Visualization of inhomogeneous local magnetic field gradient due to susceptibility contrast

H. Cho[1], S. Ryu[2], J. L. Ackerman[3], and Y-Q. Song[2]

[1]Memorial Sloan Cancer Center, New York, NY, United States, [2]Schlumberger Doll Research, Cambridge, MA, United States, [3]Martinos Center, Department of Radiology, Massachusetts General Hospital, Cambridge, MA, United States

Introduction

When two materials with different magnetic susceptibilities are present in a uniform magnetic field, spatially varying fields (internal gradients) typically arise due to local distortions in the magnetic field. In biological tissues, the susceptibility contrast is present between cells or cellular compartments such as trabecular bones and marrow, or blood plasma and erythrocytes[1,2]. The effect of the internal gradient on MR relaxation or diffusion measurements has been investigated with the goal of either removing it with new pulse sequences[3,4] or utilizing it to obtain the structural information that internal gradients provide[5]. In this work, we report a diffusion MR imaging method which can spatially resolve the strength and the directionality of local internal gradients. The method is demonstrated with a 2D model system composed of cylindrical capillary glass tubes of uniform size (ID =1.15mm, wall=0.2mm). The result shows good agreement with detailed theoretical calculations.

Methods

A slice-selective stimulated echo sequence with spin-warp imaging is employed. Transverse spin magnetization after the first $\pi/2$ pulse develops a spatially dependent phase due to the internal gradients. At the end of the encoding period, the transverse magnetization is flipped back into the longitudinal direction and spins are allowed to diffuse during the Δ period. A third $\pi/2$ pulse is then applied to produce a stimulated echo for the detection and imaging. The decay of the echo is measured at a series of Δ, values from which the strength of internal gradients can be extracted from the decay rates of echo signal after the bulk T1 calibration. When the external pulsed field gradients (PFG) with different orientations are applied during the encoding period, the cross terms between the PFGs and the internal gradients give rise to an interference pattern in the decay rates, and thus the directionality of the local internal gradient can also be determined. The numerical calculation of the internal field was performed using the measured spin density image with the shortest diffusion time (50ms) to obtain a high resolution replica of the experimental setup. The induced (demagnetization) field along the external field direction was calculated in the Fourier space by superposition of the dipole field from each voxel of the solid taken as a point source, valid to first order in the susceptibility difference[6]. Experiments were performed on a 4.7T Oxford magnet with Bruker console.

Results

Figures 1A and 1B show the measured decay rates map and the calculated internal gradient map, respectively (B_0 perpendicular to the image plane). Figures 1C and 1D compare both quantities across a single pore for various packing conditions as shown in (A) and (B) with labeled red lines. Overall agreement is excellent. For rectangular packing (profiles 1 and 2), slow decay (weak internal gradient) in the symmetric center of the pore between the tubes is apparent and the decay rate gradually increases toward the capillary tubes walls. For triangular packing (profile 3), fast and uniform decay is observed across the pore. A double minimum in the decay rate stands out in pores characterized by pentagonal packing (profile 4). Figure 2A shows theoretical calculations of angle resolved internal gradients. Figure 2B shows corresponding extracted decay rates due to cross-terms between internal and external gradients. Arrows represent the PFG directions.

Conclusions

Experimental stimulated echo decay rates due to diffusion in internal gradients are shown to be directly proportional to the local gradient strength obtained from theoretical calculations in a 2D model system of uniform glass tubes with water in the pores between the tubes. The spatially resolved interference patterns of decay rates between internal and external PFGs along different gradient orientations are also obtained and corresponding cross-terms are extracted. This work demonstrates a simple yet a useful method for quantifying the strength and the directionality of local susceptibility induced magnetic fields.

References

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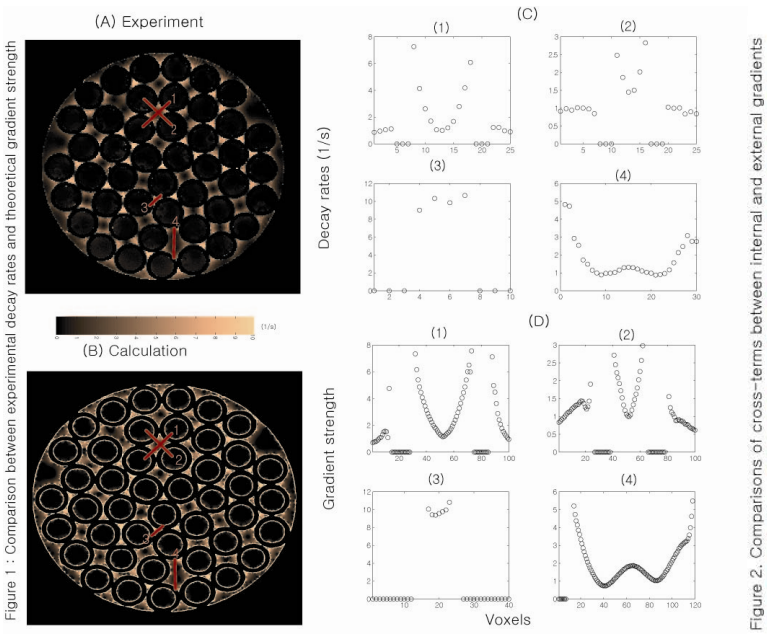

Figure 1 : Comparison between experimental decay rates and theoretical gradient strength

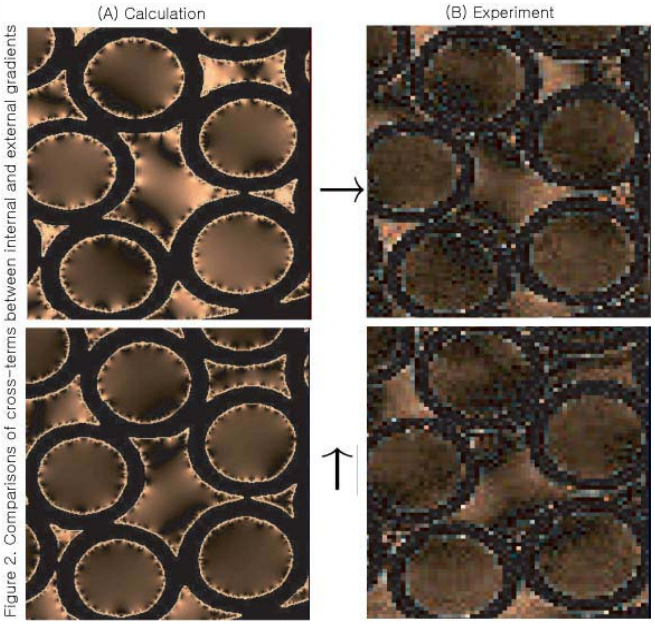

Figure 2. Comparisons of cross-terms between internal and external gradients