Neuroanatomic Fiber Orientation Maps (FOMs)
Acquisition, Segmentation, Visualisation, and Image Alignment

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Abstract. A new neuroanatomic method is described which allows to map the orientation of central nervous fibers in gross histological sections. Polarised light is used to calculate the angle of inclination and direction of the fibers in each pixel. Serial fiber orientation maps (FOMs) can be aligned and 3D reconstructed. This volume allows to identify and segment the major fiber tracts. The feasible goal is a human central nervous fiber atlas.

1 Introduction

The development of diffusion tensor mapping in neuroradiology allows to derive information about the three-dimensional orientation of fiber tracts in the living human brain. A new neuroanatomic method was developed to obtain similar spatial information about the orientation of fiber tracts in anatomic serial brain sections. This paper gives an overview of the methods used to explore these anatomical data.

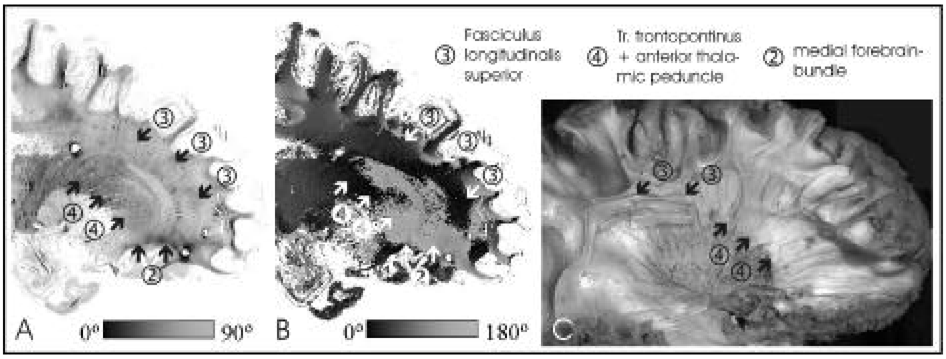

Fig. 1: FOMs of the prefrontal cortex. A) Inclination map. B) Direction map. C) Verification of the fiber tracts with the macroscopic dissection technique of Klingler.

2 Material and Methods

2.1 Acquisition

Polarised light is used to estimate the three-dimensional course (angles of direction and inclination, Fig. 1) of nerve fibers in brain slices [1]. Gross histological brain sections of formalin-fixed human brains were digitised under azimuths from 0 to 80° using two polars only. These sequences were used to estimate the angle of inclination of fibers (in the z-direction). The same sections were digitised under azimuths from 0 to 160° in steps of 20° using a quarter wave plate additionally. These sequences were used to estimate the angle of direction of the fibers in xy-direction.

2.2 Segmentation of fiber tracts

The software MATLAB 6.0 (MathWorks Inc.) with the Image Processing Toolbox was used to realise the following algorithms. Two fibers can be regarded as belonging to the same bundle of fibers if the fibers are parallel and close. Parallelism can be measured by means of an inner vector product; the very definition of the inner vector product contains the angle between the vectors u and v. For each combination of fibers the degree of parallelism can be computed. Closeness of fibers can be computed by the Euclidean distance. An element-by-element multiplication of both results gives the degree to which each fiber is related to the others. One pixel covers approximately an area of 100 µm x 100 µm.

2.3 Visualisation

Angles of inclination and direction can be visualised in two grey scale images. To allow visualisation in one image those angles were transformed into unit vectors and the x, y, and z-coordinates of the vector were visualised as R, G, B colours.

2.4 Alignment

Table 1. The different parameters for serial image alignment.

Consistent matrix transformation	Cross correlation coefficient	Euclidian distance
$D = \sum_i^n \left(\frac{(I_{A_i} - I_{B_i})}{C_i} \right)$ with $C_i = \max\left(\frac{I_A}{I_B}, \frac{I_B}{I_A} \right)$	$C = \frac{\sum_x \sum_y A(x,y) * B(x,y)}{\left[\sum_x \sum_y A(x,y)^2\right]^{\frac{1}{2}} * \left[\sum_x \sum_y B(x,y)^2\right]^{\frac{1}{2}}}$	$ED = \sqrt{\sum_i^n \left(I_{A_i} - I_{B_i}\right)^2}$
Minimise	Maximise	Minimise

Rigid (isomorphic) transformations were computed on the serial sections of the brain stem. That means, that an image is translated and rotated in respect to its predecessor. Three different parameters [2] were applied in order to define the optimal fit of the images: the 'consistent matrix transformation' method, the 'cross correlation' method, and the Euclidian distance.

2.5 3D reconstruction

The aligned sections were imported into the 3D Slicer [3], which allows to slice the volume. Major fiber tracts in the brain stem were segmented manually and 3D reconstructed. This way a 3D fiber tract model of the brain stem was developed.

