Diffusion Signal Decomposition using Periodical Sampling in Gradient Direction Domain and Fourier Approximation

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INTRODUCTION: Diffusion MRI measures water diffusion along multiple directions and correlates with nerve fibre alignment. Although diffusion signal reflects the restricted water diffusion of fibre tracts, other tissue compartments and noise contribute to the acquired signal, affecting the accuracy of tractography. Decomposing restricted diffusion from the diffusion signal is known to improve the results from tractography (1). Existing methods decompose diffusion signals either using multi-compartment or diffusion kurtosis models (2, 3). In this work, we proposed data driven decomposition of the diffusion signal. We describe a periodic spiral-sampling scheme to measure the diffusion signal in a "gradient direction" domain. With this scheme, periodicity in the acquired diffusion signal reflects restricted diffusion. In contrast, free diffusion and noise are independent of acquisition orientation and do not contribute to signal periodicity. Signal decomposition is achieved by finding the optimum Fourier series approximation of the diffusion signal. We tested the effect of Periodic Spiral Sampling Fourier Decomposition (PSSFD) of the diffusion-signal on the accuracy of tractography in *ex-vivo* images of the mouse brain.

METHOD: *Periodic spiral sampling*: The method entails the sampling of diffusion gradient directions periodically in a spiral over the unit sphere. Spherical spiral coordinates were obtained from the following expression:

$$\mathbf{d}_i = \begin{bmatrix} x & y & z \end{bmatrix} = \begin{bmatrix} \sin(t/2r)\cos t & \sin(t/2r)\sin t & \cos(t/2r) \end{bmatrix}, t = i\theta \,|\, k = 0,1,...,r$$

where **d** is the direction of the applied diffusion gradient, θ is the azimuth or angular step, and $r = 2\pi/\theta$ is the number of zenith steps. We used equal angular steps in both azimuth and zenith-coordinate directions. Fig.1 shows an example of the proposed sampling scheme, its corresponding diffusion signal (**E**), and its Fourier transform ($f\{\mathbf{E}\}$).

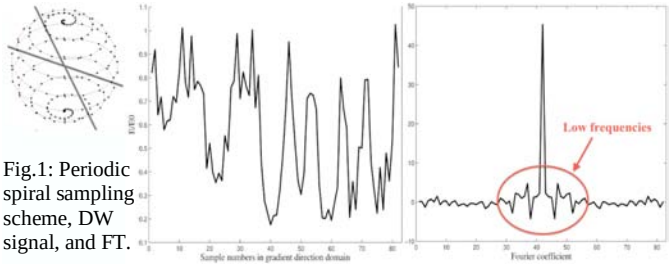

Fig.1: Periodic spiral sampling scheme, DW signal, and FT.

Diffusion signal decomposition: Decomposition is carried out by finding the optimum cutoff frequency (Fourier series approximation fit) to low pass filter $f\{\mathbf{E}\}$. Multi-criterion optimization problem defined as follow is used to minimize the deviation of decomposed signal from the diffusion-weighted signal (4):

$$\begin{aligned} &\text{minimize (w.r.t } \mathbf{R}_+^2) \quad (\left\|\mathbf{E}_d - \mathbf{E}\right\|_2, \text{ number of Fourier series order}) \\ &\text{subject to} \qquad\qquad n < 30 \end{aligned}$$

where $\mathbf{E_d}$ is the decomposed signal, and n is the order number for Fourier series approximation, which is kept small to omit high frequency noise.

Mouse brain data acquisition: An 8-week-old male mouse (C57BL/6J) was fixed and imaged on a 16.4 T Bruker scanner (Bruker Biospin, Karlsruhe, Germany) using a 15 mm SAW coil (M2M Imaging, USA). MRI data were acquired using periodic spiral sampling. Eighty-two diffusion-weighted samples with 20° angular steps and b-value of 1,000 s/mm^2 were acquired using echo planar imaging (TR=400 ms, TE=38 ms, δ=2.5 ms and Δ=12 ms). FOV was set to 11×18×10 mm^3 with 100 μm isptropic resolution.

