Diffusion Spectrum Imaging tractography in complex cerebral white matter: an investigation of the centrum semiovale

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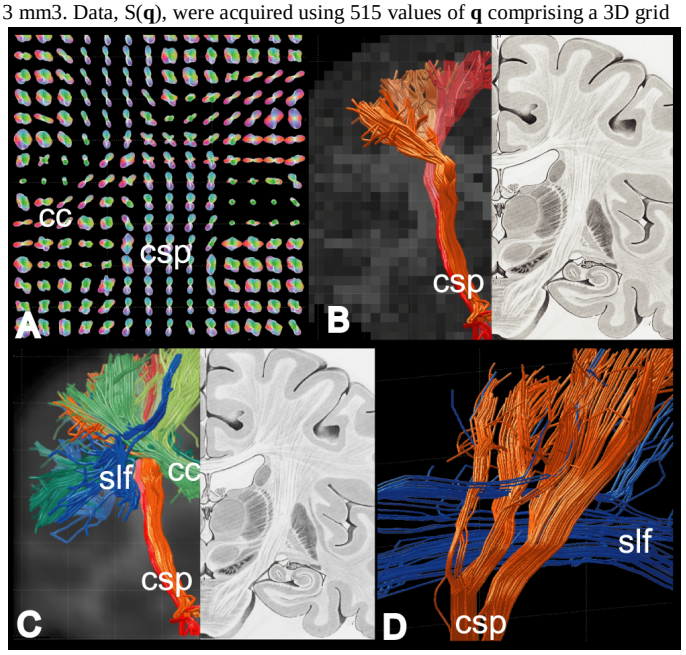
Introduction

Brain fiber tracking is a very challenging issue as we need to solve a difficult inverse problem i.e. retrieve continuous intermixing trajectories from a discretized, low-pass filtered position-orientation space of finite resolution. In particular fiber crossing is a recognized problem for Diffusion Tensor Imaging (DTI) tractography [1] as the diffusion tensor can only identify accurately the fiber orientation when the axonal population in each MRI voxel is unique. Recently, we have described a novel approach to diffusion MRI, Diffusion Spectrum Imaging (DSI) which affords the capacity to accurately image multiple fiber directions at each location (Fig A) [2,3]. DTI tractography has proved to be very successful in reconstructing several pathways but has trouble addressing properly the architecture of the largest fiber crossing area in the brain: the centrum semiovale. In the present study, we evaluate the capacity of a simple tractography method based on DSI to define the essential fiber crossing anatomy in that part of the brain. It is the largest area of the brain where many important tracts intermix, including the inter-hemispheric callosal projections, the superior longitudinal fasciculus, the cortico-spinal tract and therefore is a crucial test and objectif for any tractography study.

Material and Methods

The MR diffusion images of a hemi-brain were obtained on a healthy volunteer with a 3T Allegra scanner (Siemens, Erlangen, Germany). We used a twice-refocused spin echo EPI sequence [4] with TR/TE/Δ= 3000/154/66 ms and a spatial resolution of 3 mm3. Data, S(**q**), were acquired using 515 values of **q** comprising a 3D grid the interior of a sphere of radius r=5 grid units, where bmax = 17000 mm2/s.

Data reconstruction: The key concept of DSI [2] is that at each voxel, the signal data S(**q**) comprise a sampling of the 3D Fourier transform of the probability density function (pdf) $P(\mathbf{R})$ of the voxel averaged spin translation **R:** $P(\mathbf{R}) = \int S(\mathbf{q}) e^{-i\mathbf{q}^T\mathbf{R}} d\mathbf{q}$. We can write $P(\mathbf{R}) = \int_{\mathbf{r}\in Voxel} P(\mathbf{r}\,|\,\mathbf{r}+\mathbf{R})\rho(\mathbf{r})d\mathbf{r}$ where $P(\mathbf{r}|\mathbf{r}+\mathbf{R})$ is the conditional displacement pdf from location **r** to **r** + **R** for a given mixing time Δ and the initial spin density, ρ(**r**). In the case of in vivo imaging, the phase of S(**q**) is confounded by macroscopic motion, but $P(\mathbf{R})$ can still be reconstructed by hypothesizing that the diffusion pdf is symmetric which implies that its Fourier transform is real and positive. Therefore we reconstruct as: $P(\mathbf{R}) = \left|\int S(\mathbf{q}) e^{-i\mathbf{q}^T\mathbf{R}} d\mathbf{q}\right|$. To avoid ringing in the reconstruction, S(**q**) is multiplied by a Hanning window before the data is Fourier transformed. As for the present application we are only interested in the fiber orientation distribution, a weighted radial sum is computed in order to get a spin displacement orientation distribution function: $ODF(\mathbf{u}) = \int_0^\infty \mu P(\mu\mathbf{u}) d\mu$, where **u** is a vector on the unit sphere .