3 Results

Two sets of serial sections of human brain stems were digitised comprising 250 slices each. 261 serial, sagittal slices of an entire human brain were digitised. The angles of inclination and direction can be visualised as grey scale values yielding two maps of each slice (inclination and direction maps, Figs. 1A and B), or as an alternative visualised as false colours (e.g. red, green, blue). For visualisation of three-dimensional orientation in one image the three coordinates x, y, and z were visualised as R, G, B-colour maps. This way, the major fiber tracts known in the human brain were visually

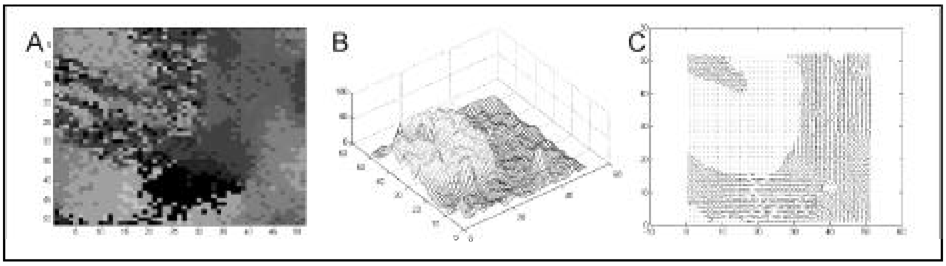

Fig. 2: A) Fiber direction map. B) Mesh plot of gradient. Flat plateaus near zero indicate a homogeneous area with parallel fibers, large mountains indicate many directional changes. C) Quiver plot of likely fiber bundles. Only fibers with a small gradient are displayed

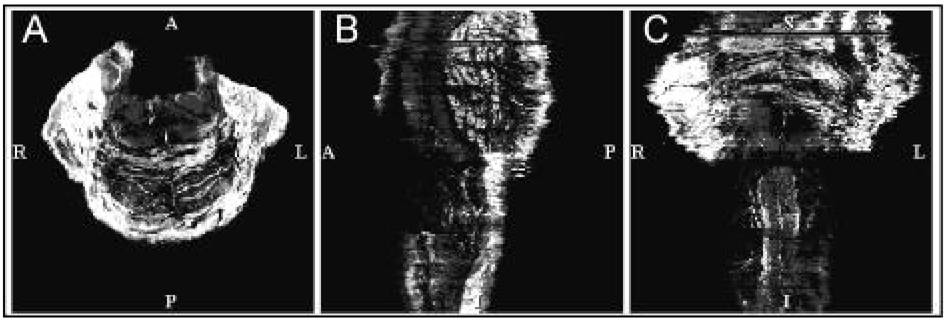

Fig. 3: 3D reconstructed brain stem. A) Axial section. B) Sagittal section. C) Coronal section.

recognised, verified, and compared to specimen prepared with the classical dissection technique of Klingler (Fig. 1C).

The segmentation method was able to differentiate the white and the grey matter (Fig. 2). In addition, the borders between different fiber tracts could be detected, which is a prerequisite for the three dimensional segmentation of large fiber tracts in the brain model. The serial sections of the human brain stem were used to calculate a three-dimensional model (fig. 3). The Euclidian distance method yielded the best results for automatic image alignment. Figure 4 shows the white substance of the brain stem model.

4 Discussion

Since the described anatomic method has a much higher resolution than diffusion tensor mapping, it allows the generation of a digital fiber model of the human brain. The model could be used as a fiber atlas for neurosurgical planning since major fiber tracts such as the pyramidal tract have to be carefully avoided in a neurosurgical procedure. Moreover, it could be used as a method for evaluation of the diffusion tensor maps known from magnetic resonance imaging. Two kinds of atlases are feasible: 1) a fiber orientation atlas representing a vector in each voxel, and 2) a volume-based atlas representing the major fiber tracts in the brain.

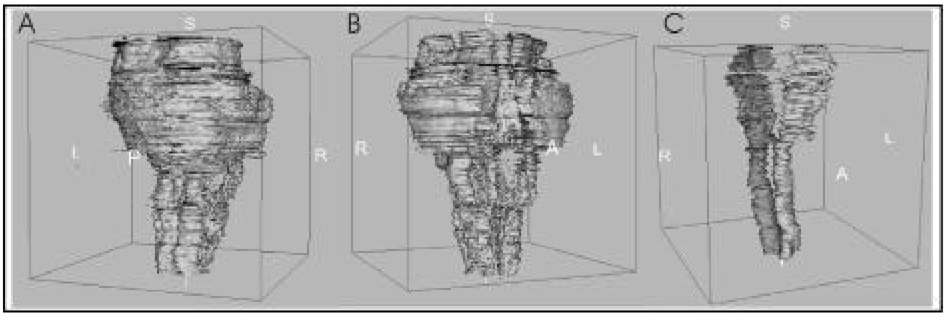

Fig. 4: 3D model of the brain stem. A) White matter of the brain stem. Anterior view. B) White matter of the brain stem. Posterior view. C) Reconstructed pyramidal tracts in the brain stem.

5 References

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