A global approach to diffusion tensor neighborhood tractography

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Introduction: Neighborhood tractography offers the potential to improve the reliability and reproducibility of automated white matter pathway extraction and associated measurements of connectivity and tract integrity. Neighborhood tractography frameworks have been proposed for local tractography methods, particularly those based on streamline, or probabilistic streamline algorithms [1,2]. In this work, a neighborhood tractography procedure is developed for global tractography algorithms, such as those based on front evolution, and an initial evaluation is performed using an implementation of fast marching tractography.

Methods: A modified version of the fast marching tractography (FMT) algorithm proposed by Parker et al. [3] was implemented, incorporating a normalized version of the speed function $F(\mathbf{r})$ defined by Staempfli et al. [4], such that

$$F^{pp}(\mathbf{r}) = \min\left(|e_1(\mathbf{r})\cdot n(\mathbf{r})|^2, |e_1(\mathbf{r}')\cdot n(\mathbf{r})|^2, |e_1(\mathbf{r})\cdot e_1(\mathbf{r}')|^2\right) \qquad F^{po}(\mathbf{r}) = \min\left(1-|e_3(\mathbf{r})\cdot n(\mathbf{r})|, |e_1(\mathbf{r}')\cdot n(\mathbf{r})|^2, 1-|e_3(\mathbf{r})\cdot e_1(\mathbf{r}')|\right)$$

$$F^{op}(\mathbf{r}) = \min\left(|e_1(\mathbf{r})\cdot n(\mathbf{r})|^2, 1-|e_3(\mathbf{r}')\cdot n(\mathbf{r})|, |n(\mathbf{r})\cdot n(\mathbf{r}')|\right) \qquad F^{oo}(\mathbf{r}) = \min\left(1-|e_3(\mathbf{r})\cdot n(\mathbf{r})|, 1-|e_3(\mathbf{r}')\cdot n(\mathbf{r})|, |e_3(\mathbf{r})\cdot e_3(\mathbf{r}')|, |n(\mathbf{r}).n(\mathbf{r}')|\right),$$

where the superscripts p and o represent front propagation from voxels $\mathbf{r}'$ to $\mathbf{r}$ between prolate and/or oblate tensors, e_1 is the principal eigenvector, e_3 the minor eigenvector and $n(\mathbf{r})$ is the normal to the front at position $\mathbf{r}$. The FMT algorithm produces arrival time maps from which geodesic pathways γ can be obtained from all voxels back to a seed by performing gradient descent through the arrival time field. An estimate of the connectivity between the seed and all other voxels in the brain can then be obtained by calculating the cost function $\Phi_1(\gamma) = \min F(\gamma(\tau))$ along each path. The FMT algorithm was incorporated into a neighborhood tractography framework with a view to automating the procedure for obtaining connectivity maps from white matter pathways of interest. Seed voxels were defined in standard MNI brain space in several white matter fibers and these were transposed into the native space of each individual subject using the transformation matrix obtained from affine registration of the subject's T_2-weighted EPI image to the MNI-152 template. A 3D neighborhood (7 × 7 × 7) was then defined around the native space seed voxel, and the FMT algorithm was run to obtain connectivity maps for each of the neighborhood voxels. All connectivity maps obtained from the neighborhood were compared to a reference connectivity map for the pathway of interest using normalized cross-correlation to estimate the similarity to the reference. In this preliminary work, reference maps were taken from the group-averaged brain atlas available from Johns Hopkins University [5]. Each voxel in the neighborhood was then ranked by similarity to the reference with the most similar map being chosen as that representative of the pathway(s) of interest. To validate the effectiveness of the algorithm, diffusion tensor imaging data was acquired from seven healthy volunteers (mean age: 32 ± 5 yrs) on a GE Signa 1.5T clinical scanner using 64 non-collinear gradient directions (TR / TE = 16500 / 95.5 ms, 128 × 128 matrix, 256 × 256 mm FOV, 2mm slice thickness, acquisition time ≈ 20 minutes). The neighborhood tractography algorithm described above was applied to each subject by seeding in the genu and splenium of the corpus callosum and the left cingulum bundle. For each white matter pathway, the resulting connectivity maps were compared to those obtained directly from the native space coordinates obtained by registration alone.

