Accurate Quantification of Diffusion in Heterogeneous Systems Using the New Magic Asymmetric Gradient (MAG) Technique

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INTRODUCTION

Pulsed field gradient (PFG) measurements have been used to characterize surface to volume ratio and tortuosity of complex structures, which has found wide application in the field of porous media[1]. However, it is known that porous media and biological systems are heterogeneous and comprised of areas with strongly differing magnetic susceptibilities [2], leading to the presence of strong background gradients. At high field, these susceptibility gradients can be comparable to or even stronger than the laboratory gradients applied during PFG experiments. This leads to additional dephasing due to these endogenous gradients, as well as the cross terms between them and the applied PFGs. The recently proposed magic asymmetric gradient (MAG) technique suppress the cross term during the encoding and decoding intervals, respectively, and can correct for contributions from varying background gradients. So far, MAG technique has been demonstrated on homogeneous samples with simulated background gradients[3] or samples with bulk susceptibility field[4]. In this study, we showed for the first time, that the MAG technique can quantify molecular displacement accurately in a microscopic heterogeneous system. The combination of the MAG and bipolar PFG technique can provide a unique contrast of quantifying varying background gradients.

MATERIALS AND METHODS

Microspherical glass beads (100 μm) were transferred into a 5 mm NMR tube (Sigma Aldrich) filled up with $CuSO_4$ doped deionized water. The sample was then vortexed and vacuumed for 10 minutes to reduce trapped air bubble between beads. Additional sample of D_2O containing small amount of H_2O was used as the control phantom. The diffusion measurements were conducted at 500 MHz using bipolar PFG and MAG sequences while the samples remained at 300 K (TR=6 sec, pre and post gradient delay $\delta_1=\delta_2$=1ms, gradient pulse duration δ=2ms). The evolution time Δ is systematically changed from 8, 16, 32, 64, 128, 256 to 512 ms.)

RESULTS

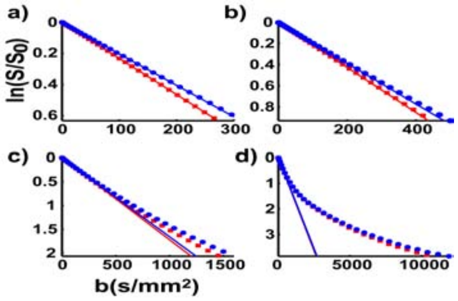

Fig. 1, Diffusion measurements of MAG & bPFG sequences with the evolution time being a) 8ms b) 16ms c) 64ms d) 512ms.

The spectral linewidth of the glass beads sample was measured to be 1.5 kHz, indicating strong susceptibility fields. Diffusion measurement from the heterogeneous phantom using MAG technique (red dots, Fig. 1) attenuates faster than the bipolar PFG sequence (blue dots, Fig. 1) at short diffusion time. The difference is reduced when the evolution time is beyond 256 ms, where the background gradient effects are averaged by diffusion attenuation during the long evolution interval. The evolution times for Fig.1 a, b, c and d were 8, 16, 64 and 512 ms, respectively. The apparent diffusion coefficient (ADC) is fitted using a mono-exponential function of low b values (<200 s/mm^2) and the fitting is displayed in solid lines for bipolar PFG (blue) and MAG (red) techniques, respectively. The reduction of displacement can be observed at long evolution intervals when the diffusion measurement at high b values clearly deviates from the mono-exponential fitting, as spin enters restricted diffusion regime. Fig. 2a shows that at short echo time (Δ=8ms), the MAG measurement is equal to free diffusion while the bPFG measurement is reduced. It shows that MAG technique provides uncorrupted measurement at very strong susceptibility field. In addition, the normalized ADC measurement (D_{bpfg}/D_{mag}) from beads sample increases from 0.86 to unity when the diffusion time increases from 8 to 256 ms or more (Fig. 2b). This may be attributed to dominating diffusion effects during the evolution time where it is not affected by background gradients. Also, field averaging by spin displacement may also contribute to the normalization at long evolution time.

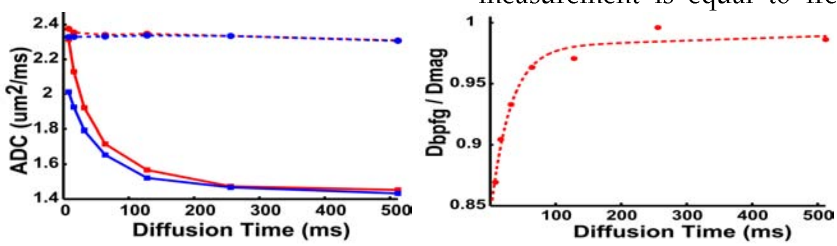

Fig. 2, **a)**ADC measurement on homogeneous (dashed line) and heterogeneous glass beads phantom (solid line). MAG and bPFG techniques were shown in red and blue, respectively. **b)** Ratio of bPFG & MAG diffusion rates as a function of evolution time.

DISCUSSION

This study shows that the MAG sequence provides accurate diffusion measurements in structured systems even at the presence of strong susceptibility fields. In addition, the diffusion measurements at varying evolution time can quantify the tortuosity of the system accurately, superior than conventional bipolar PFG technique. The MAG technique may provide a novel contrast mechanism characterizing complex structure such as angiogenesis where it is known to be with strong microscopic heterogeneity.

REFERENCE

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