Cortical Surface Based Representation of Diffusion: A Marmoset Study

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Introduction: As high resolution Diffusion MRI acquisitions have become more available, the presence of anisotropic diffusion in the adult cerebral cortex has been documented [1]. In this work, we propose a local coordinate framework collinear to the normal to the pial surface that would enable representation of diffusion orientational patterns in the cortex unaffected by the global orientational bias of the cortical folding. For an initial assessment, the method is applied to ex-vivo marmoset data due to the relatively simple shape of the cortical surface in this animal compared to the human cortex.

Materials & Methods:

Data: A formalin fixed healthy marmoset brain was placed in a plastic tube filled with Fomblin. It was scanned in a 40 mm diameter birdcage RF coil on a 7T Bruker Biospec scanner. A spin-echo, diffusion weighted, multi-segmented EPI sequence was used, in a phase-encoded 3D acquisition mode: TR=700 ms, TE=40 ms, 16 segments, matrix size 192x256, 160 slices, 150 µm isotropic voxel size. Large b-value (4800 s/mm2, δ/Δ = 6.4/16ms) images were collected for 126 directions on a single shell in the q-space [1]. Six b=0s/mm^2 images were acquired which also serve as T2-weighted images. The total scan time was about 75 hours. The diffusion weighted images were first corrected for eddy-currents artifacts and the diffusion tensors were computed in the image native space using non-linear regression [2]. Additionally, spherical harmonics representations (up to order 6) were also computed using in-house software with constant solid angle representation of the signal [3].

Cortex processing: A multi-channel segmentation approach was initially conducted using FA, ADC, T2W and myelin content images to discriminate between WM, GM and CSF. Marching-cubes based isosurface extraction algorithms were employed to extract the cortex pial surface and GM/WM interface out of the GM segmentation maps. Surface normals were computed from each surface vertex. The middle layers of the cortex were computed through interpolation between pial surface and GM/WM interface. Additionally, the pial surface was flattened onto a planar structure in order to have all surface normals point in the same direction.

Diffusion tensor representation: The primary eigenvector (e_1) of the diffusion tensors were first plotted on extracted surfaces. Given that the cortex is mostly isotropic, one would expect e_1 to be noisy but the homogeneity of e_1 on the outer surface can be considered as an indication of the quality of the acquisition. Subsequently, a map indicating the difference between the surface and diffusion architectures was generated from e_1 and surface normals n, with $\theta = cos^{-1}(e_1.n)$.

Spherical harmonics representation: Diffusion tensors cannot produce detailed information in the cortex due to the isotropic nature of GM. Spherical harmonics (SH) were used to extract similar diffusion patterns from within the cortex. The principal direction represented by SH was first used to rotate the entire SH coefficients onto the surface normal. During the flattening process, SH were rotated again in such a way that at the end of the process the primary directions from all the voxels had the same direction. An Expectation-Maximization (EM) segmentation algorithm was carried out on the invariant features of SH to cluster similar diffusion patterns out of the cortex. This approach purposefully only considered the shape information of the complex diffusion profile rather than orientation because considering the orientation with respect to the new coordinate framework is mostly similar between the SH.

Results: Even though the cortex is almost isotropic, in this high quality data the primary eigenvectors showed coherent patterns, mostly lined up with the surface normals. This fact can be better observed with the angular difference map of Figure 1. In this figure, the top row indicates the angular difference between the surface and e_1 at the pial surface level. At this level, there is a patterned difference in between these two quantities indicated by the bright tones. This can be attributed to diffusion being constrained by the boundary surface, as well as imaging artifact effects. The bottom row displays the same map computed from a middle layer of the cortex. In this layer, diffusion is mostly radial and parallel to the surface normals in most regions, while deviations from this behavior occur on some regions, such as the sulci. Figure 2 depicts the class label maps obtained from the segmentation of the spherical harmonics shapes. Just below the pial surface level (left image), most of the cortex tends to have similar complex diffusion shapes with a few localized exceptions and the entirety of the frontal lobes. At deeper levels, the shapes depict a more structured pattern and new classes of diffusion shapes (other than the one indicated by purple) start to dominate. Figure 3 displays representative spherical harmonics from three classes. One of the harmonics classes represents the isotropic regions, whereas the other classes contain samples with low anisotropy single fiber voxels and multiple fiber populations. For these representative shapes, the orientations are not normalized.

Discussions: In this work we presented a novel approach to analyze cortical anisotropy and cortical diffusion by providing a coordinate framework locally defined by the cortical surface of interest. This approach enables analysis and visualization on fine level diffusion properties that are not directly visible in image space coordinate frameworks.

References: 1. McNab J. et al. ISMRM, 2011, **2.** Tuch DS, MRM 52:1358-1372, 2004.; **3**. Rohde G et al., TBE, 2005.; 4. Aganj et al, MRM, 2010.

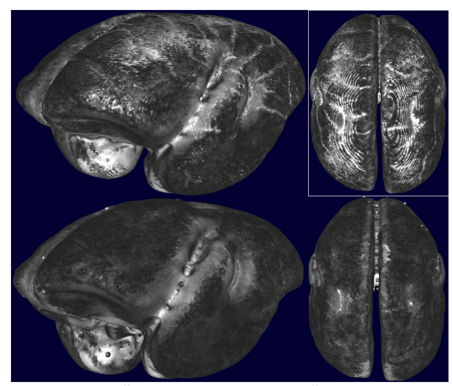

Figure 1. Angular difference map between primary diffusion direction and the surface normals. The values range in [0-90] and darker tones more parallelism between the vectors where brighter tones indicate angular difference. The top

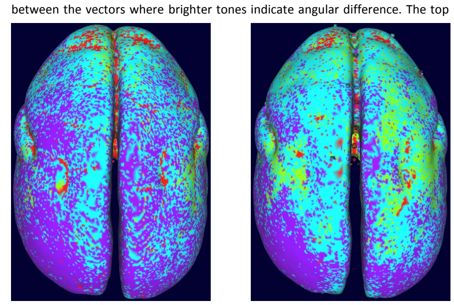

Figure 2. Segmentation of spherical harmonics shape. Colors indicate different shape class labels. Left image represents the classes for the sub-pial surface and the right image classes for the middle layer of the cortex.

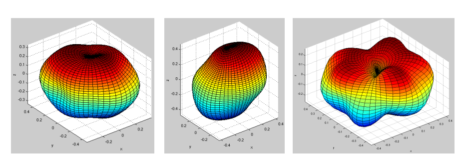

Figure 3. Dominant spherical harmonics shapes of the classes displayed in Figure 2.