Double-PFG Filtered Diffusion Tensors

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TARGET AUDIENCE Developers of diffusion MRI acquisition and analysis methods.

PURPOSE Double-pulsed field gradient (double PFG) is a generalization of the single PFG acquisition methods. Instead of applying a single pair of sensitizing gradients, the double PFG acquisition applies two pairs of sensitizing gradients (separated by a mixing time), and as a result the attenuation is affected by the combined effect of molecule displacement during the two pairs. The approach was recently implemented on clinical scanners, allowing in-vivo human scans [e.g., 1]. Different applications have demonstrated that varying the angle between the two pairs result with signal modulation that provides information about anisotropies that cannot be measured with single PFG [2]. Double PFG was also utilized to measure exchange between compartments [3]. In this context of exchange measurement, it is common to refer to the first gradient block as a filtering block, which is designed to attenuate fast diffusing water molecules, such as those found in the extracellular space. Here, we propose to use the terminology of filtering blocks, combined with a specialized gradient acquisition scheme in order to provide a simple model, which relates a special case of the double PFG signal to diffusion tensors. By using a tensor model we are able to make an intuitive connection between the single and double PFG methods, which also allows application of existing DTI analysis methods and tools.

METHODS

Images were acquired using a stimulated-echo based double-PFG sequence at a clinical MRI scanner (Philips Achieva 3T). Imaging parameters were: TE1 = 39 ms, TE2 = 55 ms, TR = 2500 ms, voxel size of 3X3X3 mm^3 The diffusion encoding of the first and second gradient pairs were performed in the directions specified by the icosahedron (6 directions), giving a total of 6x6=36 measurements [4]. The b-value of each gradient pair was 500 s/mm^2, yielding a total b-value of 1000 s/mm^2. The mixing time was approximately 25 ms. In addition we acquired a set of six filtered b0, i.e., a double PFG acquisition with a filtering block, and a second block with a b-value that approaches 0. In order to fit tensors we divided the 36 measurement to six, such that each filtering block had six different sensitizing gradients related to it, in addition to the filtered b0 with the same filtering block. These 7 measurements were used to fit tensors for each voxel in the image, resulting with 6 filtered tensors, one for each filtering block.

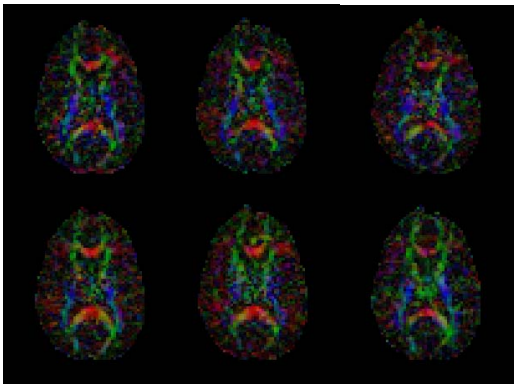

Fig.1: Filtered diffusion tensors obtained from 6 different filtering blocks. The filtering blocks were spread uniformly along a 6 direction – icosahedron gradient scheme.

RESULTS

Figure 1 presents the color by orientation maps of the 6 filtered tensors that were computed for each filtering block. Figure 2 shows enlargement of the maps in an area that is known to have crossing fibers. The figures show that in areas of single fiber, such as for example the corpus callosum (in red) the orientation of the filtered tensor is persistent across the 6 filtered tensors and is aligned with the expected orientation of the fiber. In areas of crossing fibers, or of gray matter, the orientation of the tensor depends on the filtering block. For example, in the highlighted area, some filtered tensors show the green posterior to anterior fibers, while other filtered tensors show the blue/purple cortico-spinal tracts.

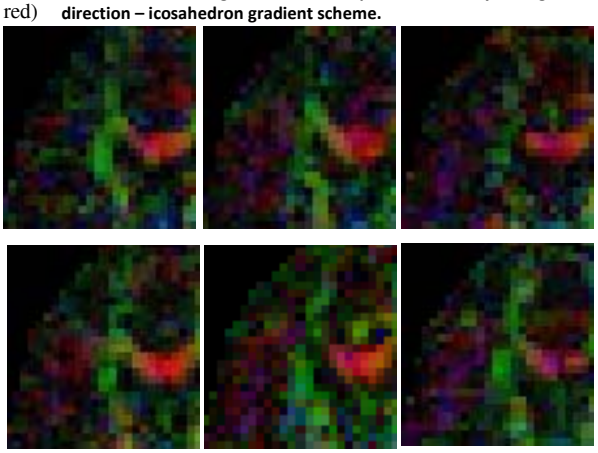

Fig.2: The orientation of the tensors depends on the filtering block in non-homogenous voxels (e.g., crossing fibers, gray matter), but is persistent in areas of single fiber orientation (e.g., the corpus callosum in red.)

DISCUSSION

Fitting a tensor for each filtering block g_1, we get attenuation signal that depends on the second gradient block, g_2, and on the filtered tensor $\mathbf{D}(g_1)$. A simple way to describe the signal would be to assume that for each filtering block, the attenuated signal follows the DTI model, in which case the attenuation is expected to be

$$E(g_1,g_2) = \exp(-b_2 g_2^T \mathbf{D}(g_1) g_2),$$

where $E(g_1,g_2)$ is the signal acquired with gradient pairs g_1, and g_2, normalized by $b0(g_1)$, the filtered b0. The variability of $\mathbf{D}(g_1)$ across the filtering blocks can be used to measure white matter complexity: low variability are expected in single fiber voxels, and high variability in complex white matter architecture. This is since the filtering block attenuates fast diffusion along the first gradient pair. Therefore, in crossing fibers, when the filtering block is aligned with one of the fibers, it will attenuate it, leaving signal only from the remaining fiber. Since $\mathbf{D}(g_i)$ (i=1,2..6) are diffusion tensors, they can be easily included in analysis methods that are based on DTI, such as fiber tracking, where instead of using the single tensor provided by DTI, one could chose any of the $D(g_i)$ tensors.

CONCLUSIONS

While most current double PFG methods concentrate on parameterization of new types of anisotropies in gray matter, we provide here a simple and intuitive framework to explore the utility of double PFG for mapping white matter. The preliminary results shown here suggest that using filtered tensors has the potential to resolve complex fiber architecture in an intuitive, signal driven way, which is different than the typically complex model based HARDI methods.

REFERENCES [1] Westin et al., ISMRM 2012. [2] Ozarslan et al., MRM 2009. [3] Nilsson et al., MRM 2012. [4] Westin et al., ISMRM 2013. Grant support: NIH P41RR013218, P41EB015902, R01MH074794 ; NARSAD young investigator grant from the Brain & Behavior Research Foundation. Swedish Research Council (2011-5176, 2011-4334, 2012-3682)