Mapping Fiber Density Distribution with Diffusion Spectrum Imaging

K-H. Cho[1], Y-P. Chao[1], Y-C. Li[2], J-H. Chen[1], C-P. Lin[2,3]

[1]Interdisciplinary MRI/MRS Laboratory, DEPT. OF ELECTRICAL ENGINEERING, NATIONAL TAIWAN UNIVERSITY, Taipei, Taiwan, [2]Institute of Radiological Sciences, National Yang-Ming University, Taipei, Taiwan, [3]Institute of Neuroscience, National Yang-Ming University, Taipei, Taiwan

Abstract

Neural fiber density is highly correlated with normal brain function as well as brain abnormalities. However, in vivo mapping of neural fiber density has not been reported. Here we demonstrate that diffusion spectrum imaging (DSI), by probing 3D probability density profiles of water molecular diffusion, is capable of resolving not only crossing fibers but also neural density distribution. We tested and quantified this capability with two-compartment simulation and found that the length of primary orientation density function is proportional to neural density. Using phantom models, the capability of DSI in mapping neural density distribution was validated.

Introduction

Knowledge of neural connectivity and density are of critical importance in the understanding of normal brain functions as well as brain abnormalities. Recently advanced diffusion MRI is capable of mapping neural fiber connectivity accurately [1, 2]. However, in vivo measurement of neural density has not been reported. In this paper, we demonstrate that 3D probability density profiles of water molecular diffusion within each voxel provided by DSI, a technique of 3D q-space measurement, are capable of resolving not only crossing fibers but also neural density distribution [3]. To quantify the relationship between neural density distribution and probability density profiles within a voxel, two-compartment simulation with non-exchange diffusion assumption was studied [4]. Our result shows that the length of primary orientation density function (ODF) provided by diffusion probability profiles is proportional to the neural density distribution. To validate the relationship, two phantom models of 90^o crossing capillaries in 1:1 and 2:1 ratios were studied [3]. Our result shows that the length of two primary ODFs is consistent with the phantom design and demonstrates the capability of mapping neural density in vivo using diffusion MRI.

Material and method

The non-exchanged model and two-tensor compartment system was adopted in this investigation. The signal can be modeled by $S(b) = S_0 \{f \times \exp[-bgD_1g'] + (1 - f) \times \exp[-bgD_2g']\}$, where f is the fractional volume of white matter component, D_1 and D_2 are the diffusion coefficients of two components, and g is the unit vector of gradient direction. The two compartment diffusion model is simulated in the case of two white matter compartment [1.4, 0.35, 0.35] (unit: 10^{-3} mm^2/sec) in orthogonal crossing. The simulation was repeated with f of 1/2, 2/3, and 3/4 to yield fiber density ratio of 1:1, 2:1 and 3:1, respectively with b-value of 7000 sec/mm^2. Images of DSI were acquired using spin echo diffusion sequences with 515 diffusion-encodings comprising isotropic 3D grid points in the **q** space contained within a spherical volume of 5 radial increments. DSI analysis based on the relationship that echo signal $S(\mathbf{q})$ and diffusion probability density profiles $P(\mathbf{r})$ is a Fourier pair, that is $S(\mathbf{q}) = F[P(\mathbf{r})]$. The radial projection of the diffusion spectrum, called fiber orientation distribution function (ODF), $\psi(\mathbf{u})$, represents the probability of finding a fiber oriented in the direction of the unit vector, **u**. $\psi(\mathbf{u}) = \int_0^{r_{max}} P(r\mathbf{u})\, r^2\, dr$. Since $P(r\mathbf{u})$ is proportional to fiber density, $\psi(\mathbf{u})$ will also be proportional to fiber density.

Two phantom models were designed to simulate intersecting fibers with 1:1 and 2:1 crossing fiber ratios. They comprise 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 stacked on each other in an interleaved fashion [3]. MR experiment was performed in a 9.4 T MRI system (Bruker, Germany). Images were acquired using stimulated echo diffusion sequence with 515 diffusion-encoding directions in the **q** space [2]. The in-plane resolution is 0.7 mm and the thickness is 3 mm. Diffusion gradient has intensity = 132 mTm^{-1}, duration (δ) = 5 ms, diffusion time (Δ) = 250 ms, yielding diffusion sensitivity = 8000 s mm^{-2}.