Tracking technique: The fiber tracking is based on a streamline algorithm that was adapted for DSI data. (1) As for DTI where the crucial step is the reduction of the data from a tensor to the main eigenvector, here the data is reduced from an ODF to a set of direction vectors $V = \{\mathbf{v}^l, 0 \le l \le |V|\}$ pointing towards local maxima. (2) The curve grows by expanding from a position $\mathbf{p}_i$ by a fixed step size μ along the vector ($\mathbf{v}_i^{m_i}$) that is the most collinear to the previous displacement vector $\mathbf{v}_{i-1}^{m_{i-1}}$: $\mathbf{p}_{i+1} = \mathbf{p}_i + \mu\mathbf{v}_i^{m_i}$ with $m_i = \underset{0\le l_i\le L_i}{\arg\max}\left\{\left|\left\langle \mathbf{v}_i^{l_i}, \mathbf{v}_{i-1}^{m_{i-1}}\right\rangle\right|\right\}$. (3) The general methodology is based on a) an initialization of fibers over a first region of interest (ROI) with random initial directions and b) only the fibers that pass through a second ROI at some distance of the first are retained. Additional selection is performed based on the mean average diffusion coefficient along the fibers (see Validity Index in [5]).

Results

In Fig. B the cortico-spinal tract (csp) has been mapped by initializing fibers along the motor strip and capturing the fibers that end in the pons. According to known anatomy [6] the fibers displayed in red represent the part of the pyramidal tract that starts in the apical part of the precentral gyrus and middle part of the pararcentral lobule and correspond to the motor function of the trunk and legs. Whereas the fibers in orange, taking their origin between the superior and inferior genu of the central sulcus (i.e. of the precentral gyrus), correspond to (the fibers serving) the motor function of the arm and hand. The callosal fibers (in green, cc) passing in the region of the centrum ovale were initiated in the parietal cortex and those passing the mid-sagittal plane via the corpus callosum were retained (Fig. C). One can see that the fibers of the corpus callosum are widely distributed throughout the parietal cortex from the apex down to its lower limit at the lateral sulcus. The superior longitudinal fasciculus (in blue, slf) has also been tracked in order to show the complex intermixing of several fiber populations that occur in the centrum semiovale (Fig. C and D).

Discussion

In order to map accurately the brain connectivity from diffusion MRI there is a compelling necessity to acquire data that handle appropriately diffusion in complex tissue architecture as this type of tissue organization is widespread in the white matter. It is even crucial for structures as prominent as the cortico-spinal tract and the corpus callosum. DSI is a novel imaging technique that is able to image accurately water diffusion of complex tissue architecture with very limited a priori, thus enabling to address the fiber-crossing problem. We showed that, based on DSI, even a very simple fiber-tracking algorithm using hardly any a priori anatomical information allows realistic reconstruction of the fiber tracts passing through the centrum semiovale, reasonable first test case for tractography. The whole cortico-spinal tract could be mapped accurately but the more lateral motor fibers corresponding to cortico-bulbar tract that are responsible for the cephalic motricity, were not well visualized. These sparse fibers that undergo high curvature at the level of the centrum semiovale are the most challenging to identify and may need higher resolution. It is also possible that a better understanding of the influence of tract curvature on diffusion in a voxel will help to tackle this question.

Conclusion

DSI makes tractography in complex fiber architecture possible, as an elementary tracking method proves sufficiently robust to map the major axonal trajectories in the centrum semi-ovale.

References

[1] Basser PJ, et al. Magn. Reson. Med. 44 :625-632, 2000. [2]Wedeen VJ, et al. Proc. ISMRM. 8:82, 2000. [3] Lin CP, et al. Neuroimage. 19:482-95, 2003-11-10. [4] Reese TG, et al. Magn Reson Med. 49:177-82, 2003. [5] Hagmann P, et all. Neuroimage. 19:545-54, 2003. [6] Neurofunctional Systems.Kretschmann HJ et al.Thieme, 1998

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