Simultaneously Measuring Axonal Diameter Distribution and Direction of Rat Brain Using Q-space Diffusion Tensor Magnetic Resonance Imaging

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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. The study proposed a novel technique, q-space diffusion tensor imaging (qDTI), combined with two image reconstruction methods based on the assumption to simultaneously map axonal diameter distribution and direction of rat brain. One was tensor-based method. The 3D Gaussian displacement distribution could be obtained directly by the displacement tensor (Fig. 1, bottom row). The other was displacement projection method. 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). They provided MR images in which physical parameters of water diffusion such as the mean displacement and maximum diffusivity of water molecules were used as image contrast. Our results demonstrated that two qDTI methods both produced reasonable distribution of effective axonal diameters and directions in rat brain.

Materials and Methods

The experiment was performed on a 3T MRI system (Biospec, Bruker, Germany). A stimulated echo diffusion weighted sequence was performed to obtain qDTI, with TR/TE = 2000/29.2 ms, NEX = 2, in-plane resolution = 0.14 mm, and slice thickness = 1.2 mm. The diffusion-encoding scheme constituted 6 diffusion-encoding directions, {1, +/-1, 0}, {0, +/-1, 1}, {+/-1, 0, 1}, with multiple q sampling. With diffusion time (Δ) = 100 ms, diffusion duration (δ) = 8 ms, and diffusion gradient intensities changing from 0 to 400 mTm^{-1}, we obtained diffusion attenuated images with diffusion sensitivity (b values) changing from 0 to 7.5 x 10^4 s mm^{-2}.

For data analysis of q-space imaging, we first applied zero filling at high b values to avoid Fourier truncation. According to Fourier relationship between the signal intensity and the displacement probability in q-space, Fourier transform of signal attenuation in the q-axis was the displacement distribution of water molecules inside the tissue [2]. From the full width at half height of displacement distribution, effective axonal diameters of callosal fibers (displacement mapping, r) can be acquired. The probability (P) 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). 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 effective axonal diameter was calculated by the 2nd eigenvalue x 3rd eigenvalue, and the axonal direction was defined as 1st eigenvector.

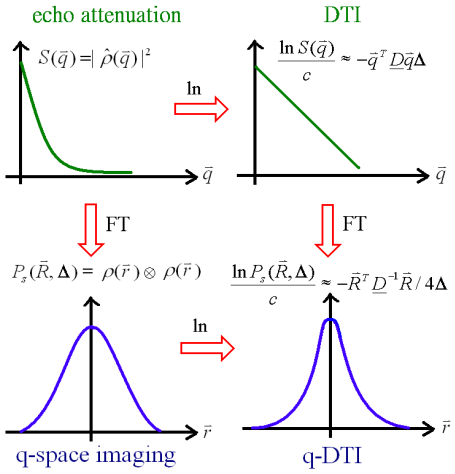
$$\lim_{r\to\infty} P(r,\Delta|0,0) = \frac{1}{\sqrt{|\underline{D}|(4\pi\Delta)^3}} e^{-r^T \underline{D}^{-1} r/(4\Delta)} \quad (1)$$

In the displacement projection method, the axonal direction was first obtained from 1st eigenvector of general DTI calculation. Because 6 diffusion-encoding directions with multiple q sampling were acquired, 6 maps of displacement along those diffusion-encoding directions could be calculated as described above. The effective axonal diameter was defined as the average of 6 displacements projected to the plane composed with 2nd and 3rd eigenvectors.

Results and Discussions

Figure 2 shows the distributions of axonal diameters and directions of rat brain using qDTI technique with tensor-based reconstruction method (Fig. 2a) and displacement projection reconstruction method (Fig. 2b), respectively. The green vectors represent the local fiber directions, and the background values reflect the effective diameters of these fibers, as indicated by image brightness. For example, the left to right direction of corpus callosum can be obviously observed in Fig. 2, and the effective axonal diameter of the callosal fibers is smaller than the surrounding tissue. In the displacement projection method, the units in the background values are μm (Fig. 2b). The diameters of callosal fibers are found to be 1-3 μm, which is very close to the true value.

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



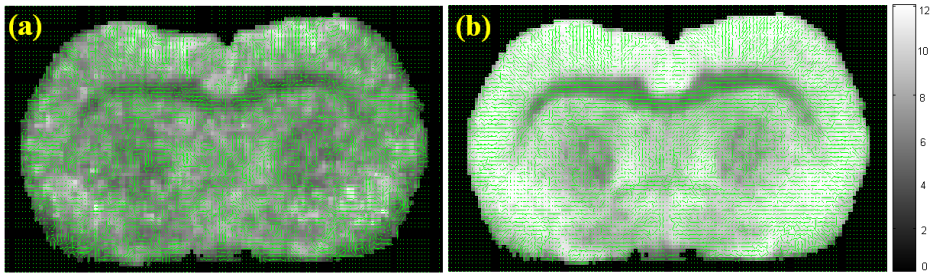


Fig. 1 Fourier and logarithmic relationships among varied diffusion MR imaging methods.
Fig. 2 (a) Mapping of axonal diameter distribution and direction of rat brain with (a) tensor-based method and (b) displacement projection method.

Conclusions

Effective axonal diameter distribution and direction can be observed simultaneously in rat 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] PJ Basser, MRM 2002; 47: 392-397. [2] VJ Wedeen, et al., MRM 2005; 54: 1377-86. [3] Y Assaf et al., MRM 2008; 59: 1347-1354.