Human Brain Mapping of Orientationally Invariant Axonal Diameter Using Q-space Diffusion Tensor MRI

J-C. Weng[1,2]

[1]School of Medical Imaging and Radiological Sciences, Chung Shan Medical University, Taichung, Taiwan, [2]Department of Medical Imaging, Chung Shan Medical University Hospital, Taichung, Taiwan

Introduction

Fundamental relationships between diffusion tensor imaging (DTI) and q-space imaging can be derived which establish conditions when these two complementary MR methods are equivalent. When the 3D displacement distribution is measured by q-space imaging with large displacement and small q vector, the result is similar to 3D Gaussian assumed in DTI [1]. Combing displacement information from q-space imaging and fiber direction from DTI, distribution of axonal diameters and directions could be derived at the same time. Based on the assumption, the study proposed a novel technique, q-space diffusion tensor imaging (qDTI), to map orientationally invariant axonal diameter distribution of human brain. The goal could be achieved with any of two image reconstruction methods described below. One was tensor-based method. The 3D Gaussian displacement distribution could be obtained directly from the displacement tensor (Fig. 1, bottom row). The other was displacement projection method. The fiber directions were first calculated from conventional DTI, and the mean displacement as well as maximum diffusivity of water molecules along specific direction were then obtained with q-space imaging. The effective axonal diameter was defined as the average of several displacements projected to the direction of the fiber cross section (Fig. 1, right column). Our results demonstrated that two qDTI methods both produced reasonable distribution of orientationally invariant axonal diameters in human brain.

Materials and Methods

The images of human brains were acquired using 3T MRI system (Tim Trio, Siemens MAGNETOM, Germany). A multi-slice spin echo diffusion weighted echo planar imaging (EPI) sequence was performed to obtain qDTI, with TR/TE = 1000/132 ms, in-plane resolution = 2.5 mm, and slice thickness = 10 mm. The diffusion-encoding scheme constituted 24 diffusion-encoding directions with multiple q sampling. Diffusion attenuated images were obtained with diffusion sensitivity (b values) changing from 0 to 5000 s/mm^2.

For data analysis of q-space imaging, the displacement distribution of water molecules inside the tissue could be obtained by taking Fourier transform of signal attenuation in the q-axis [2]. From the full width at half height of displacement distribution, effective axonal diameters (displacement mapping) could be acquired. The probability at zero displacement was given by the height of the distribution at zero displacement, which provided information reciprocal to the effective axonal diameter [3].

In the tensor-based method, 3D Gaussian displacement distribution could be obtained directly from the displacement tensor (D) as shown in Fig. 2. Eq. (1) was used to calculate the displacement tensor, which was proposed by Basser [1]. The displacement tensor could be obtained using mapping of displacement (r) and probability (P) at zero displacement described above. The eigenvalues and corresponding eigenvectors were then simply derived from the displacement tensor. The orientationally invariant axonal diameter was calculated by the 2nd eigenvalue x 3rd eigenvalue, and the axonal direction was defined as 1st eigenvector.

$$\lim_{r\to\infty} P(r,\Delta|0,0) = \frac{1}{\sqrt{|\underline{D}|(4\pi\Delta)^3}} e^{-r^T \underline{D}^{-1} r/(4\Delta)} \qquad (1)$$

In the displacement projection method, the axonal direction was first obtained from 1st eigenvector of conventional DTI calculation. Because 24 diffusion-encoding directions with multiple q sampling were acquired, 24 maps of displacement along those diffusion-encoding directions could be calculated as described above. The effective axonal diameter was defined as the average of 24 displacements projected to the plane composed with 2nd and 3rd eigenvectors.

Results and Discussions

Our results showed the reasonable distributions of orientationally invariant axonal diameters of human brain using qDTI technique with tensor-based reconstruction method and displacement projection reconstruction method, respectively (Fig. 3). The yellow color vectors represented the local fiber directions, and the background values reflected the orientationally invariant diameters of these fibers, as indicated by color bar. For example, the main direction of corpus callosum and corticospinal tracts could be obviously observed, and the orientationally invariant axonal diameter of the callosal fibers and corticospinal tracts were smaller than the surrounding tissue.

There were several advantages of the proposed qDTI. The orientationally invariant displacement in each pixel was used to provide novel image contrast indicating axonal diameters. Structural information beyond the spatial resolution of conventional MRI could be inferred without resorting to a complicated tissue model. The novel technique however required a more complicated model in which intracellular and extracellular compartments of specific geometry and exchange between the compartments were taken into consideration.

Fig. 1

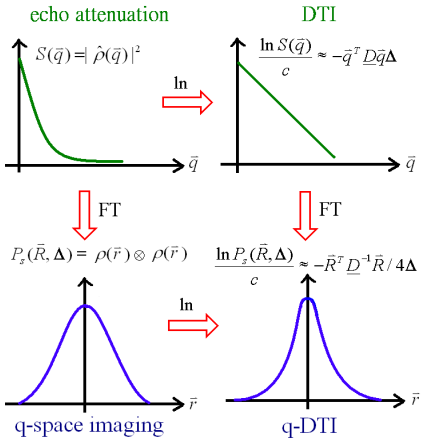

Fig.2

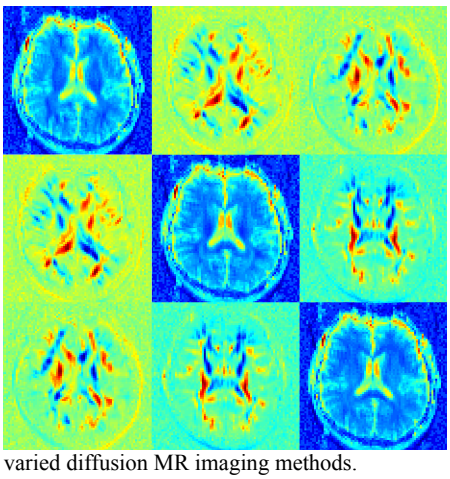

Fig. 3

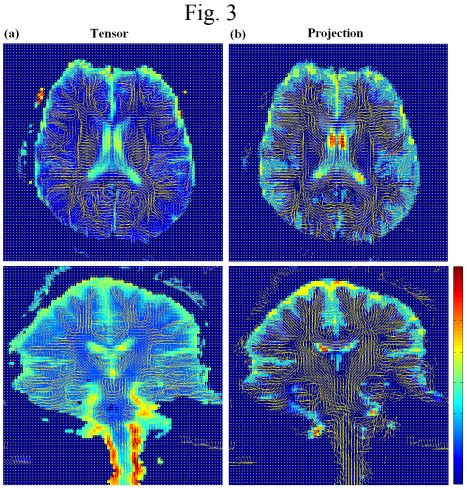

Fig. 1. Fourier and logarithmic relationships among varied diffusion MR imaging methods.
Fig. 2. Displacement tensor elements. Each image responded to one element in the displacement tensor.
Fig. 3. Orientationally invariant axonal diameter mapping of the human brain with (a) tensor-based method and (b) displacement projection method.

Conclusions

Orientationally invariant axonal diameter distribution could be observed in human brain using qDTI. The brain regions might be affected differently in the development of disease, and their structural parameters such as size and shape might associate with cognitive or functional tests involved in different modes of interactions. This technique might be useful in probing the status of myelination in the development of disease.

References

[1] Basser, P.J., MRM 2002; 47(2): 392-397. [2] Wedeen, V.J., MRM 2005; 54(6): 1377-86. [3] Assaf, Y., MRM 2008; 59(6): 1347-54.