Optimal Encoding Points for Diffusion Spectrum Imaging: Using Bi-Gaussian Extrapolation

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Introduction

DSI is capable of mapping complex fiber architecture within MR voxel by characterizing water diffusion behavior [1,2]. To fully describe the complex diffusion phenomenon, adequate q-space sampling points are requested and therefore result in a long acquisition time. Additionally, truncation error in 3D probability density function (PDF) reconstruction is generally occurred due to the limit of clinical gradient strength. To avoid these drawbacks while preserving complex fiber orientations, this study reduced DSI sampling points as well as maximum q-value by applying an extrapolation kernel over the q-space. We assumed that the diffusion curve in human tissue is a bi-Gaussian distribution, which will not affect the PDF orientation after DSI reconstruction [3]. Both Monte-Carlo simulation and MR experiments showed that this method can preserve the PDF patterns and orientations while reducing DSI acquisition time to 1/2 or 1/4. Bypassing acquisition time and available gradient limitation of clinical system, this method might be further applied for human study.

Materials and Methods

Both Monte-Carlo simulation and phantom experiments were studied to evaluate the feasibility of using bi-Gaussian function for preserving PDF orientation of reduced DSI. Monte-Carlo simulation was performed to simulate molecular diffusion processes within a MR voxel. Both 90º and 45º crossing fibers were simulated, using fiber diameter = 10 μm, $D = 2 \times 10^{-9}$ m^2 s^{-1}, $\delta/\Delta = 6/250$ ms, $G_{max} = 115$ mT m^{-1} yielding $q_{max} = 2.94 \times 10^{-2}$ μm^{-1}. 515 sampling points encoded at a 3D Cartesian lattice within a spherical volume was considered as a standard [2] for DSI reconstruction. In addition to Monte-Carlo simulation, both phantom and rat models were studied. The phantom model using 90º and 45º crossing phantoms were constructed by plastic capillaries with ID/OD = 50/350 μm [2]. In the rat model, rat brain was dissected from the cranium and was placed fixedly in an acrylic holder filled with 4% formaldehyde solution. MR experiment was performed in a 3T Medspec/Biospec MRI system (Bruker Companies, Ettlingen, Germany) with an inserted gradient system. 515 encoding points in q-space were acquired as a standard for DSI reconstruction. A diffusion stimulated echo sequence was used for phantom model, with matrix size = 32 × 32, FOV = 22 × 22 × 3.5 mm^3, δ/Δ = 6/250 ms, and $G_{max} = 112$ mT m^{-1} yielding $b_{max} = 8000$ s mm^{-2}. A diffusion spin echo sequence was used for animal model, with matrix size = 128 × 128, FOV = 20 × 20 × 1 mm^3, $\delta/\Delta = 4.5/10$ ms, and $b_{max} = 22000$ s mm^{-2}. All the procedures of animal experiment adhered to the Guidelines for Care and Use of Experimental Animals of the Lab Animal Center in National Yang-Ming University.

DSI analysis using our own software was based on the relationship that echo signal $S(\mathbf{q})$ and diffusion PDF $P(\mathbf{r})$ are a Fourier pair, that is $S(\mathbf{q}) = F[P(\mathbf{r})]$. The orientation density function (ODF) was determined by computing the $P(\mathbf{r}) \cdot \mathbf{r}^2$ along each radial direction. The 3D ODF reflects distribution of fiber orientations within each voxel [5]. Reduced encoding points of 257 and 123 were extrapolated to 515 points using a bi-Gaussian kernel for comparison [3, 4]. Primary orientation vectors of ODF were identified at each voxel.

Results

Monte-Carlo simulation in both 90º and 45º crossing fibers showed that ODF pattern and orientations can be preserved by using bi-Gaussian extrapolation kernel on reduced encoding q-space points (Table 1). DSI acquisition time can therefore be decreased to 1/2 or 1/4. Figure 1 shows the ODF of 90º and 45º crossing phantoms reconstructed from different encoding points. T2WI of both phantom models showed the capillary phantom design, which clearly demonstrated the crossing fiber orientation. ODF pattern are well conserved by using our reduced encoding method. The deviation angles listed in Table 1 shows that the errors from the reduced encoding method were less than 8.6° ± 9.9°, which is close to the noise level [2]. Figure 2 shows DSI result of rat model from different encoding points. ODF of cerebral cortex and corpus callosum has minor pattern change while primary orientation retained.

