Comparison between discrete and continuous propagator indices from Cartesian q-space DSI sampling

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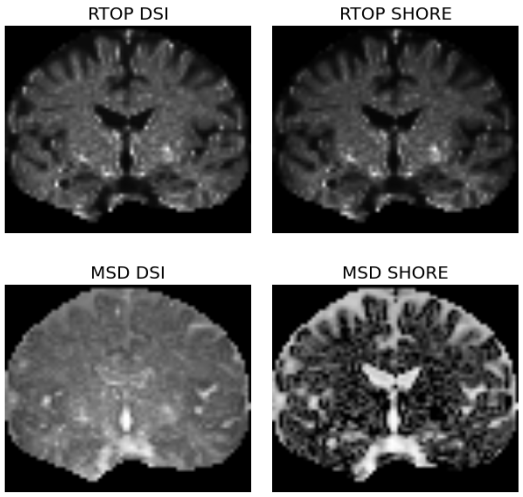
PURPOSE – DSI[1] is often considered the state-of-the-art technique to analyze q-space measurements sampled from a Cartesian grid. The 3D fast Fourier transform is used to directly obtain a discrete version of the EAP (Ensemble Average Propagator). DSI was one of the first techniques used to infer complex fiber configurations as it allows resolving crossings. In principle, DSI also captures some radial information which, in theory, can be used to extract diffusion features of the EAP. However, a discrete propagator representation suffers from a limited frequency band, which makes infinite integration impossible. Hence, EAP derived indices[2,3] are problematic and quantitatively questionable, as one needs to artificially normalize and approximate the infinite integrals. Combined with the recent popularity of DSI in the Human Connectome Project[4], it is important to investigate the different angular and EAP indices that can be computed from these DSI datasets. In this work, we investigate alternatives to the discrete model-free approach of DSI and investigate the Simple Harmonic Oscillator based Reconstruction and Estimation[3] (SHORE) models based on the evaluation of (i) the orientation distribution function (ODF) ; (ii) the return to the origin probability[2,3] (RTOP) and (iii) the mean square displacement[3] (MSD).

METHODS – *DSI model*: the discrete EAP $P_D(\mathbf{ru})$ is obtained by applying the 3D inverse FFT to the DSI signal after normalization by the b_0 image, Hanning filtering and zero padding[1]. We use the implementation provided by Dipy[5] (Diffusion in Python). *SHORE model*: the implementation of the SHORE basis from Merlet et al[6] is used. The coefficients c_{nml} are calculated by fitting the basis ϕ_{nml} to the normalized signal using a regularized least-squares procedure and used to calculate the continuous propagator $P_C(\mathbf{ru})$. *Metrics*: the ODF, RTOP and MSD were considered. The ODF is the radial integral of the EAP and provides information about the main diffusion directions; the RTOP is the value of the propagator in the origin (*r=0*) and is considered proportional to the level of restricted diffusion, and the MSD is given by the second order moment of the EAP. In DSI, these metrics are computed numerically from a discrete EAP and a discrete summation, whereas analytical solutions of the ODF, RTOP and MSD are derived for the continuous SHORE representation. To our knowledge, the analytical solution of the MSD is derived and used for the first time here.

SNR	DNC DSI	DNC SHORE	AE DSI	AE SHORE
10	0.772	0.627	12.90	11.74
15	0.649	0.646	7.70	7.46
20	0.551	0.632	6.09	6.52
25	0.564	0.632	5.71	6.13
30	0.530	0.626	5.46	6.01
100	0.484	0.599	4.87	5.50



RESULTS – Performance was evaluated on both simulated and real data. Simulated data were generated using the CHARMED model from ISBI HARDI reconstruction challenge 2013[7]. The following conditions were considered: two crossing fibers with minimum crossing angle of 30°, resulting in a total of 902 different voxels. The performance on synthetic data at different SNR levels was assessed based on the difference in the number of fiber compartments (DNC) and the angular error (AE), as reported in the Table. Results show that the SHORE model works better than DSI in terms of both DNC and AE in the presence of high levels of noise (SNR < 20). With respect to real data, a standard DSI acquisition mimicking the original DSI protocol[1] was done on a 3T system. Single-shot spin-echo EPI measurements with isotropic 2 mm spatial resolution and 515 DW measurements were acquired comprising q-space points of a cubic lattice within the sphere of radius five. TE/TR= 116 ms/14.9 s, 96x96 matrix, 60 axial slices, delta and Delta were 45.4 and 57.7 ms and maximal b-value of bmax = 6000 s/mm2. Because of the lack of ground truth for these indices, a qualitative comparison was performed. The RTOP provides information on the degree of anisotropy of the EAP[2,3], thus it is expected to be higher in the white matter. MSD is expected to be higher in the regions where the water is free to diffuse, like the ventricles. The ODF can be evaluated locally in the ROIs where it is known that there are single (corpus callosum) or crossings (corticospinal tract) fibers. Qualitatively, SHORE RTOP presents similar contrast with respect to DSI. MSD analysis clearly demonstrates the inefficiency of discrete DSI due to the low contrast even the ventricles, while the SHORE based MSD presents a higher contrast between CSF and WM-GM regions, as illustrated in the Figure.

DISCUSSION & CONCLUSION – Results indicate that the 3D-SHORE continuous representation provides an improved estimation of the EAP scalar maps and similar performances on the ODF reconstruction. In particular, the MSD data analysis enabled the identification of the areas of free diffusion, (CSF) that were impossible to detect based on the DSI technique. DSI reconstructs a discrete EAP, which makes advanced EAP feature extraction inadequate. Using a continuous representation such as SHORE, novel metrics such as kurtosis, moments and others metrics recently published[2] are better defined and have a great potential. Moreover, since it was demonstrated that the SHORE reconstructs the ODF as well as the original DSI reconstruction, high quality tractography will be possible from the SHORE ODF. Future work will investigate the suitability of the considered metrics for tissue characterization in both normal and pathological conditions.

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