Mapping Orientation Distribution Function with Spherical Encoding

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Synopsis DSI reflects the distribution of fiber orientations by mapping of 3D probability density function and its spherical projection of proton diffusion by **q**-space diffusion MRI. However, DSI scanning currently requires 515 diffusion-encoding directions, it is very time consuming. Here we developed a spherical encoding method to obtain the spherical projection directly. We found that the salient orientation of fibers can be extracted from summation of the product of diffusion echo signal and an angle function. This method saves at least 50% of scanning time than that needed in DSI and has an accuracy of $-1.33^o \pm 6.79^o$ in defining crossing fibers.

Introduction Multi-fiber orientations within a voxel have been acquired by high angular resolution diffusion weighted imaging (HARD) [1,2] and diffusion spectrum imaging (DSI) [3]. HARD is a method to get the fiber orientation distribution under the assumption that the distribution is the superposition of multiple tensors. The method is still based on the Gaussian tensor model. DSI bypasses the Gaussian assumption and obtains the distribution of fiber orientations by directly obtaining the mapping of 3D probability density function (PDF) and its spherical projection of proton diffusion, i.e. orientation distribution function (ODF), with **q** space diffusion MRI. Here we developed a spherical encoding method to obtain the ODF directly without the Gaussian assumption. This method also alleviates the difficulty of DSI data acquisition, which is time consuming and requires stringent gradient performance. We used the same high angular spherical encoding as that in HARD but calculated ODF by spherical Fourier transform. We found that the salient orientation of fibers can be extracted from the summation of the product of echo signal and an angle function. Our results show that only half of the scanning time is needed in our proposed method compared with that in DSI and an accuracy of $-1.33^o \pm 6.79^o$ was achieved when defining fibers at 90^o-crossing in our phantom.

Materials and Methods A phantom model was designed to simulate intersecting fibers. It comprises sheets of parallel plastic capillaries with inner and outer diameters of 50 μm and 350 μm, respectively. The capillaries were filled with water and sheets of two different orientations were stacked on each other in an interleaved fashion [4]. Images were acquired using stimulated echo diffusion sequence with 253 diffusion-encoding directions in a 5 fold-tessellated icosahedral sphere in the **q** space [1]. The in-plane resolution is 0.7 mm and the thickness is 4 mm. Diffusion gradient has intensity = 85 mTm^{-1}, duration = 5 ms, diffusion time = 250 ms, yielding diffusion sensitivity = 3211 s mm^{-2}.

ODF analysis is based on the relationship that echo signal $S(\mathbf{q})$ and diffusion PDF $P(\mathbf{r})$ is a Fourier pair, i.e., $P(\mathbf{r}) = FT^{-1}[S(\mathbf{q})]$ [5]. The Fourier formulas can be express in spherical coordinates R,Θ,Φ as [6],

$$P(R,\Theta,\Phi) = \int^{\pi} \int^{2\pi} \int^{\infty} S(r,\theta,\phi) \exp[i 2\pi Rr(\cos\Theta\cos\theta + \sin\Theta\sin\theta\cos(\phi-\Phi))] r^2 \sin\theta\, dr\, d\phi\, d\theta \quad (1)$$

Since we are interested in the ODF that is the orientation projection from PDF, Eq.1 can be rewritten as followed

$$ODF(\Theta,\Phi) = \int^{\infty} P(R,\Theta,\Phi)\, dR = \int^{\pi} \int^{2\pi} \int^{\infty} \int^{\infty} S(r,\theta,\phi) \exp[i 2\pi Rr(\cos\Theta\cos\theta + \sin\Theta\sin\theta\cos(\phi-\Phi))] r^2 \sin\theta\, dR\, dr\, d\phi\, d\theta \quad (2)$$

ODF at each orientation can therefore be acquired from Eq.2. For example, if we wish to acquire the ODF at $\Theta=0$, $\Phi=0$, Eq.2 can be rewritten as

$$ODF(\Theta=0,\Phi=0) = \int^{\pi} \int^{2\pi} \int^{\infty} \int^{\infty} S(r,\theta,\phi) \exp[i 2\pi Rr(\cos\theta)] r^2 \sin\theta\, dR\, dr\, d\phi\, d\theta \quad (3)$$

