Determination of Neuron Fiber Orientation and Structure with Highly Angular-Resolved Diffusion Attenuated Imaging and Analysis

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Abstract

Conventional DTI method uses a single-tensor (fiber-direction)-per-voxel model, and has limitations to determine and resolve fiber orientations for voxels with multiple crossings. Some new tensor models have been proposed recently to overcome the limitations of the single-tensor-per-voxel model, but they retain the pitfalls of tensor models, and multiple tensor components are *estimated* and *derived* through various optimization methods. In this work, we proposed a new method to determine the neuron fiber orientation and structure based on highly-angular-resolved diffusion attenuated imaging and analysis.

Introduction

An important goal for diffusion tensor imaging (DTI) is the accurate determination of the local fiber orientation and structures using tensor models. A major problem for most DTI methods, however, is their limitations in resolving and determining multiple fiber orientations in voxels with neuron fiber crossings because conventional DTI methods assume a single tensor per voxel [1]. Recently, some new tensor models have been proposed to overcome some of these limitations. For example, a multiple-tensor model [2] was used as an alternate solution, where non-linear optimization is used to *estimate* the multiple tensor components. A *q*-space measurement method was also introduced to *derive* the diffusion probability distribution [3]. A recent multi-tensor model [4] was proposed to measure the fiber orientation using high angular DTI, which, however, also kept the pitfalls associated with the tensor modeling. In this work, we propose a new method to determine the neuron fiber orientation and structure based on highly-angular-resolved diffusion attenuated imaging and analysis, where all fiber orientations are preserved for analysis.

Theory

Consider a series of diffusion-attenuated images acquired along a large number of diffusion-encoding gradient directions (n directions). These encoding directions are evenly distributed on a 3D sphere, representing the spherical angular resolutions. The MR signal changes of each voxel due to diffusion attenuation, applied along each direction (i=0->n) can be written as

$$\ln(S_0/S_i) = b \cdot g_i^T \cdot D \cdot g_i \approx b \cdot u_i^T \cdot D \cdot u_i \, ,$$

where S_0 is the voxel intensity with no diffusion-weighting (b=0), and S_i is the voxel intensity with diffusion-weighting (non-zero b-values). g_i is the diffusion-encoding direction (gradient vector), and D is apparent diffusion coefficient. u_i is the diffusion tensor direction, or the true diffusion direction, if there is only one fiber orientation in the voxel. The true diffusion directions can be related to one or more of the diffusion-encoding directions via a rotational operator. Depending on the angular resolution of the diffusion encoding gradients, the rotation angles can be large or small, but, as the number of diffusion encoding directions increases, the true diffusion directions in a voxel will match with the encoding gradient directions. This equation also states that the signal attenuation due to diffusion is proportional to the projection of the diffusibility along each direction. If we map the diffusibilities along all of the diffusion-encoding directions, the directions with highest diffusibilities will indicate the principal diffusion directions for voxels contain multi-fiber crossings.

Methods

All data were acquired with a dual-echo EPI based diffusion-weighted imaging sequence on a 3T scanner (GE Medical Systems, Milwaukee, WI). For each subject, a series of high angular-resolved DWIs were acquired with typical parameters of TR of 3s, TE = 85.2 ms, 24 cm FOV, 128 x 128 image matrix and axial slices with thickness of 4mm. b-values of 1000 s/mm^2 were used for all of the DWIs. Data sets with 25, 55, 99 directions were collected; a reference set with 6 directions was also collected. Anisotropic diffusion analyses were performed using in-house image processing software. For comparison, fractional anisotropic (FA) maps, and fiber orientation maps were also generated using DTI method.

Results

Using spherical plots of diffusion attenuation index (DAI), $\ln(S_0/S_i)$, along diffusion encoding directions, we were able to determine dominating diffusion directions. Multiple directions are preserved in this analysis and thus local fiber orientations can be derived. Figure 1 shows the derived fiber orientation maps from a region of interest using DAI analysis with DWIs of 25, 55 and 99 directions, respectively. Multiple fiber orientations are shown for voxels containing crossed fibers. To validate the accuracy of fiber orientation determination, DTI-derived orientation maps were also calculated. Comparison using the data set with 55 directions showed that the fiber orientations derived from two methods matched very well. With 98% confidence level, the orientation differences were less than 10 degree for voxels from the regions with highly-organized structures, where only one dominating diffusion direction is determined in each voxel. Accurate comparisons between DAI and DTI for isotropic and fiber-mixed voxels were difficult since DTI only generates one dominating direction in each voxel. Statistical analysis for the orientation differences from dominating directions showed that the differences are within 15 degree with a 92% of confidence level.

Discussion and Conclusion

Highly-angular-resolved diffusion attenuated imaging and analysis allow us to directly visualize and extract fiber orientations. Structural information between isotropic voxels and fiber crossing voxels can be easily distinguished and resolved, which was the major limitation of the existing diffusion tensor models. The accuracy of the fiber orientation and structure determination using DAIs increases as the number of diffusion encoding directions increases, i.e., in higher angular resolution DWI experiments. This method could be useful for generating more accurate fiber tractograms, as well as anisotropic diffusion images, in combination with conventional DTI methods.

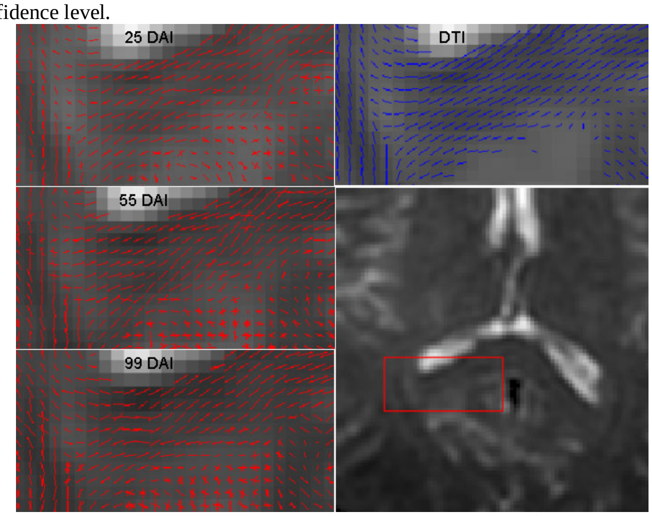

Figure 1. Fiber orientation maps generated with DAI analysis from 25, 55 and 99 directions, in comparison with the result using DTI analysis, from the selected region of interest.

References

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