Entropy Spectrum Pathways (ESP) A Comprehensive Framework for the Understanding of Network Connectivity, Particularly fMRI

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TECHNOLOGY DESCRIPTION

Presented here is a method for the characterization of connectivity within complex data. The method can be used on a wide range of application in which connectivity needs to be inferred from complex multidimensional data such as magnetic resonance imaging data of the human brain using diffusion tensor magnetic resonance imaging for characterization of neuronal fibers and brain connectivity, or in the analysis of networks in the human brain using functional MRI, or in other applications in which networks play an important role.

Characterization of connectivity with data is a complex procedure that is often approached with ad-hoc methods. The method herein leverages both a solid theoretical basis and relatively straightforward computational approach to assessing global connectivity within complex data sets. The method, called Entropy Spectrum Pathways, or ESP, is based on the description of pathways according to their entropy, and describes a method by which to rank the significance of the pathways. This is a generalization of the concept of the maximum entropy random walk, which appears in the literature as a description of a diffusion process that possesses localization of probabilities, but falls short as a framework for understanding connectivity in a complex system.

APPLICATIONS

As an illustration of possible applications, described below is one practical example of ESP processing of magnetic resonance diffusion tensor imaging (MR-DTI) data. DTI data is often used for neural fiber tractography in the studies of brain connectivity. This is a complex and severely ill-posed problem. Within an imaging volume, local (voxel) DTI data measurements are used to reconstruct a (possibly high dimensional) tensor in each voxel that is able to capture some broad aspects of the underlying tissue microstructure, but on a scale much greater than the fibers themselves. From these tensor estimates, one can reconstruct the purported pathways of neural fiber bundles throughout the brain that produced the underlying variations in the diffusion signal. Imaging resolution is never (currently) fine enough to resolve individual fibers though, and thus individual voxel measurements are degraded by averaging over fiber bundles. Given the great complexity of the neural structure of the human brain, reconstruction of the macroscopic neural pathways from large volumes of noisy, highly multidimensional tensors derived from measurements of microscopic signal variations poses a significant theoretical and computational challenge.

The reconstruction of the macroscopic neural fiber pathways from the microscopic measurements of the local diffusion from DTI data is precisely the type of problem suited for the ESP formalism. The goal is to determine the most probable global pathways (neural fibers) consistent with measured values (diffusion tensors) based upon the available prior information. The ESP formalism provides a general method for the incorporation of prior information regarding the relationship between voxels.

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OTHER INFORMATION

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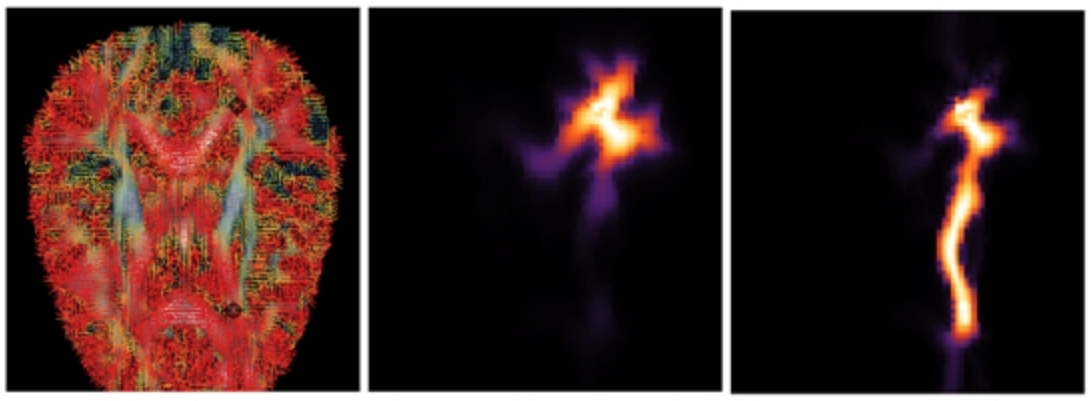

(a) DT-MRI data (b) Fiber tracking with GRW (c) Fiber Tracking with ESP

FIG. 1. The application of ESP to neural fiber tractography using diffusion tensor magnetic resonance imaging (DT-MRI) and comparison with the generic uniform random walk (GRW). Data were collected on a normal human subject on a 3T GE Excite MR system with an 8-channel phase-array head coil using a spin echo echo-planar acquisition optimized for minimum echo time and the reduction of eddy current artifacts. Diffusion weighted images were collected along 61 gradient directions distributed according to the electrostatic repulsion model at a b-value of $b = 1500$ *s/mm*2. The acquisition parameters were: *TE/TR* = 93/10, 900 ms, *FOV* = 240 mm, *NEX* = 1, matrix = 128 × 128 with 34 contiguous 3 mm slices. Two field maps were collected for unwarping to correct for signal loss and geometric distortion due to *B*0 field inhomogeneities. Total scan time including field maps was approximately 16 minutes. We include here only a short comparison of the final trajectory generated between two chosen points by ESP (Figure 1c) and GRW (Figure 1b) (using the same number of time steps *nt* = 500). A composite map of *FA* overlaid with the principal eigenvectors is shown for a single slice in Figure 1a.

The work herein in available as a software implementation and will have ready application to neuroscience studies involved in the quantification of connectivity, including neural fiber connectivity using diffusion tensor imaging, functional connectivity using functional MRI, or anatomical connectivity using segmentation analysis. This work also has application in the study of any complex network, including the Internet, plant biology and weather data.

This work is patent pending and available for commercial development worldwide.

PATENT STATUS

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United States Of America	Issued Patent	9,645,212	05/09/2017	2014-234

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