By properly selecting a b-value to make a distinct of the crossing fibers [2], and using the geometric symmetry of diffusion anisotropy, i.e. $S(r,\theta,\phi) = S(r,\pi-\theta,\pi+\phi)$, ODF(0,0) can be expressed as

$$ODF(0,0) = \int^{\pi} \int^{2\pi} S(\theta,\phi) \left(\int_0^1 \cos[i 2\pi R(\cos\theta)]\, dR \right) \sin\theta\, d\phi\, d\theta \quad (4)$$

ODF could be further reduced to the form,

$$ODF(0,0) = \int^{\pi} \int^{2\pi} S(\theta)\, G(\theta)\, d\phi\, d\theta \quad (5)$$

where we let $G(\theta) = \int_0^1 \cos[2\pi R(\cos\theta)] \sin\theta\, dR$ (Fig.1).

From Eq. 5, we know that ODF (0,0) can be acquired from summation of the product of diffusion echo signal and a θ function, G(θ) (Fig.1), where θ is the angle between diffusion echo signal and the direction of interested ODF (0,0). ODF at each direction can also be acquired in the same way after coordinate rotation.

Results The result of T2WI co-registered ODF of phantoms showed that this method is able to map the orientations of crossing fibers (Fig. 2a). Our results show that the accuracy of ODF in defining the 90^o phantom was $-1.33^o \pm 6.79^o$, which is larger than the error from DSI, $1.89^o \pm 4.85^o$ [4]. This error may come from the reduction of image numbers, the selection of b value, and the un-corrected b values from image gradients [7]. As shown in Fig. 2b, un-corrected b values from image gradients will contribute unbalanced b values to various encoding directions, leading to distorted ODFs (Fig. 2b).

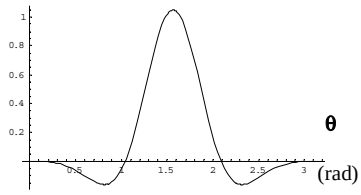


Fig.1 Plot of $\left(\int_0^1 \cos[2\pi R \cos\theta]\, \sin\theta\, dR \right)$ for θ from 0 to π. This function matches the fact that diffusion encoding of single fibers will have a maximum signal at vertical direction.

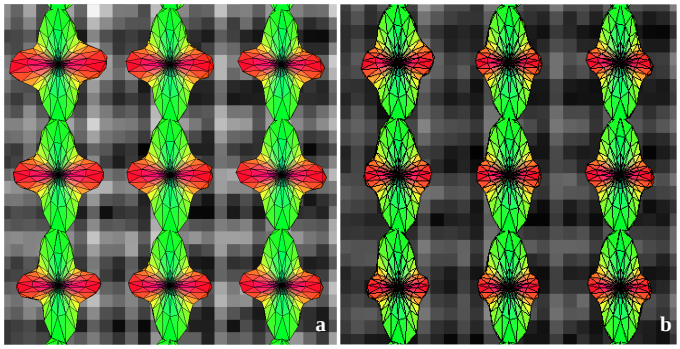


Fig. 2 ODF of 90^o phantom with (a) and without (b) b value correction for image gradients. Fig. 2a clearly shows the salient orientations of phantom and has an error of $-1.33^o \pm 6.79^o$ between phantom model. Fig 2b shows distorted ODF. This indicates that b matrix correction is necessary for any attempt in single b value high angular resolution encoding.

Conclusions Our results have shown that ODF of multi-fibers can be acquired by the spherical encoding scheme in **q** space. Although our method yields a larger error than that of DSI, our method saves 50% scanning time. By using 253 encoding directions in the 5 fold-tessellated icosahedral sphere, we have an angular resolution of 14.6^o. In fact, we could save more scanning time if the encoding directions could be further reduced while still preserving adequate signal to noise ratio, e.g. angular resolution of 16.9^o in the 4 fold-tessellated icosahedral spherical encoding. Our results also indicate that the extra b-value from image gradients is crucial for any attempt to map multi-fibers with one b-value high angular resolution encoding methods. In conclusion, using this spherical encoding method, we can acquire the ODF of multi-fibers.

References

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