Building an Atlas of the Subcortical White Matter: Identification and Assignment of Common Anatomical Structures

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Introduction: Subcortical white matter (SWM) bridges the deep white matter and the cortex. It is known to contain short cortical association fibers (e.g. U fibers), but its anatomy has not been well documented. The purpose of this study was to develop atlases of the SWM using diffusion tensor imaging (DTI). DTI is an MRI modality that can delineate white matter architectures based on the orientation information of axons. This could be an ideal method to investigate the detailed anatomy of the SWM. One of the difficulties of anatomical study of the SWM is variability among individuals. To extract common anatomical features in the SWM, we performed a population-averaged study, using DTI data from 81 healthy subjects normalized to the ICBM-152 template (ICBM-DTI-81 atlas). In this map, we identified and segmented SWM structures that were found reproducibly accross subjects. The anatomic knowledge obtained from this group study was then used to create a single-subject atlas in the ICBM-152 and Talairach coordinates. We believe that these atlases will be useful resources to identify and report white matter regions affected by diseases or used as a template for automated white matter parcellation.

Methods: (1) Creation of the population-averaged atlas (ICBM-DTI-81): Data from 81 healthy subjects (right-handed, 20-59 years old) were collected as a part of the International Consortium of Brain Mapping (ICBM) study using Siemens 1.5T scanners. DT imaging data were acquired by using a single-shot EPI sequence with sensitivity encoding and a parallel imaging factor of 2.0. The imaging matrix was 96 x 96, with an FOV of 240 x 240 mm (nominal resolution: 2.5mm). A total of 60 slices covered the entire brain without gaps. Diffusion weighting was encoded along 30 independent orientations, and the b-value was 1000 mm^2/s. The DTI data were normalized to the ICBM-152 template using diffusion-weighted images and a 12-mode affine transformation. The transformation matrix was then applied to the calculated diffusion tensor field. A population-averaged image was created by averaging all the collected tensor fields. **(2) Creation of the single-subject atlas:** The data were obtained from a 32-year-old healthy woman. A Philips 1.5T MR unit was used. Parallel imaging factor was 2.5. The imaging matrix was 112 x 112, with an FOV of 246 x 246 mm (nominal resolution: 2.2mm). After correcting subject's motion, Eddy current and b0 distortion, images were re-sampled to 1 mm isotropic resolution (246x246x121 matrix, JHU-DTI atlas). The atlas was linearly transformed to the ICBM-152 space and non-linearly transformed to Talairach space to create atlases based on MNI coordinates (JHU-DTI-MNI atlas) and Talairach coordinates (JHU-DTI-Talairach atlas). **(3) Parcellation of the white matter:** We defined the white matter / cortex boundary using an FA threshold of 0.15 in ICBM-DTI-81. For the parcellation of the deep white matter, we adopted our previous white matter parcellation map (WMPM, www.loni.ucla.edu/ Atlases and mri.kennedykrieger.org). The SWM was defined as the white matter between the WMPM and the cortex. **(4) Tractography of inter- and intra-blade association fibers:** The existence of short association fibers was determined using the parcellated SWM structures as regions of interest (ROIs) for tractography.

