DSI Tractography of CNS Fiber Architecture and Cortical Architectonics

V. J. Wedeen[1], R. Wang[1], T. Benner[1], P. Hagmann[2,3], W-Y. Tseng[4], T. G. Reese[1], A. G. Sorensen[1], A. de Crespigny[1]

[1]Martinos Center for Biomedical Imaging, Dept. of Radiology, Massachusetts General Hospital, Charlestown, MA, United States, [2]Signal Processing Institute, Swiss Federal Institute of Technology, Lausanne, Switzerland, [3]Dept. of Radiology, University Hospital, Lausanne, Switzerland, [4]3Center for Optoelectronic Biomedicine, National Taiwan University College of Medicine, Taipei, Taiwan

Introduction

A goal of diffusion MRI is to define and map the geometric coherences of tissue, particularly of fiber architectures. Diffusion spectrum (DSI) and related methods have the capacity to detect and map complex orientational coherences within the MRI voxel, including fiber orientation, crossing and planar structure. Here, we investigate the capacity to extend these coherences over multi-voxel scales by a simple tractography.

Imaging and tractography general methods

DSI data are acquired as a set of diffusion-weighted images, specifically, 515 values in q-space comprising the points of a cubical lattice contained in the interior of a spherical volume. This maximum radius of this q-volume, q_{max}, corresponds to a diffusion sensitivity b_{max} typically equal to $8{\cdot}10^3$ $s{\cdot}cm^{-2}$ in vivo, $3{\cdot}10^4$ $s{\cdot}cm^{-2}$ in fixed tissue.
Following reconstruction of the orientational dependence of the spin displacement density by integral transform at each voxel (for DSI 3D-FT followed by radial projection, for q-ball Funk-Radon transform), data at each voxel are reduced to the set of vectors V_i that are the orientations of maximum diffusion. Fiber tracts are reconstructed with a streamline algorithm: tracts are initiated at every voxel for every orientation vector of maximum diffusion V_i and extended into a new voxel along the vector of maximum diffusion closest to its incoming orientation. Fibers terminate when no maximum vector exists within a fixed angular tolerance, typically set to 0.5 radian.

Human studies in vivo

Method: DSI and q-ball tractography were performed in normal volunteers at 1.5 and 3T. Data were acquired with a multislice SE 3000/150 sequences, using 2 RF 180° pulses for improved efficiency and gradient stability, with $b_{max} = 8.5{\cdot}10^3$ s cm^{-2} and isotropic resolutions of 2.3 to 3.0 mm.
Results: DSI tractography in humans reveal major white matter fiber bundles and their intersections, including the pontine decussation of the cerebellar peduncles and the 3-way crossings of the centrum semiovale not accurately seen with DTI (Fig. 1). In general, higher b-value improved resolution of fiber intersections but reduced SNR, with $b_{max} = 5{\cdot}10^3$ $s{\cdot}cm^{-2}$ a rough lower limit to resolve deep intersections. Q-ball imaging generally produced better images of deep white matter than dsi but was less robust in mixed gray and white matter, thalamus and basal ganglia.

Animal studies ex-vivo

Method: DSI of isolated fixed Gd-doped brains of macaque, rabbit and mouse were acquired at 4.7T, using 3D spatial encoding (2D EPI, 1D phase-encoding of the third dimension), $b_{max} = 2{\cdot}10^4$ to $4{\cdot}10^4$ $s{\cdot}cm^{-2}$ and isotropic resolutions of 512, 300 and 175μm, respectively.
Results: In addition to deep white matter, radial orientations are demonstrated throughout the cerebral cortex in all cases, including the hippocampal cortex CA1 and the olfactory bulbs. Long-range cortical connectivity was demonstrated occasionally, interrupted subcortically by high curvature. Sparse horizontal fiber orientations within the cortical ribbon were demonstrated in most cases.

