Periodic sampling in the gradient direction domain facilitates noise reduction in diffusion weighted imaging

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Introduction

Diffusion-weighted imaging (DWI) exploits underlying tissue properties by estimating diffusion in a selection of sampling directions [1]. Various techniques of sampling and denoising trading off image quality for acquisition time have been reported [2,3]. To counter the effect of noise, DWI data are commonly smoothed in the image domain [4]. We describe a novel DWI sampling scheme over the unit sphere that improves denoising at the voxel level in a newly defined 'gradient direction' domain.

Method

Periodic spiral sampling and denoising: 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:

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

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. The number of sampling directions is $N = 2r^2$. Figure 1 shows the proposed sampling scheme for a simulated voxel with two fibres. We define the 'gradient direction' domain as a domain on which the diffusion signal in a given voxel changes with varying gradient direction. The periodic sampling scheme will yield periodic diffusion signal observed on this domain and the periodicity can be exploited for denoising. Fourier-based denoising was performed by zero filling high frequencies.

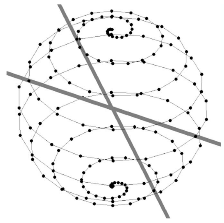

Figure 1. Periodic spiral sampling scheme. Only one hemisphere is sampled in practice.

Synthetic data: We simulated the diffusion signal based on spiral sampling and conventional evenly distributed sampling and compared the denoising rate and the accuracy with which the orientation distribution function (ODF) could be estimated across a range of signal-to-noise (SNR) ratios, *b*-values, and numbers of gradient directions. Synthetic data were generated using a multi-tensor model and Rician noise was added with each tensor being defined by the Stejskal and Tanner diffusion equation [5]. Five hundred voxels were simulated using both periodic spiral and evenly distributed sampling. Fibres were oriented randomly, with 490 voxels containing two fibres and 10 containing a single fibre orientation. Regularized Q-Ball imaging [6] was applied to the noisy and denoised synthetic data to reconstruct the ODF.

Mouse brain data: Here, we provide the results of denoising in two different corpus callosum voxels of an *ex vivo* mouse brain. 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. 82 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). The field-of-view was set to 11×18×10 mm^3 with a resolution of 100×100×100 µm^3.

Table 1. Denoising ratio comparison

SNR	N	*b*-value (s/mm^2)	Improvement ratio (%)	
			Even samples	Periodic spiral
5	82	1000	15	**48**
		2000	15	**64**
	226	1000	18	**64**
		2000	18	**81**
10	82	1000	-17	**29**
		2000	-25	**34**
	226	1000	-19	**41**
		2000	-28	**45**
20	82	1000	-38	**16**
		2000	-48	**17**
	226	1000	-41	**25**
		2000	-51	**27**

Results and Discussion

Synthetic data: Table 1 illustrates the denoising ratios at different SNR levels. For evenly distributed sampling, the SNR improvement was less than 20% for low SNR data, and denoising had adverse consequences for SNR over 10. In contrast, SNR gains were evident across all data when periodic spiral sampled was used. Periodic spiral sampling provided better SNR for larger *b*-values. Figure 2 shows that the ODF reconstruction is more accurate for denoised signal acquired with periodic spiral sampling compared to even sampling. The proposed method explicitly reveals the location of local extrema of the diffusion signal in each voxel. The local extrema of the plots denote the dominant orientation of the underlying fibre.

Mouse brain data: Figure 3 illustrates the results of denoising in two voxels within the corpus callosum of an *ex vivo* mouse brain. The data support the verisimilitude of the simulations. Local minima are associated with sampling directions parallel to fibre bundles. The correspondence of local minima in the two signals is in keeping with the uniformity of fibre orientation within the corpus callosum.

Conclusion

Periodic spiral sampling combined with Fourier-based denoising achieves significant SNR improvement and has the potential to improve the performance of High Angular Resolution Diffusion Imaging (HARDI) techniques such as Q-Ball, Constrained Spherical Deconvolution (CSD) or ActiveAx [7-9]. In future work, we plan to use this scheme for compressed sensing diffusion MRI with the aim of reducing data acquisition time.

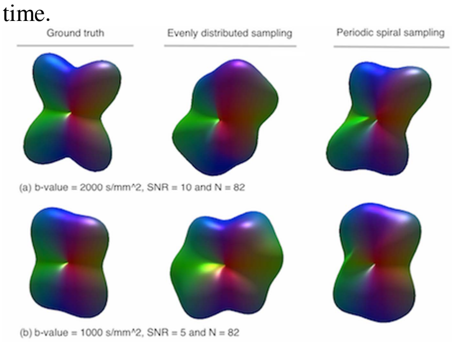

Figure 2: ODF reconstruction comparison.

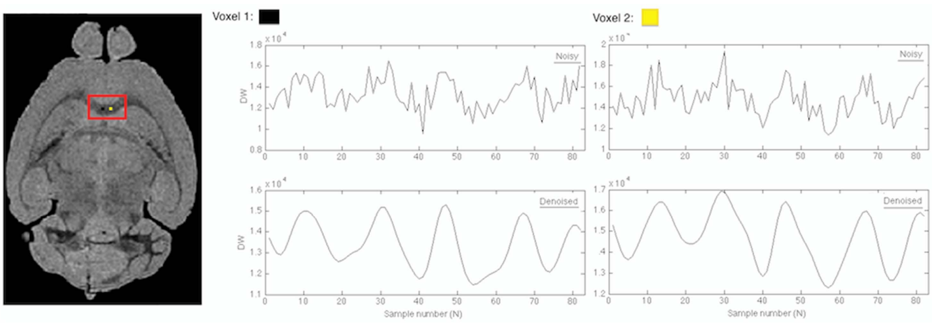

Figure 3: Mouse brain DWI (left) and diffusion signal of two voxels in corpus callosum (yellow and black).

Reference: [1] Johansen-Berg, Neuroimage (2011) [2] Jones, Imaging in Medicine (2010) [3] Cohen, ch. 9, Diffusion MRI; edited by Jones (2011) [4] Pajevic, ch. 20, Diffusion MRI; edited by Jones (2011) [5] Canales-Rodríguez, MRM (2009) [6] Descoteaux, MRM (2007) [7] Tuch, MRM (2004) [8] Tournier, Neuroimage (2007) [9] Alexander, MRM (2008)