Observation of Anisotropy at Different Length Scales in Optic and Sciatic Nerve Specimens

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INTRODUCTION

Double-PFG MR is a promising technique that could help overcome some of the difficulties associated with single-PFG acquisitions [1,2]. As shown in Figure 1, double-PFG acquisitions comprise another pair of diffusion gradients separated from the first by a mixing time, t_m. Of specific interest is the dependence of the MR signal on the mixing time and the angle between the two gradients. By carefully characterizing these dependencies, information not available in single-PFG acquisitions can be attained. Among this information is anisotropy at different length scales. For example, the anisotropy of the magnetization within the pore space can be detected at very short mixing times. This microscopic anisotropy (μA) induced by the restricting barriers can be observed even when the compartments are isotropic and can be exploited to determine the compartment size [3,4]. At long mixing times, the effect of μA disappears, and one can exploit the angular dependence of the signal to characterize the shape of the compartments, or the compartment shape anisotropy (CSA) [5]. Finally at the coarsest length scale, it is possible to characterize the coherence in a population of compartments. This kind of anisotropy is referred to as ensemble anisotropy (EA). Figure 2 illustrates when these different scenarios for anisotropy may be exhibited. In this work, we present for the first time, how EA can be quantified simultaneously with the axon diameter.

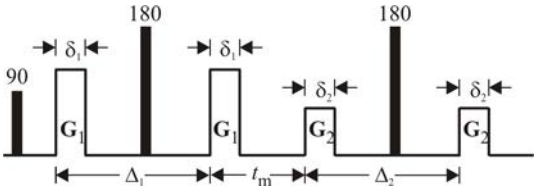

Fig. 1: The spin echo version of the double-PFG experiment.

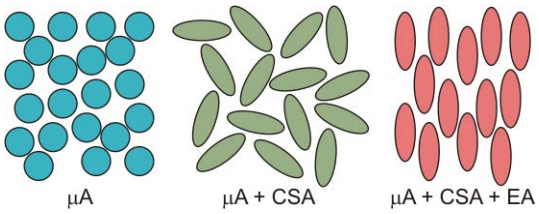

Fig. 2: Anisotropy at different length scales.

THEORY and RESULTS

In this work, previously developed theory [6] of restricted diffusion observed via completely arbitrary pulse sequences (hence taking into account all parameters of the double-PFG sequence) was extended to account for the ensemble anisotropy of the specimens. To this end, a population of long cylinders was modeled where the orientation of the cylinders was distributed according to a von Mises distribution with a concentration (coherence) parameter K. Figure 3 shows the restricted diffusion profile at short and long mixing times for different values of K. The signal was assumed to have a freely diffusing component as well with a different diffusivity than what is used in the restricted compartment.

The model was fitted to data obtained from excised swine optic and sciatic nerve specimens. The acquisition was performed at 8.4T with δ=2ms, Δ=200ms, and t_m=0 and 30ms. The specimens were aligned parallel with the main magnetic field. However, the sciatic nerve specimen had some curvature along its axis. The gradients were applied on the transverse (xy) plane.

Fitting of the fiber distibution model yielded an ID value of 6.43 μm for the optic nerve, and 7.39 μm for the sciatic nerve. The estimates for the concentration parameter were K=10.2 for the optic nerve, and K=6.95 for the sciatic nerve, respectively. For the optic nerve, since the data exhibited no CSA at the longer mixing time of 30ms, a coherently oriented fiber model could be employed as well, while for the sciatic nerve sample, the angular dependence at tm=30 ms prompted the necessity for taking into account a dispersion in the fiber orientations. This observation demonstrates the discriminative power of the double-PFG acquisitions. Figure 4 depicts a representative fitting result.

DISCUSSION and CONCLUSION

For the first time, we presented the simultaneous characterization of μA along with EA. Characterizing the orientational dispersion of the fibers via a von Mises distribution enabled the quantification of EA by estimating only one additional parameter. The experiments at longer mixing times provided the specificity for the incoherence of the cells in the sciatic nerve sample. This incoherence may be originating from the apparent natural curvature of the specimen.

References: [1] D. G. Cory, et al., Polym Preprints 31, p.149, 1990. [2] P.P. Mitra, Phys Rev B, 51, 15074, 1995. [3] E. Ozarslan, P.J. Basser, J Chem Phys, 128, 154511 (2008). [4] N. Shemesh, et al. J Magn Reson, 198, 15-23 (2008). [5] E. Ozarslan, J Magn Reson, 199, p. 56, (2009). [6] E. Ozarslan, et al., J Chem Phys, 130, 104702 (2009).

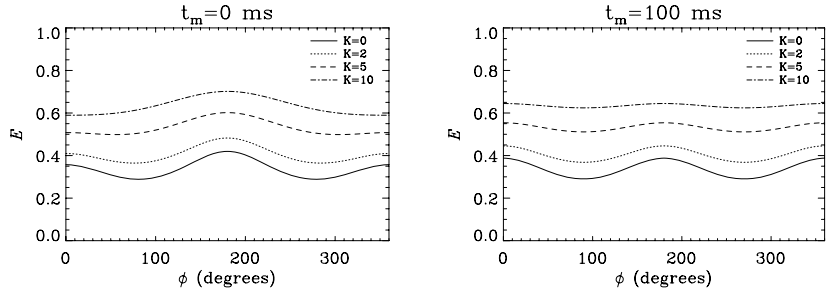

Fig. 3: Simulations of the d-PFG MR signal intensity for cylinders with an inner diameter of 8μm at different levels of concentration parameter (K) of a von Mises distribution. At short mixing times, and when K is large (coherently oriented cells), the signal exhibits the characteristic behavior of μA. At long mixing times, the μA is lost when K is large. On the other hand, when the population is incoherent (randomly oriented compartments), an angular dependence characteristic of CSA is predicted.

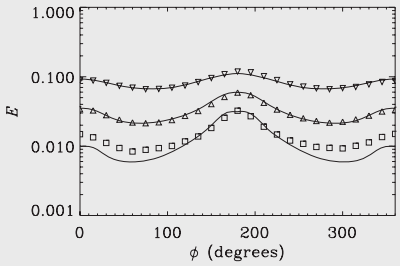

Fig. 4 A representative fitting result obtained for the excised swine sciatic nerve specimen at t_m=0. The data at three q-values (20.9, 39.85, and 58.65 mm^{-1}) were used simultaneously in the estimations.