Finer Discrimination of Fiber Orientation at High q Diffusion MR: Theoretical and Experimental Confirmation

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Synopsis

Recently, it was found that the signal attenuation observed in diffusion MR experiments of a pack of cylindrical impermeable microcapillary tubes have high directional sensitivity. We have modeled this signal decay as a function of q using the restricted component of the newly proposed CHARMED model, which describes intra-axonal diffusion. CHARMED fits the data nicely, and more importantly predicts the high sensitivity of the diffraction pattern on the tube orientation. These findings suggest that high q diffusion imaging has the potential to better resolve directional characteristics of white matter as compared to DTI or other low q diffusion imaging methods.

Introduction

Q-space diffusion MR [1, 2], is increasingly being used to obtain microstructural information in neuronal tissues [3-7] on a micron scale, well below voxel dimensions of conventional MRI. It was found recently that the diffraction pattern in q-space data obtained from a pack of impermeable glass microcapillaries exhibits a strong angular dependence [8] (Figure 1). To better understand the origin of this phenomenon, we used the 3-D restricted model of water diffusion embodied in the Composite Hindered and Restricted Model of Diffusion (CHARMED) framework, originally developed to describe water diffusion in white matter [9]. Here we compare the experimental and theoretical predictions for the strong angular dependence of the signal decay in ensembles of microtubes and offer a physical explanation for the observed effect.

Methods

NMR diffusion experiments were performed on packs of 4-cm hollow cylindrical tubes (microcapillaries) having a diameter of 20, 16 or 9 µm (Polymicro Technologies), using an 8.4T NMR spectrometer equipped with a Micro5 gradient system capable of producing pulse gradients of up to 190 gauss/cm in each of the three directions. The microcapillaries were filled with water and aligned along the z-axis in the magnet. A diffusion weighted stimulated echo sequences was used with the following parameters: TR = 3 s, TE= 20 ms, δ= 2 ms and a diffusion time Δ of 1000 ms with G_{max} 160 gauss/cm, resulting in q_{max} of 1362 cm^{-1}. Signal attenuation vs q was measured for different rotational angles (α) with respect to the +z-axis from 0^0 to 180^0 (see Figure 1). For angles in which q-space diffraction patterns were observed we evaluated the effect of the diffusion time on features of the observed diffraction pattern. Simulations were performed using the restricted component of the CHARMED model using an in-house Matlab program.

Results

Figures 2 shows the experimental signal decay as a function of q in 20 µm tubes for different diffusion times for $\alpha = 90^0$, along with the simulations obtained from CHARMED. This figure shows excellent agreement between experimental data and the 3-D model of restricted diffusion within CHARMED. It also demonstrates the importance of satisfying the long diffusion time limit ($l^2/2D \leq \Delta$). Diffraction patterns are only observed experimentally and predicted in the simulations when Δ is long enough with respect to the diameter (l) of the tubes to allow most of the spins to sense the impermeable wall. Figure 3 shows the signal attenuation as a function of q-value for different rotation angles studied juxtaposed with CHARMED model predictions. Interestingly, the diffraction patterns are observed only when diffusion gradients were applied nearly perpendicular ($90^0 \pm 5^0$) to the long axis of the microcapillaries. Indeed, this surprising dependency on rotation angle (α) was also predicted in simulations that were able to reproduce the experimental data over the entire set of angles studied. These diffusion measurements were also performed on 16 and 9 µm tubes and on mixtures thereof. In all cases very good agreement was found between the experiments and simulations.

Discussion

Importantly, we found that the restricted part of the CHARMED model can describe accurately the signal decay and the peculiar dependency of the diffraction pattern on the rotation angle for wide range of experimental conditions in a bundle of restricted tubes. This behavior follows because the net signal attenuation can be written as the product of two terms, one describing the 1-D Gaussian diffusion along the free axis of the tubes, and another describing the restricted diffusion perpendicular to the axis of the tubes. The former dominates the latter at most angles except when displacements are probed perpendicular to the tube walls. This strong angular dependence suggests that high q diffusion imaging has the potential to resolve structural and directional characteristics of white matter better than DTI or other low q diffusion imaging methods.

References

[1] Callaghan PT et al, J Magn Reson 1990;90:177-182. [2] Cory DG, Garroway AN, Magn Reson Med 1990;14:435-444. [3] Assaf Y, Cohen Y, NMR Biomed 1999,12:336-344. [4] Assaf Y, Mayk A, Cohen Y, Magn Reson Med 2000;44:713-722. [5] Assaf Y et al., Magn Reson Med 2002;47:115-126. [6] Assaf Y, Cohen Y, NMR Biomed 2002,15:516-542. [7] Chin C-L et al., Magn Reson Med 2004;52:733-740. [8] Avram L, Assaf Y, Cohen Y, J Magn Reson 2004;169:30-38. [9] Assaf Y, et al., Magn Reson Med 2004;52:965-978.

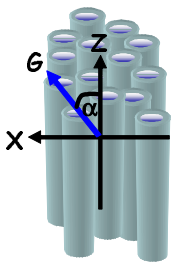

Figure 1. A scheme of the sample studied and definition of the rotational angle (α).

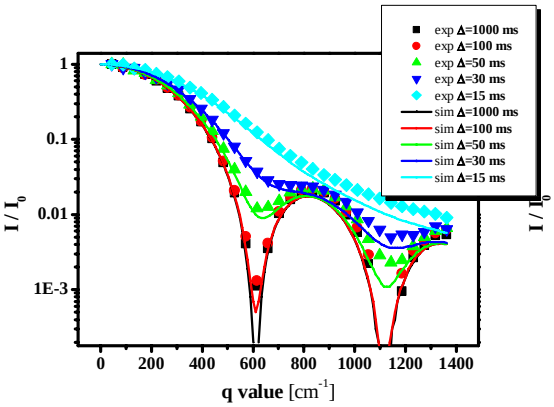

Figure 2. Signal decay as a function of q values and the calculated values obtained by simulation for different diffusion time (Δ).

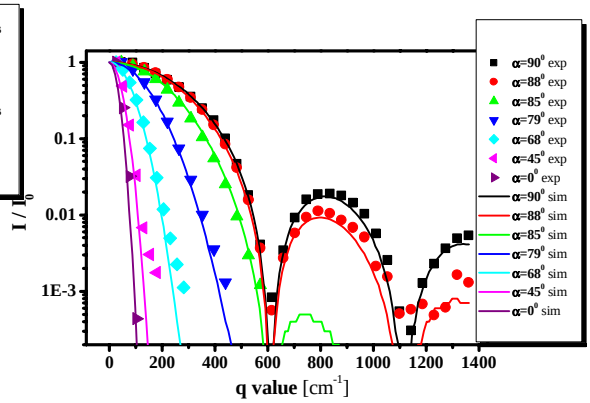

Figure 3. Signal decay as a function of q values and the calculated values obtained by simulation for different rotational angles.