Tractography of horizontal intra-cortical structures

Previous DSI studies of the cerebral cortex have revealed 2D or planar order beyond the linear or 1D order associated with simple fiber orientation. To see if this 2D order indicates orientation of horizontal, or 'transverse', intracortical fiber architecture, specialized 2D tractography was devised.
Method: At each voxel, planes of maximum diffusion are by Fourier duality planes orthogonal to orientational maxima vectors W_i of the raw signal S(q). In the cortical ribbon, radial orientation is pervasive and corresponds to the leading orientational maximum of diffusion V_1. Accordingly, horizontal components of the cortical planar architecture are vectors U_i perpendicular to V_1 and W_i, $U_i = V_1 \times W_i$, which we integrate as above.
Results: Horizontal integration of planar structure yields fiber tracts matching known horizontal cortical fibers in the cerebellum and in the hippocampus CA1. In the neocortex, the new solutions agree with but extend the sparse horizontal fiber solutions of direct tracing, to all cortical areas and depths. In many cases, intra cortical contrast corresponds to recognized architectural and functional boundaries within, e.g., cingulate-pericingulate, pre-post central) and many specialized cortical areas are conspicuous.

Discussion

Tractography with DSI and related high angular resolution methods yields anatomically plausible images rich in intravoxel complexity. As in all biomedical imaging, unresolved underlying ultrastructure is an ill-posed problem. This accepted, diffusion tractography is the imaging of orientational coherence. By analogy to MRA with maximum intensity projection (MIP), present tractography can be seen as high angular resolution diffusion with "maximum coherence projection": first detecting intra-voxel diffusion maxima, then connecting maximal inter-voxel alignments. Pursuing the analogy, fiber statistical significance being roughly proportional to fiber length, the roles of conventional display contrast "center" and "window" settings here correspond to selection of mean and range of fiber lengths to display. Accordingly, DSI fiber tracts take their place as a contrast mechanism, of infinite dimension.

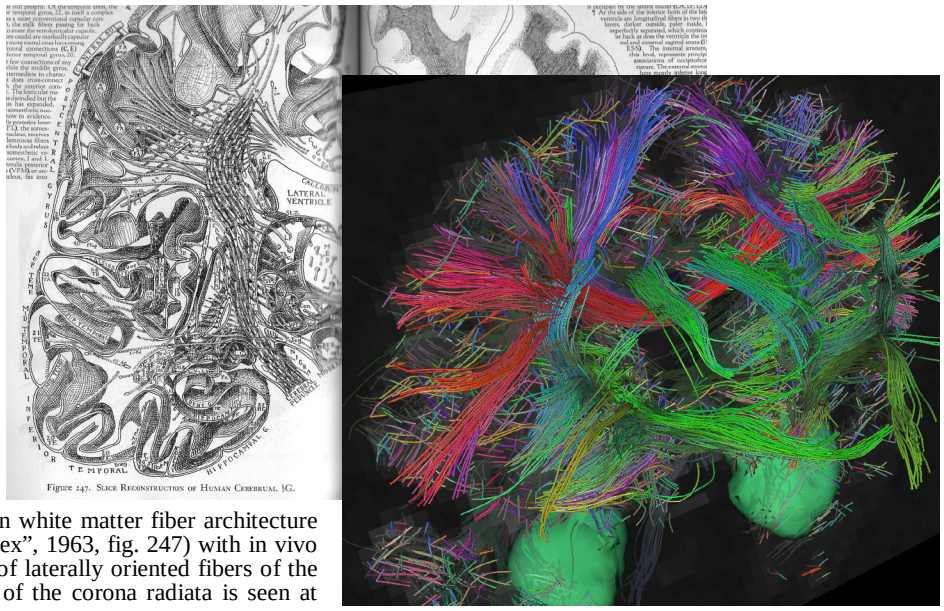

Figure 247. Slice Reconstruction of Human Cerebrum, §G.

Fig. 1. Coparison of classic demonstration of human white matter fiber architecture (WJS Krieg, "The Connections of the Cerebral Cortex", 1963, fig. 247) with in vivo DSI tractography at a similar location. Intersection of laterally oriented fibers of the corpus callosum with axially oriented components of the corona radiata is seen at center left (amygdalae in green).