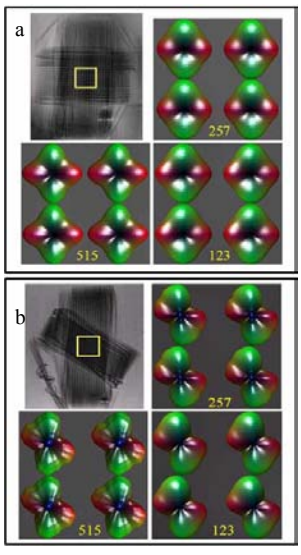
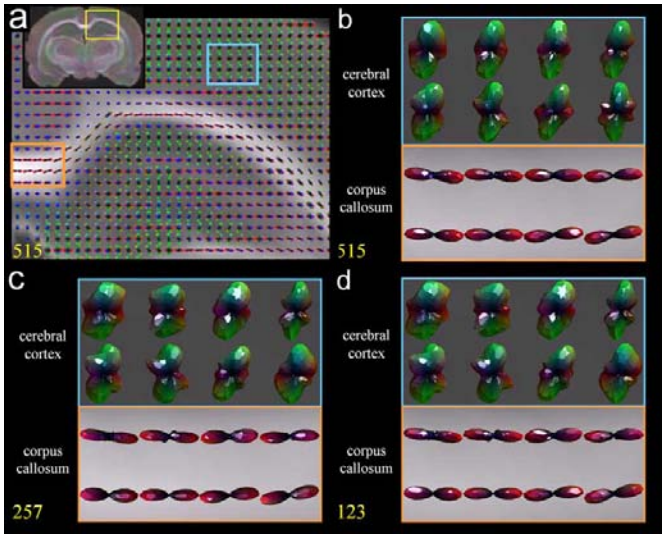


Table 1. (mean ± SD)	515	257	123
Simulation 45º	0.1°±1.8°	1.1°±1.5°	6.5°±7.9°
Simulation 90º	0.1°±1.5°	0.1°±1.5°	0.7°±2.0°
Phantom 90º	1.6°±1.6°	4.1°±3.6°	4.3°±5.1°
Phantom 45º	3.0°±4.1°	4.3°±8.3°	8.6°±9.9°

Table 1, Deviation angles of Monte-Carlo simulation and phantom models from different encoding points.

◄ Fig.1, ODF of 90 and 45 crossing phantom models from 515, 257, and 123 DSI encoding points. Deviation angles of the reduced encoding method were listed in Table 1. Both ODF pattern and deviation angles show that our method can reduce DSI acquisition time while preserving ODF orientations.

► Fig. 2, Corpus callosum and cerebral cortex were selected to evaluate our reduced DSI encoding method. Fig. 2-b, -c, -d show the ODF of 515, 257, and 123 DSI encoding points, respectively, which are enclosed by rectangle in Fig. 2-a.



Conclusion

Reduction of DSI acquisition time is necessary for clinical applications. By applying a bi-Gaussian fitting kernel, this study showed that extrapolation in q-space is useful in retaining ODF orientation. Bi-Gaussian model has been adopted to 1-D diffusion signal decay due to the existence of the fast and slow diffusion component in biological tissues [3,4]. Both Monte-Carlo and phantom model showed that ODF pattern and orientations were well conserved by using this extrapolation kernel on reduced encoding points. Furthermore, truncation errors and angular resolution can be eliminated and improved respectively by applying the extrapolation method. Nevertheless, the validity of data extrapolation might be seriously affected by singal noise. Therefore, 257 encoding points might be the best choice under SNR consideration though 123 encoding points showed the possibility of conserving ODF orientation. In conclusion, bi-Gaussian kernel can be used to extrapolate q-space points from reduced encoding points to reduce the DSI acquisition time while preserving the ODF orientations.

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References

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