Results

Figure 1 shows the result of diffusion simulation with crossing fiber density ratios of 1:1, 2:1, and 3:1. The ratios of primary ODF length are 1 (Fig. 1a), 1.983 (Fig. 1b) and 2.949 (Fig. 1c) which are almost the same with the fiber density ratios. Figure 2 shows the result of phantom models with fiber density of 1:1 and 2:1. The ratios of ODF length is of the two models are 1.094 ± 0.025 (Fig. 2a) and 2.012 ± 0.142 (Fig. 2b), which is consistent with our simulation. The error of phantom model results might come from MR noise and the cross talk of imaging gradient and diffusion gradient in micro-imaging system.

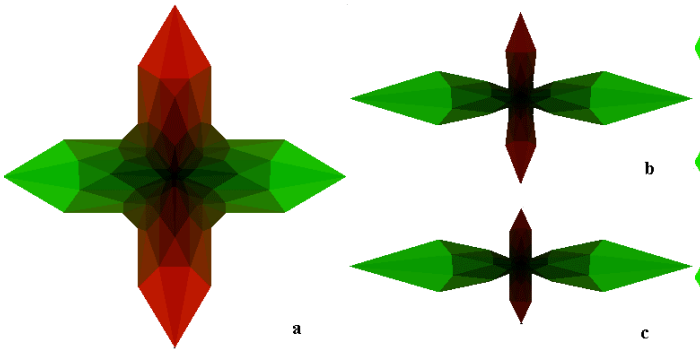

Fig 1. Two-compartment diffusion simulation with fiber density ratio of (a) f = 1/2 (density ratio = 1), (b) f = 2/3 (density ratio =2), and (c) f = 3/4 (density ratio = 3)

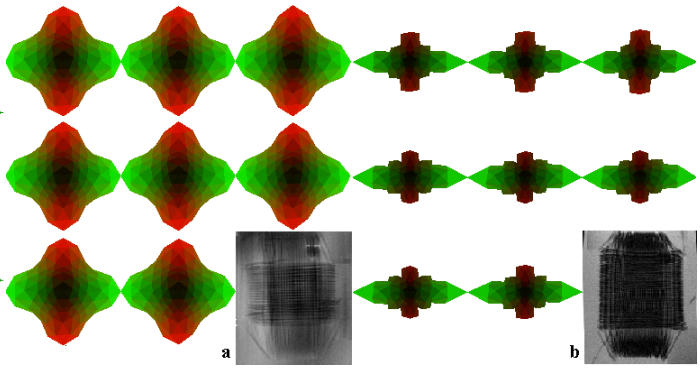

Fig 2. DSI results of phantom models with different density ratio. (a) density ratio = 1, ratio of ODF length is 1.094 ± 0.025 and (b) density ratio =2, ratio of ODF length is 2.012 ± 0.142.

Conclusion

Our result shows that fiber density distribution within each voxel can be quantified with 3D probability density profiles of water molecular diffusion. Using DSI, linear relationship between fiber density ratio and primary ODF length were observed in both simulation results and phantom models. Though there are lots of factors might affect the primary length of ODF, e.g. demyelization and axonal diameter, the absence of myelin results in increasing of λ2, λ3 of 20% yields length of ODF ratio almost unchanged [5]. Neural density plays the most important part of the ODF length. In addition, to have accurate results, the requirement of $\Delta >> \delta$ for q-space measurement is very important for the fiber density quantification. In conclusion, using DSI, we demonstrate first in vivo measurement of fiber density distribution.

Reference

1. P.J. Basser et al, Biophys. J. ,1994, 66(1), p259 2. V.J. Wedeen et al, Proc. ISMRM 2000, p82. 3. C.P. Lin et al, Neuroimage, 2003, 19, p482. 4. A.L. Alexander et al, MRM 2001, 45, p.770. 5. S.K. Song et al, Neuroimage, 2002, 17, p1429.