Incorporating DTI-derived orientation information into a double-PFG framework

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INTRODUCTION

The ability of the double pulsed field gradient (double-PFG) technique to provide microstructural information at low diffusion weightings (i.e., without using strong gradients) could make the method feasible for routine clinical practice. In the examination of fibrous tissues with some prior knowledge of the underlying fiber orientation, e.g., spinal cord, the double-PFG acquisition can be performed by fixing the direction of the gradients belonging to the first PFG block and repeating the acquisitions with different orientations of the second gradient, thus significantly reducing the number of necessary acquisitions. However, in order for this scheme to yield accurate results, the plane of the circle sampled by the gradients has to be perfectly perpendicular to the axis of the fibers. This requirement is difficult to fulfill in practice, because an accurate knowledge of the fiber orientation is not available *a priori*, and the fiber orientation may vary from voxel to voxel within white matter. To overcome this issue, we propose to use an independent diffusion tensor imaging (DTI) acquisition in conjunction with a double-PFG acquisition with circular sampling.

THEORY

The theory of MR signal for restricted diffusion within cylindrical pores is available for arbitrary pulse sequences [1]. In this framework, a general gradient waveform is expressed as a piecewise constant function, and an infinite-dimensional matrix, whose elements are related to the eigenvalues of the Laplacian operator and the size of the pore [2], are computed for each of the time intervals. Exponentiating and subsequently multiplying these matrices, one obtains a matrix whose very first element yields the signal attenuation. For the double-PFG experiment with no delay between the two PFG blocks, we shall denote the resulting signal attenuation as $E_\perp(\mathbf{q}_1,\mathbf{q}_2)$ where the two **q**-vectors ($\mathbf{q}=(2\pi)^{-1}\gamma\delta\mathbf{G}$, γ is the gyromagnetic ratio, **G** is the gradient vector, and δ is the gradient duration) are assumed to be perpendicular to the cylinder. Similarly, the free diffusion solution [3] is given by $E_f(\mathbf{q}_1,\mathbf{q}_2)=\exp(-4\pi^2 D_0[(\Delta-\delta/3)(q_1^2+q_2^2)-(\delta/3)\mathbf{q}_1\cdot\mathbf{q}_2])$, where $q_{1,2}=|\mathbf{q}_{1,2}|$, and D_0 is the bulk diffusivity.

Of particular interest for the purposes of this study is the cylindrical geometry wherein the orientation of the cylinder, denoted by **u**, should be taken into account. Decomposing the **q**-vectors into components parallel with and perpendicular to ($\mathbf{q}_\perp$) the cylinder's symmetry axis[4,3] makes it possible to write the attenuation due to diffusion within the cylinder as the product of two attenuations, i.e., $E_r(\mathbf{q}_1,\mathbf{q}_2)=E_\perp(\mathbf{q}_{1\perp},\mathbf{q}_{2\perp})\,E_f((\mathbf{q}_1\cdot\mathbf{u})\,\mathbf{u},(\mathbf{q}_2\cdot\mathbf{u})\,\mathbf{u})$. These expressions for restricted and free diffusion can be combined in a biexponential model [5], $E(\mathbf{q}_1,\mathbf{q}_2)=f_r E_r(\mathbf{q}_1,\mathbf{q}_2)+f_f E_f(\mathbf{q}_1,\mathbf{q}_2)$, which accounts for freely diffusing water molecules whose volume fraction is f_f, and $f_r=1-f_f$.

DATA ACQUISITION

Imaging was performed on a specimen of celery stalk. The MRI protocol included a series of 18 double-PFG scans followed by a diffusion tensor imaging (DTI) protocol with 44 single-PFG spin echo acquisitions. The parameters for the DTI acquisition were: TE/TR=59/3000 ms, δ/Δ=3/50 ms, field of view=22 mm, matrix size=128×128, resolution=172×172×2000 mm^3. Two images with no diffusion gradients were acquired followed by 42 diffusion weighted images (21 directions, 2 *b*-values up to 340 s/mm^2, where $b=4\pi^2q^2(\Delta-\delta/3)$). Double-PFG filtered imaging [6] was performed with the same geometry. The double-PFG parameters were: TE/TR=12/3000 ms, δ/Δ =3.15/50 ms. A total of eighteen double-PFG images were acquired, one at q=0 mm^{-1}, three at q=9.9 mm^{-1}, and seven images were collected at each of q=13.9 and 19.8 mm^{-1}. The number of averages was 8, yielding a total acquisition time of 51 minutes for each image.