Data analysis: The Constrained Spherical Deconvolution (CSD) method of Tournier et al. (5) with a maximum harmonic order (l_{max}) of 6 was employed to reconstruct the Fibre Orientation Distribution (FOD) using the MRTrix 0.2.10 software package (6). A manually selected ROI was generated at the Anterior Commissure (AC) for qualitative and quantitative comparison. The ROI was selected because of the prior knowledge about the fibre orientation in that region facilitating the follow up validation of FOD reconstruction and TDI mapping. Probabilistic tractography with 1000 streamlines was calculated, to generate a Track Density Imaging (TDI) map (7). In addition, the number of tracks was counted in the selected ROI shown in (Fig. 4.a).

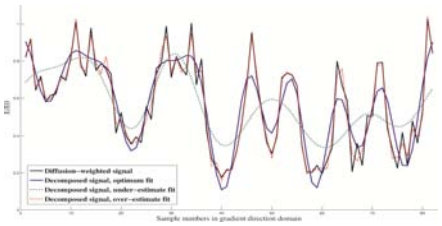
Fig. 2: DW signal, and Decomposed signal with different approximations. (Optimal fit here is n=10).

RESULTS: Fig.2 shows the diffusion-weighted signal from a voxel in the ROI of AC and its Fourier series approximations. Optimum Fourier approximation of diffusion signal preserves the signal spectrum while removing its high frequencies. Fig. 3 shows two voxels with different diffusion signal profiles: voxel-1 is located in AC, and has profile, which suggests a single fibre orientation; voxel-2 is located in Dorsal 3rd Ventricle (D3V) where fibres should not be present. Fig.3 (left) shows that the PSSFD method improved FOD reconstruction in both cases: in voxel-1, decomposition removes an incorrect minor orthogonal FOD; and in voxel-2, it resulted in more isotropic FOD reconstruction than conventional FOD. The reconstruction results agree with the anatomical prior knowledge about the fibre bundles in AC and D3V. Fig.4 demonstrates the TDI of AC both with and without diffusion signal decomposition and tract counts in the ROI. Conventional tractography and TDI overestimates the tracts in the ROI compared with TDI of decomposed data. The overestimation can be seen as the streamlines appearing in the region that should not have fibres bundles, as indicated by the arrow (Fig. 4a).

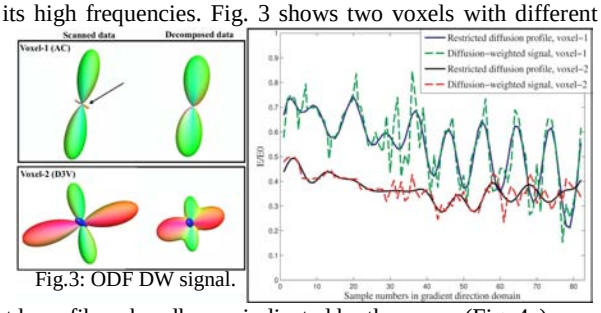

Fig.3: ODF DW signal.

DISCUSSION and CONCLUSION: We found that Periodic Spiral Sampling Fourier Decomposition scheme improves the accuracy of FOD reconstruction and tractography of AC: at highly restricted diffusion white matter regions and at fully isotropic regions. PSSFD was achieved by acquiring diffusion signal using periodic spiral sampling and optimal fitting of Fourier approximation, with the assumption that restricted diffusion is sensitive to acquisition orientation, while free diffusion follows random motion regardless of orientation. The proposed method limits the requirement of high b-value acquisition, where noise contribution is larger than diffusion attenuation level. Tissue microstructural analysis should be done in future for quantitative validation of decomposed data. Preliminary results suggest that PSSFD can improve the existing methods with evenly distributed sampled data by rearranging them to be similar to periodic spiral scheme.

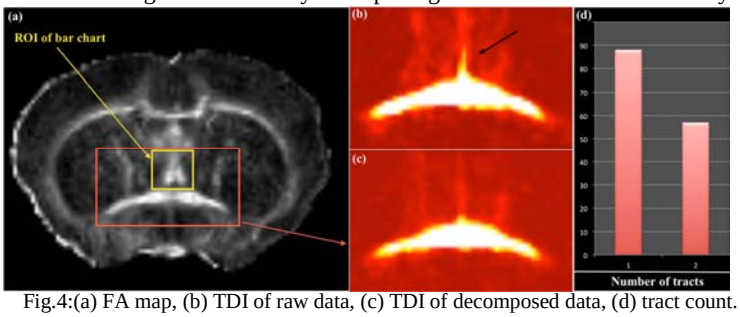

Fig.4:(a) FA map, (b) TDI of raw data, (c) TDI of decomposed data, (d) tract count.

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