Anisotropy Induced by Macroscopic Boundaries: Surface Normal Mapping Using DWI

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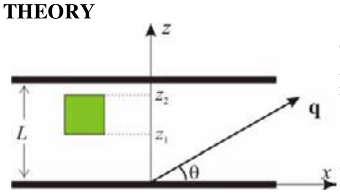
INTRODUCTION

Diffusion imaging has traditionally been used to infer information regarding tissue microstructure when the characteristic dimensions of the underlying geometry are smaller than the voxel size. However, the diffusion signal is sensitive to structures whose sizes are comparable to or greater than the voxels of the image. In this work, using a simple system of infinite parallel planes, we demonstrate that when the voxel is situated close to the boundaries, diffusion signal may be anisotropic even if the voxel itself contains no structure. This information can be used to extract the direction perpendicular to the bounding surfaces. The expected behavior is experimentally verified on a sample of a hollow cylinder where water molecules are trapped between two nearly concentric cylinders. The proposed method can be utilized to infer information from various tissues with macroscopic boundaries such as the cerebral cortex and the colon wall.

THEORY



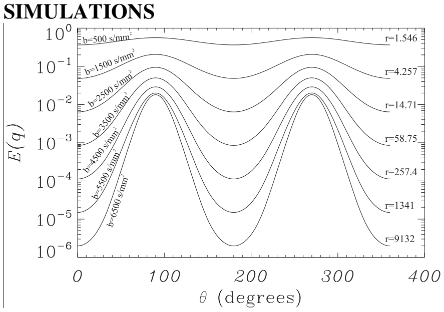
The figure on the left depicts the geometry being considered. The water molecules are allowed to diffuse between two parallel planes located at z=0 and z=L. The applied diffusion-sensitizing gradient makes an angle θ with the positive x-axis. The green box depicts the voxel from which the signal is acquired. Starting from the eigenfunction expansion of the Green's function [1], we derived the magnetization density. Upon integration over the voxel, the expected signal from the voxel is obtained to be

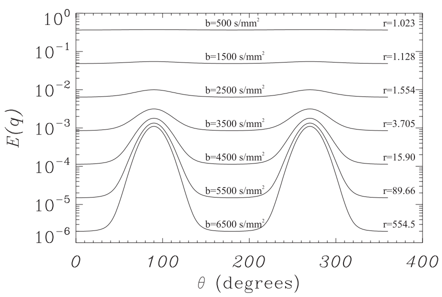
$$E([z_1,z_2],q_z,t) = i\,C(q_z)\frac{e^{2\pi i q_z z_1}-e^{2\pi i q_z z_2}}{2\pi q_z(z_2-z_1)} + \frac{2L}{z_2-z_1}\sum_{k=1}^{\infty} e^{-k^2\pi^2 Dt/L^2}U_k(q_z)\times \frac{\left[e^{2\pi i q_z z_1}\left(-2iLq_z\cos(k\pi z_1/L)-k\sin(k\pi z_1/L)\right)+e^{2\pi i q_z z_2}\left(2iLq_z\cos(k\pi z_2/L)+k\sin(k\pi z_2/L)\right)\right]}{\pi(k^2-4L^2q_z^2)}$$

where $C(q_z)=\frac{\sin(2\pi Lq_z)}{2\pi Lq_z}-i\frac{1-\cos(2\pi Lq_z)}{2\pi Lq_z}$, and $U_k(q_z)=(-1)^{k+1}\frac{2Lq_z\sin(2\pi Lq_z)}{\pi(k^2-4q_z^2L^2)}-i\frac{2Lq_z(-1)+(-1)^k\cos(2\pi q_z L)}{\pi(k^2-4q_z^2L^2)}$.

In the expressions above, we included the portion of the signal that depends on the motion along the z direction. For the true signal, $E(\mathbf{q}, t)$, the above expression needs to be multiplied with the free diffusion component along x- and y-axes.

SIMULATIONS

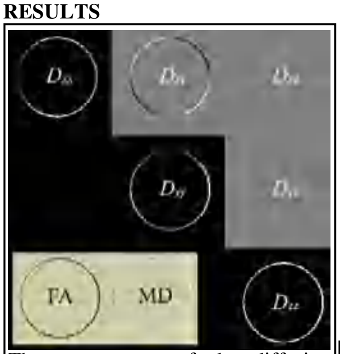




The figures show the absolute values of the expected signal attenuations as a function of the angle between the gradient and the x-axis for various b-values when L/t = 60µm/50ms (left) and L/t = 2mm/120ms (right). In both cases, free space diffusion coefficient was set to 2.02×10^{-3}mm²/s. The z_1/z_2 values were taken to be 0/20µm (left) and 0/0.67mm (right). The r values listed on the right-hand side of each plot indicate the ratio of the signal at θ=90° to the same at θ=0°, and serves as a measure of anisotropy.

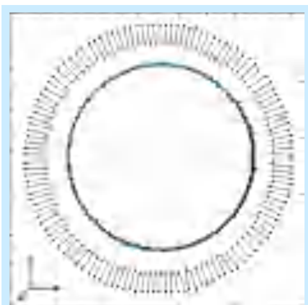
Clearly, the diffusion-weighted signal exhibits a significant level of anisotropy even at moderate b-values and feasible diffusion times. Since the minimum signal attenuation is obtained when the gradient direction is perpendicular to the surface, it is reasonable to expect the eigenvector associated with the smallest eigenvalue of the diffusion tensor estimated in the voxel of interest to yield the unit vector normal to the surface nearby. Although our simulations are based on the relatively simple model of parallel planes, a qualitatively similar behavior is expected for more complicated geometries.

RESULTS



The components of the diffusion tensor estimated from the hollow cylinder sample along with the fractional anisotropy (FA) and mean difusivity (MD) images. FA and MD values were 0.44±0.11 and 1.41±0.12µm²/ms across the water filled region.

In order to observe the predicted anisotropy induced by restrictions at a length-scale greater than the voxel size, we acquired a series of diffusion-weighted images from a sample of hollow cylinder created by inserting a glass rod of diameter 4.10mm into an NMR tube of inner diameter 4.22mm (Shigemi Inc., Allison Park, PA, USA). A series of diffusion-weighted MR images were acquired at 7-T with the following parameters: TR/TE=1.88s/64ms, bandwidth=35kHz, δ=3ms, Δ=51ms, FOV=6x6cm², matrix size=128x128 and slice thickness=4mm. One image was acquired with no diffusion gradient turned on. This was followed by 6 images at b=200s/mm² and 56 images at b=1300s/mm² with gradients along different directions.



At the center is the color orientation map [2] generated by using the third eigenvector of the diffusion tensor. Also shown are these eigenvectors computed from the medial axis of the hollow cylinder. The angular deviations of the eigenvectors from the expected orientations were 1.8±1.6°.

DISCUSSION: We demonstrated that the influence of restrictions to water molecular motion on the experimentally observed anisotropy is not limited to the case when the characteristic dimensions of the structure is smaller than the voxel size. This finding lends itself to a novel application of DTI, where it is possible to accurately map the orientations of nearby restrictions using the eigenvector of the diffusion tensor associated with its smallest eigenvalue. Note that our findings are valid even when the imaging volume is completely free of the restricting walls. The proposed technique could be used to address a variety of problems such as the reconstruction of brain's cortical surface, investigating the integrity of the colon wall, bronchial tubes and other structures with macroscopic internal boundaries.

References: [1] Tanner JE and Stejskal EO, J Chem Phys, 49 (4), 1968. [2] Pajevic S and Pierpaoli C, Magn Reson Med, 42 (3), 1999.