RESULTS & DISCUSSION

In Figure 1, we illustrate images obtained from the DTI acquisition. Note the sharp contrast the vascular bundles yield in DEC and FA maps suggesting the coherence and elongation of the cells in these regions. Moreover, these cells appear to be oriented nearly in-and-out of the image plane (*z*-direction) as expected. These DTI findings can be exploited for two purposes. First, manually drawn ROIs including the phloem and xylem cells making up the vascular tissue can be further pruned by excluding those voxels with fiber orientations making an angle larger than 15^0 with the *z*-axis. Second, any small deviation of the orientation of the cells from the *z*-axis can be accounted for by feeding the DTI-derived orientation information into the double-PFG fitting procedure. The unknown parameters that were determined via the fitting routine were the fiber radius, S_0, f_f, and the bulk diffusivity, D_0. The fitting results corresponding to different ROIs can be seen in Figure 2. The estimation is performed in three different ways: (i) No information from DTI was included (red). (ii) DTI was used only to further prune the ROIs (blue). (iii) In addition to pruning the ROIs, DTI-estimated fiber orientation information was incorporated (black). Although average angular deviation of the fiber direction from the *z*-axis, as reported by DTI, was small (3.2^0), significant changes in the diameter estimates are evident when DTI-based information was incorporated. The reduced variation across different ROIs suggests the improved precision of the method. The estimates are consistent with the expected values based on microscopy performed on a celery stalk.

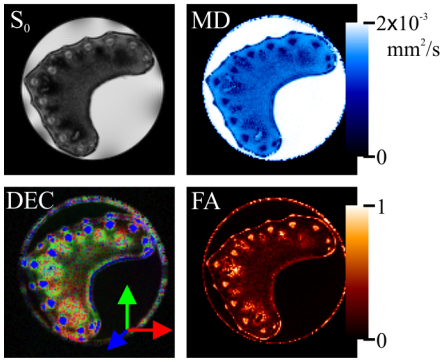

Fig. 1. DTI-derived non-diffusion weighted (S0), mean diffusivity (MD), direction encoded color (DEC), and fractional anisotropy (FA) maps.

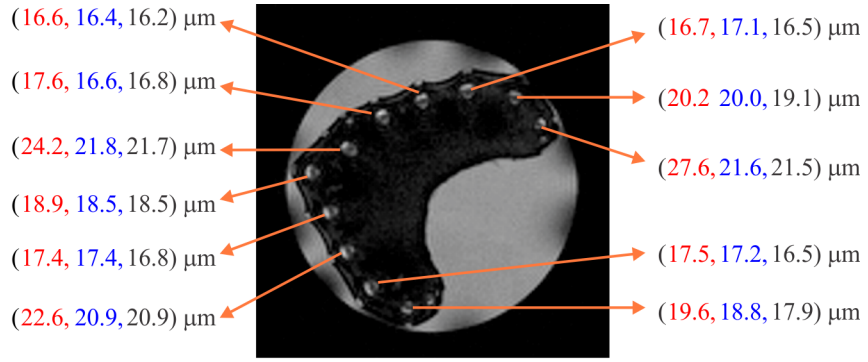

Fig. 2. A double-PFG scan with low diffusion weighting is used to show the ROIs corresponding to different vascular bundles. Arrows point to the cell diameter estimates obtained by; not employing DTI (red), using it to refine the manually selected ROIs (blue) and also incorporating the DTI-derived fiber orientation (black).

CONCLUSION

This study demonstrates how the double-PFG technique can be employed when the fiber orientation is known approximately. Small deviations from the expected fiber orientation can be accounted for by incorporating this information from a DTI data set collected in tandem. Finally, as was done previously with chive [7] and radish [8] specimens, plants can serve as excellent and convenient biological specimens to test the validity and accuracy of developed double-PFG techniques.

References: [1] Ozarslan et al., *J Chem Phys* **2009**, *130*, 104702. [2] Grebenkov, *Rev Mod Phys* **2007**, *79*, 1077-1137. [3] Ozarslan and Basser, *J Chem Phys* **2008**, *128*, 154511. [4] Assaf et al., Magn Reson Med **2004**, 52, 965-978. [5] Shemesh et al., *J Magn Reson* **2009**, *200*, 214-225. [6] Komlosh, *J Magn Reson* **2011**, *208*, 128-135. [7] Qiao, *Biophys J* **2005**, *89*, 2899-2905. [8] Koch and Finsterbusch, *Magn Reson Med* **2008**, *60*, 90-101.