Results: Fig. 1A and B show axial slices of ICBM-152 and ICBM-DTI-81. The ICBM-DTI-81 visualizes various intra-white matter structures that cannot be appreciated by ICBM-152. Anatomy of the deep white matter areas, which consist of large axonal bundles, can be clearly identified in the averaged maps (Fig. 1C), indicating that their existence and locations are common among healthy subjects. It is also clear that there are many white matter structures appreciable in the SWM regions (Fig. 1D). In Fig. 2, the averaged SWM is three-dimensionally visualized. The SWM was morphologically constructed by several "blade-like" structures (blades). We manually divided them into 9 distinctive blades. We named each blade as follows: superior frontal blade (purple); middle frontal blade (light green); inferior frontal blade (deep green); pre-central blade (yellow); post-central blade (blue); superior parietal blade (brown); parieto-temporal blade (red); temporal blade (orange); and occipital blade (light blue). Inside these blades, fibers primarily run along the radial orientation of the blades. Therefore, we did not find reproducible patterns of intra-blade fibers. As expected, inter-blade tractography identifies most major long association fibers. Among these inter-blade fibers, those not previously delineated in detail are shown in Fig.3. These were designated as follows: frontal short association fibers (yellow, connecting the superior frontal blade and the inferior frontal blade); fronto-central short association fibers (green, connecting the middle frontal blade and the pre-central blade); central short association fibers (red, connecting the pre- and post- central blades); parietal short association fibers (blue, connecting the superior parietal blade and the parieto-temporal blade); and parieto-temporal long association fibers (purple, connecting the superior parietal blade and the parieto-temporal blade / temporal blade). Based on the information obtained from the ICBM-DTI-81, we generated a single-subject atlas for comprehensive brain parcellation (Fig.4, JHU-DTI-Talairach).

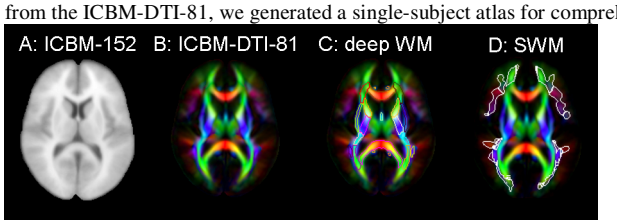

Fig.1 Population-averaged atlases and the parcellation.

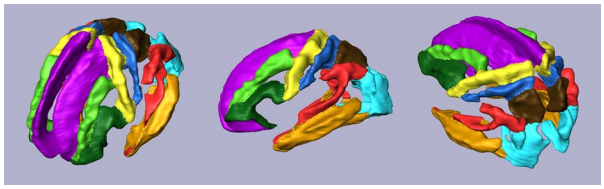

Fig.2 Nine distinctive blade-like structures identified in this study.

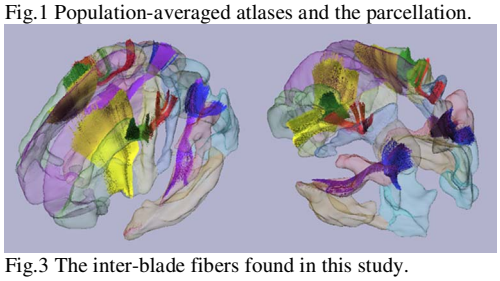

Fig.3 The inter-blade fibers found in this study.

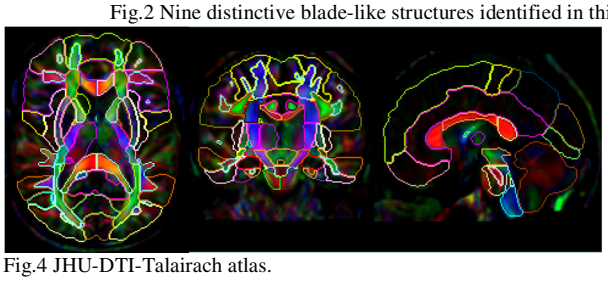

Fig.4 JHU-DTI-Talairach atlas.

Discussion: The DTI-based atlases created in this study represent the SWM structures that are common in the healthy population. The SWM consists of 9 blade-like structures, which are reproducible among subjects. Within the SWM, 4 U-fibers can be clearly identified. The atlases have established 3D coordinates of these structures in a standardized coordinate system. In past histology based studies, many cortico-cortical short association fibers were reported (1, 2), but their precise locations and the connectivity have not been well documented. We expect that the atlases reported here will establish a foundation for the understanding of the SWM anatomy and involvement of the SWM in various brain diseases. The atlases can also be used for automated brain parcellation by warping them into individual subject data, which allows volume and contrast (e.g., FA, ADC, T2, MTR, etc.) measurements in each parcellated area.

References:

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