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Inferring Axon Diameter Sizes using Monte Carlo Simulations of Magnetic Resonance Oscillating Gradient Spin Echo Sequences

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Magnetic resonance (MR) is capable of measuring diffusion coefficients of water in tissue. MR oscillating gradient spin echo (OGSE) sequences are used to make measurements at the shortest possible diffusion times so that the transition from restricted to hindered diffusion within the smallest structures can be detected. Here we simulate a cylindrical geometry using OGSE sequences and AxCaliber to determine the ability of the OGSE sequences to distinguish cylinder diameter distributions for small diameters and to better understand the physical factors affecting ADC measurements. We vary the frequency of the gradient from very small to very large to approach free diffusion in the larger simulated axons.

Monte Carlo computer simulations were conducted using a gamma distribution of non-overlapping parallel cylinders surrounded by extracellular water with lattice periodicity. This geometry aims to model the axon environment in healthy white matter regions. A cosine gradient spin echo sequence was used to generate 400 signals with different cosine frequencies (from .05 to 10 kHz) and gradient strengths (from 0 to 72580 mT/m). Simulations were run with 114688 particles and 42000 time steps. Gaussian noise was added to both components of the transverse magnetization. The cylinders were impermeable and water diffused within and outside the cylinders. The simulations were programmed in CUDA C/C++ and run on a HP Z240 workstation containing an Intel® Xeon® Processor E5-1650 6-core 3.20GHz CPU. The HP Z240 workstation contained two graphics cards, a Tesla C2075 (Fermi 2.0) graphics card for dedicated CUDA computation and a Quadro 600 (Fermi 2.1) graphics card handling the display. The mean signal was fit to the AxCaliber analytical model using χ^2 minimization.

The fitted data agree fairly well with the input model indicating our method can be used to infer axon diameter distributions from 0.5 μm to 4.5 μm. Previous small deviations between the fit data and simulated system are corrected using volume fractions rather than number fractions. This work is the first step toward combining OGSE measurements with axon diameter distribution models to infer distributions of small axon diameters in tissues. Distributions of non-parallel axons and more diffusion gradient directions will be needed to make a more complete model.

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