gradient vectors contribute to ODF in any direction, which is not fully exploited by Funk-Radon transform. In this study, the characteristics of the relation between diffusion MR signals and ODF was investigated, from which a new q-space imaging method was proposed to directly characterize the diffusion displacement distribution.

Theory The Fourier relationship between diffusion MRI signals and diffusion displacement can be rewritten as a cosine transform under the assumption that the MR signals are symmetric regarding to the origin; that is S(**q**) = S(-**q**):

$$\mathbf{p}(\bar{\mathbf{r}}) = \frac{\mathbf{1}}{\mathbf{8\pi^3 S_0}} \int_{\mathbf{R^3}} \mathbf{S}(\bar{\mathbf{q}}) \cos(\bar{\mathbf{q}} \cdot \bar{\mathbf{r}}) \mathbf{d^3}\bar{\mathbf{q}}$$

While the ODF definition is the integration along each direction in the diffusion displacement PDF space p(**r**), by replacing the PDF with ODF, the above equation can be formulated as a sinc function relationship between the MRI signals and ODF.

$$\begin{aligned}\psi(\hat{\mathbf{u}}) &= \frac{\mathbf{1}}{\mathbf{8\pi^3 S_0}} \int_{\mathbf{0}}^{\mathbf{L}} \int_{\mathbf{R^3}} \mathbf{S_\Delta}(\bar{\mathbf{q}}) \mathbf{cos}(\mathbf{r}\,\bar{\mathbf{q}} \cdot \hat{\mathbf{u}}) \mathbf{d^3}\bar{\mathbf{q}}\,\mathbf{dr} \\ &= \frac{\mathbf{L}}{\mathbf{8\pi^3 S_0}} \int_{\mathbf{R^3}} \mathbf{S_\Delta}(\bar{\mathbf{q}}) \mathbf{sinc}(\mathbf{L}\,\bar{\mathbf{q}} \cdot \hat{\mathbf{u}}) \mathbf{d^3}\bar{\mathbf{q}}\end{aligned}$$

, where L is the sampling distance in the PDF space. Instead of normalizing the ODF, we obtain b0-weighted ODF that enables inter-voxel comparison. The discrete form equation for calculating b0-weighted ODF is as follows:

$$\psi_{b0}(\hat{\mathbf{u}}) = \frac{\mathbf{L}}{8\pi^3} \sum_{\forall \bar{\mathbf{q}}} \mathbf{S_\Delta}(\bar{\mathbf{q}}) \mathbf{sinc}(\mathbf{L}\bar{\mathbf{q}} \cdot \hat{\mathbf{u}})$$

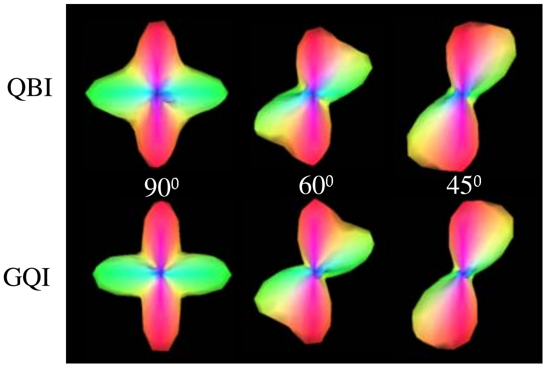

FIG. 1. The ODFs reconstructed from the simulated diffusion MR signals. The ODF of different crossing angles are presented to compare the result generated by QBI and GQI.

Materials and Methods Simulation was conducted to evaluate the accuracy of GQI in comparison with QBI. The simulation model was based on mixed Gaussian model with two equal volume fraction fiber populations crossed in 45^0, 60^0 and 90^0. The fractional anisotropy was 0.5 and mean diffusivity was 1.0×10^{-3} mm^2/s for both fiber populations. Rician noise was added under b0 SNR 50. Simulated MR signals were obtained by using a 252-direction b-table with b-value 3000 s/mm^2, and reconstructed by both QBI (spherical harmonic based)[4] and GQI in diffusion distance L = 40μm (assuming that diffusion time 80μm and diffusion gradient duration 35μm).

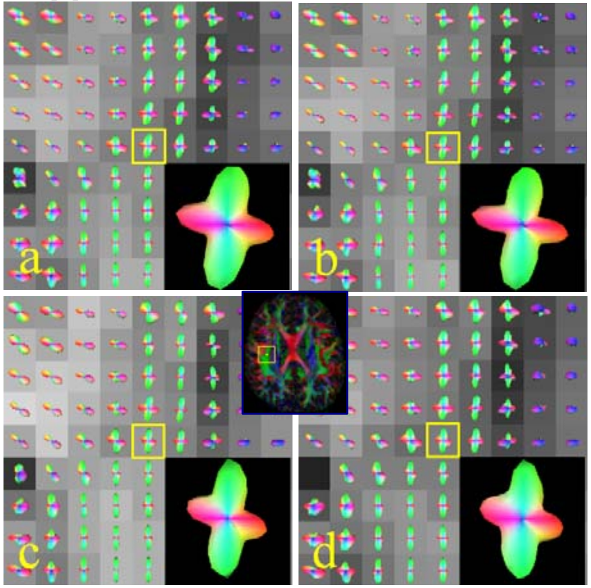

FIG. 2. Axial views of the reconstructed in vivo images including (a) HARDI reconstructed by QBI, (b) HARDI reconstructed by GQI, (c) DSI203 dataset reconstructed by DSI method, and (d) DSI203 dataset reconstructed by GQI. The ODFs in the center are zoomed in to highlight the consistency of the proposed method to QBI and DSI.

In vivo data of a 25-year-old volunteer were obtained on a Siemens 3T MRI TIM scanner with a 12-channel head coil and single-shot echo-planar imaging sequence. HARDIs were obtained by the 252-direction b-table with b-value 4000 s/mm^2, whereas DSI images were scanned in the 203-point grid scheme with b-max 5000 s/mm^2. For both scanning scheme, the field of view was 240mm x 240mm, matrix size 96x96, slice number 40, slice thickness 2.5mm, resulting in isotropic voxel size of 2.5mm. The TR = 7200ms for QBI and DSI, TE = 133ms (QBI) and 144ms (DSI), and the scanning time = 30 mins (QBI) and 25 mins (DSI). Both image datasets were reconstructed by GQI methods as well as their own reconstruction methods.

Results The simulation result is illustrated in Fig. 1. The consistency between QBI and GQI could be observed from the ODFs of different crossing angles. On the other hand, the axial views of reconstructed in vivo images are presented in Fig. 2. The result also suggested that the GQI could present consistent ODF pattern with QBI, and the GQI reconstruction of the DSI dataset also demonstrated similar pattern as DSI method. Both the simulation and in vivo result suggested that the proposed method is compatible with the QBI and DSI sampling scheme, and the ODF presentation of the GQI is consistent with QBI and DSI.

Discussion and Conclusion Besides the consistency, the proposed method is simpler to implement, and it requires less computation effort. Moreover, the feature of dataset independence enables future studies that focus on developing an optimum sampling scheme, which may reduce scanning time and make q-space imaging widely applicable in clinical studies. In addition, the b0-weighted ODFs obtained in GQI offer researchers to compare the ODFs in different voxels of the same subject, which is not provided in the previous q-space imaging studies. It is possible that a new quantitative index can be developed based on the b0-weighted ODFs, or a tracking algorithm may be benefited from this feature.

Reference [1] Callaghan, Oxford. 1991 [2] Tuch MRM 52:1358, 2004 [3] Wedeen et al. MRM 54:1377,2005 [4] Descoteaux et al. MRM 58:497, 2007