Results: Figure 1 illustrates Φ_1 connectivity maps (projections in the axial or sagittal planes) obtained from Subject 1 when the seed voxel was defined by direct transformation of the voxel in standard space, compared to those obtained from neighborhood tractography. Visual inspection of the images clearly shows an improvement in the resulting connectivity maps, when compared to the 'ideal' reference map. Also shown in Figure 2 are connectivity maps obtained from all seven subjects for the three fibers studied, all of which show good correspondence with their respective reference maps. Normalized cross-correlation values calculated between Φ_1 and the reference map averaged over all subjects were 0.24 ± 0.03, 0.22 ± 0.05, and 0.22 ± 0.05 for the genu, splenium and cingulum with directly transposed seed voxels and 0.34 ± 0.04, 0.27 ± 0.03 and 0.26 ± 0.03 for the neighborhood tractography case. In all examples, the correlation was significantly improved with greater values representing a better match to the reference ($p < 0.05$).

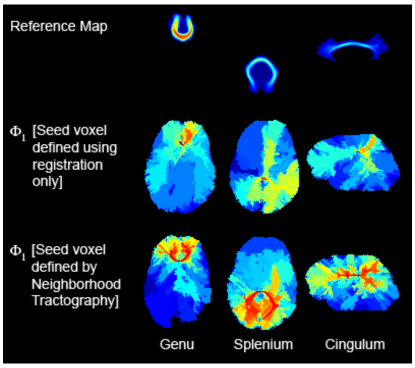

Figure 1. Comparison between connectivity maps (Φ_1) from Subject 1 obtained with the seed voxel defined by registration, compared to that by neighbourhood tractography.

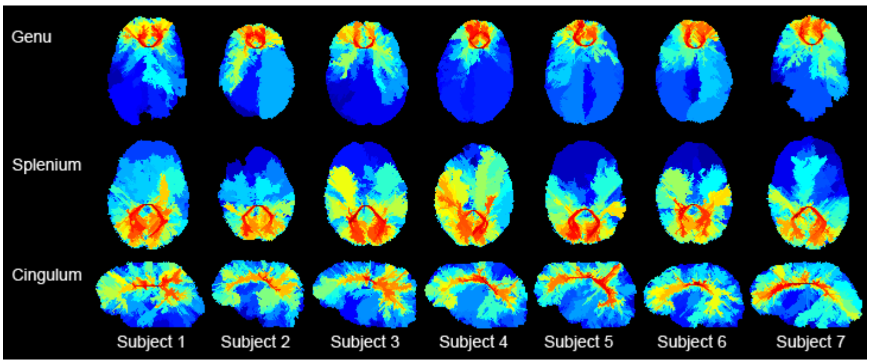

Figure 2. Connectivity maps (Φ_1) obtained for all seven subjects using the neighbourhood tractography approach. The maps are shown as projections in the axial or sagittal planes.

Discussion: In this work, a method has been presented for obtaining automated estimates of anatomical brain connectivity using a neighborhood tractography approach modified for global tractography. The method uses a-priori estimates of the expected connectivity distribution to identify the most likely output map and the initial results appear encouraging. There are several situations where a global tractography solution may be preferred to a local streamline-based algorithm. For example, when a more exploratory approach is required, or when cortical seeding is desired - a situation where streamline algorithms frequently fail to propagate. Additional work is required to develop specific global reference maps for pathways of interest, and to establish the improvement in reproducibility and reliability of resulting quantitative measures of tract connectivity and integrity.

References: [1] Clayden JD, et al. *Neuroimage* 2006;33:482-92. [2] Clayden JD, et al. *IEEE Trans Med Imaging* 2007;26:1555-61. [3] Parker GJ, et al. *IEEE Trans Med Imaging* 2002;21:505-512. [4] Staempfli P, et al. *Neuroimage* 2006;30:110-120. [5] Mori S, et al. Elsevier.

Acknowledgements: All imaging was performed at the SFC Brain Imaging Research Centre, University of Edinburgh. PAA is supported by the Scottish Office funded eDIKT2 project and the Row Fogo Charitable Trust.