Distinguishing small pore sizes using oscillating gradient spin echo sequences

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Introduction

Oscillating gradient spin echo (OGSE) sequences have been used to make measurements at short diffusion times[1-6]. OGSE probes the shortest possible diffusion time scales so that the transition from restricted to hindered diffusion within the smallest structures can be detected. Here we simulate different geometries using OGSE sequences to determine the ability of the OGSE sequences to distinguish small pore sizes and to understand better the physical factors affecting *ADC* measurements. We vary the frequency of the gradient ($f \sim 1/\Delta$) from very small to very large to approach free diffusion in the larger geometries simulated. This is the first step toward combining OGSE measurements with axon diameter measurement techniques, such as AxCaliber[7] and ActiveAx[8], for measuring very small restriction sizes.

Methods

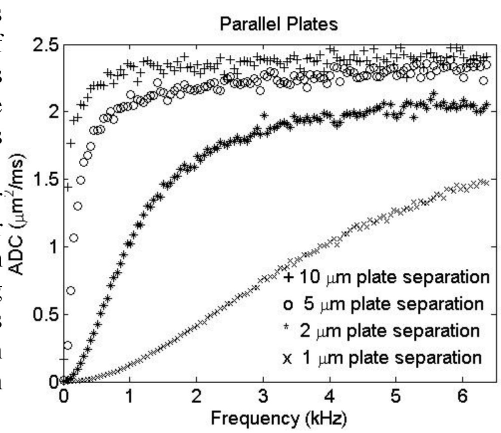
A Monte Carlo computer simulation was conducted using two different types of geometries. The first geometry consisted of parallel plates, with no permeability to water, separated by 1, 2, 5, or 10 µm. The diffusion coefficient of the water between the plates was 2.5 μm^2/ms. Two 80 ms ideal cosine gradient pulses were used, one before and one after the 180° pulse. There were n = 1 to 509 cosine waves in each gradient pulse. The gradient amplitude ranged from 0 to 22.5 mT/m in steps of 2.5 mT/m for n = 1 and varied appropriately for other values of n to keep b constant. T_2-decay was not considered.

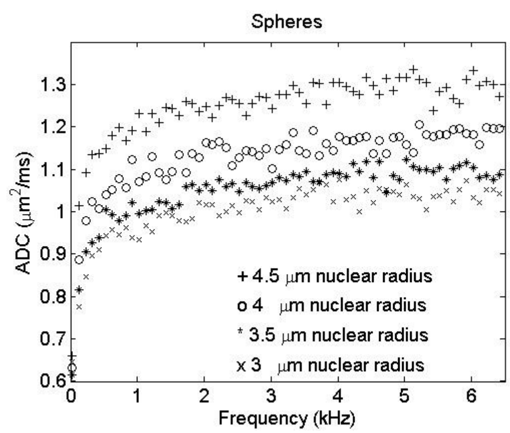
The geometry for the second simulation consisted of spheres (cells) of 5 µm radius, with nuclei of radii of 3, 3.5, 4 or 4.5 µm in a FCC lattice[6]. The diffusion coefficient for water in the nucleus was 1.31 μm^2/ms, for water in the sphere was 0.48 μm^2/ms, and for water between the spheres was 1.82 μm^2/ms. All barriers had zero permeability. Two 40-ms, ideal cosine, gradient pulses were used; one before and one after the 180° pulse. There were n = 1 to 397 cosine waves in each gradient pulse, although shown below are data up to n = ~250 because of the fairly constant trend above f = 6 kHz. The gradient amplitude ranged from 0 to 22.5 mT/m in steps of 2.5 mT/m for n = 1 and varied appropriately for other values of n to keep b constant. T_2-decay was not considered. While finite element difference methods have been applied to this geometry[6], this is the first Monte Carlo study of this geometry.

A set of N = 10,000 point particles was uniformly distributed in a random manner over each geometry. At each time step of 1 µs, the position of a particle was updated by generating a step vector with a random orientation in three-dimensional space. The magnitude of the step vector was determined by the product of the speed of the particle and the length of the time step. If the point particle reached a boundary, it would be specularly reflected because, for this simulation, the permeability of the barriers was set to zero. The simulation allowed for multiple reflections in a single time step.

Results and Discussion

Diffusion of water trapped between parallel plates separated by 5 and 10 µm appears almost unrestricted for large frequencies. Frequencies in the range of 1 kHz best distinguished these larger plate separations. Diffusion of water between parallel plates separated by 1 and 2 µm was restricted for the entire range of frequencies studied. While frequencies of ~2 kHz best distinguished these plate separations, higher frequencies appear to be needed to distinguish 1 µm separations from smaller separations. Higher frequencies better distinguish between nuclear sizes in the spherical geometry. Differing asymptotic behavior indicates variations in *ADC* with frequency can be used to infer restriction sizes in complex systems.





Conclusions

As expected, OGSE frequencies corresponding to scales in the range between completely restricted and free diffusion best distinguish restriction sizes. Combining these measurements with other techniques such as AxCaliber[7] and ActiveAx[8] can allow for the inference of restriction sizes in the samples.

References 1. Gross Messtechnik 77, 171–177 (1969). 2. Schachter JMR. 2000; 147(2):233-237. 3. Does MRM 49:206–215 (2003). 4. Gore NMR in Biomed 2010; 23: 745–756. 5. Kershaw ISMRM: 409 (2011) 6. Xu MRI 29 (2011) 380-390 7. Assaf MRM 59:1347-1354 (2008) 8. Alexander Neuroimage 52 1374-1389 (2010).