Atlas of white-matter tracts in the human spinal cord

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Target audience. Scientists and clinicians interested in spinal cord template-based analysis and multiparametric MRI.

Purpose. Template-based methods have proven to be an efficient basis for conducting quantitative MRI research. They offer a reliable way to conduct inter-subject studies and facilitate metrics extraction. This approach is being investigated for spinal cord studies, however, to our knowledge, no atlas of spinal white matter (WM) tracts has been proposed. In this work, we present a method (*i*) for constructing an atlas of WM tracts in the cervical spinal cord based on a probabilistic WM/GM template of the cord[1] and (*ii*) for integration into an existing spinal cord template[2].

Methods. The reference data from Gray's Anatomy[3], indicating the position of the WM tracts at the mid-cervical level, was first manually segmented in order to obtain a symmetric labeled image of the different tracts (30 tracts in total). The template used to generate the atlas is a symmetric, straightened probability map of the WM with an isotropic resolution of 0.5mm (3D version of [1]). *Initial registration:* the initial labeled image was first registered to the mid-C4 slice of the interpolated template. The deformable registration was performed using ANTS[4] and computed on the binary WM/GM mask using point-set expectation metric. The resulting transformation was constrained to be symmetric by averaging each voxel with its symmetric with respect to the AP axis. Each labeled region mask was then warped into the interpolated template space, resulting in a binary labeling of the tracts. *Interpolation along the cord:* the atlas was then interpolated along the cervical spinal cord template using slice-by-slice registration. The initially labeled slice was registered on each slice of the interpolated template, using both WM/GM binary masks and Gaussian-smoothed slices for a robust mixed point-set expectation / mutual information-driven deformable registration. The binary region masks were then warped like in the previous step to obtain a binary labeling of the tracts all along the cervical template. Partial volume values computation: the binary labeling of the tracts into the interpolated template space was then used to compute partial volume values. Each binary label mask was downsampled by computing the fraction occupied by the region for each voxel in the native template space. *Validation:* to demonstrate the possibility to use our atlas to quantify metrics within specific tracts, five subjects were scanned on a 3T system using a 2DRF monopolar diffusion-weighted sequence[5] (TR~2800ms, TE=89ms, matrix=192x38, 1x1x5mm^3, coverage: C1-C7, b-value = 750 s/mm^2, 30 directions, cardiac gated). Diffusion tensors were computed with FSL, and fractional anisotropy (FA) was weighted-averaged within the lateral corticospinal tracts (CST) and fasciculus gracilis (FG).

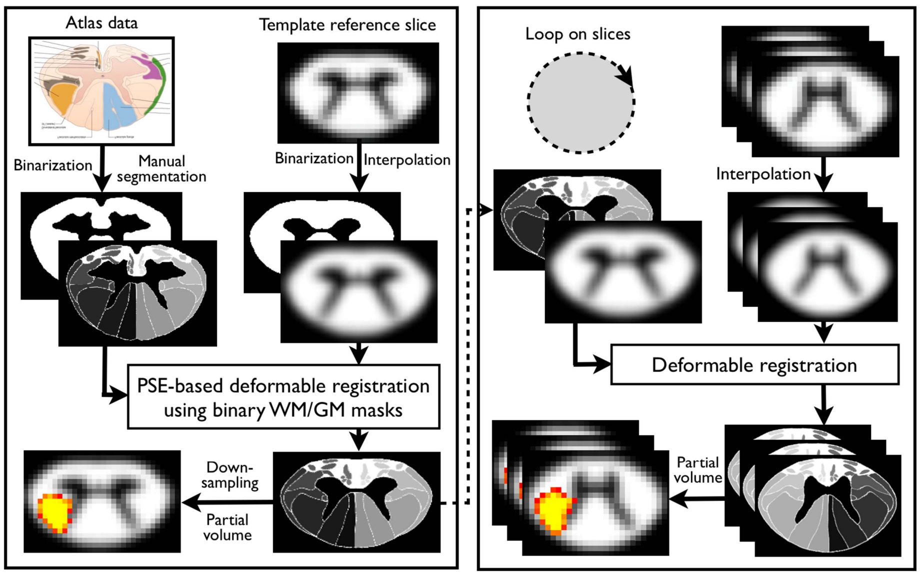

Figure 1. a. *Registration scheme for initial labeling of the reference slice. The atlas data is manually segmented, then registered to the mid-C4 slice of the template using the binary masks. The resulting labeling is then downsampled into native template space by computing partial volume values.* **b**. *Inter-slice registration for interpolation along the spinal cord. The reference slice is then registered to each slice, resulting in a labeling all along the cervical template. It is then used to compute the partial volume values.*

Results. The computed tracts across vertebral levels can be seen on Fig. 2. Quantification of FA for the five subjects yielded: 0.57 +/- 0.06 (left CST), 0.60 +/- 0.06 (right CST), 0.58 +/- 0.05 (left FG), 0.57 +/- 0.05 (right FG), which is consistent with previous investigations[6].

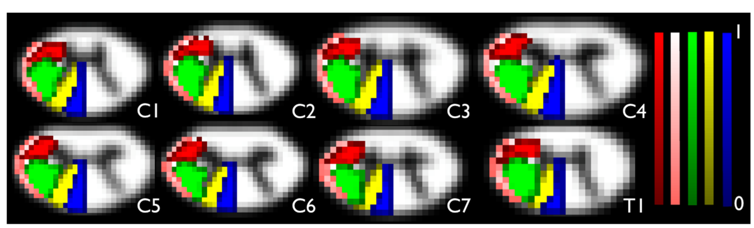

Figure 2. *Left fasciculus gracilis (blue), cuneatus (yellow), corticospinal (green), spinocerebellar (pink) and spinothalamic (red) tracts shown from C1 to T1 levels.*

Discussion and conclusion. This work presents the first initiative to construct an atlas of spinal cord WM sub-structure. In comparison with previous ROI-based approaches for multiparametric MRI, our atlas takes into account partial volume effect, hence providing a more accurate way to quantify metrics. Moreover, the existence of a common space for quantifying MRI data will limit user bias and facilitate the elaboration of multi-site studies. Although the proposed atlas is based on a well-renown source, the lack of cross-validation with other existing atlases is a limitation. Besides, the current atlas was built from a single drawing, and then propagated through warping across remaining slices. Future studies will combine various existing atlases and extend their range to the thoraco-lumbar spinal cord. The atlas is fully integrated into the MNI-Poly-AMU template and can be used for quantifying multiparametric data.

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