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Multi-label segmentation of white matter structures: Application to neonatal brains

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ABSTRACT

Accurate and consistent segmentation of brain white matter bundles at neonatal stage plays an important role in understanding brain development and detecting white matter abnormalities for the prediction of psychiatric disorders. Due to the complexity of white matter anatomy and the spatial resolution of diffusion-weighted MR imaging, multiple fiber bundles can pass through one voxel. The goal of this study is to assign one or multiple anatomical labels of white matter bundles to each voxel to reflect complex white matter anatomy of the neonatal brain. For this, we develop a supervised multi-label k-nearest neighbor (ML-kNN) classification algorithm in Riemannian diffusion tensor spaces. Our ML-kNN considers diffusion tensors lying on the Log-Euclidean Riemannian manifold of symmetric positive definite (SPD) matrices and their corresponding vector space as feature space. The ML-kNN utilizes the maximum a posteriori (MAP) principle to make the prediction of white matter labels by reasoning with the labeling information derived from the neighbors without assuming any probabilistic distribution of the features. We show that our approach automatically learns the number of white matter bundles at a location and provides anatomical annotation of the neonatal white matter. In addition, our approach also provides the binary mask for individual white matter bundles to facilitate tract-based statistical analysis in clinical studies. We apply this method to automatically segment 13 white matter bundles of the neonatal brain and examine the segmentation accuracy against semi-manual labels derived from tractography.

Introduction

Diffusion weighted magnetic resonance imaging (DW-MRI) is a unique in vivo imaging technique that allows us to visualize the three-dimensional (3D) architecture of neural fiber pathways in the human brain. Diffusion tensor imaging (DTI) is a simple mathematical model derived from DW-MRI that characterizes the diffusivity profile of water molecules in brain tissue via a single oriented 3D Gaussian probability distribution function (PDF). Detailed labeling of the white matter based on DTI provides insights for understanding white matter development (Huang et al., 2006; Loh et al., 2012; Sadeghi et al., 2013) and detecting white matter abnormalities in disease (Goodlett et al., 2009; Owen et al., 2013; Wang et al., 2011). Nevertheless, it is challenging to obtain anatomical segmentation of the white matter in the neonatal brain since it is undergoing a critical growing process along with forms of cellular maturation, such as myelination and synaptic pruning (Huttenlocher & Dabholkar, 1997; Petanjek et al., 2008). The delineation of white matter structures in the neonatal brain has thus far mainly relied on the fully manual segmentation (e.g., manually drawing regions of interest (Oishi et al., 2011) or semi-manual segmentation with the aid of DTI tractography techniques (Huang et al., 2006). Both are time consuming and require prior anatomical knowledge in order to achieve reasonable reproducibility (Kaur et al., 2014). In addition, Oishi et al. (2011) developed an atlas-based segmentation based on image registration to assign one anatomical label to each white matter voxel. To our best knowledge, no study to date has illustrated automatic segmentation that assigns multiple labels to each voxel in the white matter of the neonatal brain. The multiple labels per voxel can reflect true underlying white matter anatomy as between one and two thirds of the voxels in the human brain white matter are thought to contain multiple fiber bundles (Behrens et al., 2007). The proper white matter annotation is helpful for the interpretation of results derived from voxel-based analysis on DTI parameters, such as fractional anisotropy (FA), axial and radial diffusivity.

Although studies on automatic delineation of the neonatal brain white matter are limited, researchers have spent great efforts on developing tractography-based segmentation techniques for grouping fiber tracts into anatomically meaningful white matter bundles based on DTI data of adult's brain in the last decade (Brun et al., 2004; Clayden et al., 2007; Guevara et al., 2011; Jonasson et al., 2005; Li et al., 2010; Mayer et al., 2011; Ratnarajah et al., 2011). In general, tractography-

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