A new stereotaxic multiarchitectonic atlas of the human thalamus in a 3D MRI navigation system

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Summary. In the context of MRI-guided stereotaxy a new stereotaxic atlas of the human thalamus was developed in order to improve anatomical definition and precision in the prediction of the exact location of thalamic targets. It is based on multiarchitectonic parcellation (Nissl, myelin, calcium-binding proteins). Sagittal atlas data were digitized and registered together with 3D MRI data sets. In a coarse to fine strategy the atlas-to-patient transformation matrix is refined. Thus the atlas is tailored to the individual anatomy of the patient. The effects of the rigid transformation are directly monitored on the computer screen using visible anatomical landmarks as control.

Keywords: Brain atlas, calcium-binding proteins, magnetic resonance imaging, 3D navigation, stereotaxy, thalamus

1 Introduction

1.1 Stereotaxic atlases of the thalamus

Stereotaxic histological atlases provide information concerning the location of brain structures in a Cartesian coordinate system based on anatomical landmarks related to the ventricular system. The atlases date back to an era when CT and MR imaging of the brain were not yet available and the exact 3D location of intracerebral targets could only be inferred from their position relative to the intracerebral fluid spaces. In stereotaxic interventions for the treatment of chronical functional disorders such as neurogenic pain and Parkinson's disesase [1], the tip of a probe is advanced through a burrhole in the skull along a precalculated trajectory towards a target situated in deep diencephalic areas of the brain. Microelectrode recordings on the fly as well as electrical stimulation serve as control for the trajectory and the correct target site. At the target site, coagulation of the target or implantation of depth electrodes is performed. Although thalamic contours are partly discernible in MR imaging, intrathalamic targets cannot be visually identified in pre-operative low-field MR images. This is due to the fact that signal intensities within the thalamus are

homogeneous and that the definition of a target relies on microstructural and microfunctional criteria which have no direct correlate in routine MRI data sets.

1.2 Advantages of multiarchitectonic parcellation

The definition of thalamic nuclei and territories on the basis of cyto- and myeloarchitectonic criteria has in the past been a matter of constant debate. In the lateral nuclear group, Hassler [3] differentiated 30 nuclei, Andrew and Watkins [4] only eleven. Whereas Hassler described 8 nuclei in the medial group, Andrew and Watkins saw no justification for a subdivision of the medial thalamic mass. The classical, partly contradictory anatomical descriptions rely on cyto- and myeloarchitectonic definitions which imply fuzzy morphological classification schemes prone to subjective interpretation. Hassler [3] 'finds it impossible to recognize in many illustrations in van Buren and Borke's atlas [5], the indicated architectonic subdivisions' and relates the fact to the different morphological criteria delineating a region. Because of different categorization criteria as well as species differences in thalamic organization consequently different thalamic terminologies came into being [2]. In recent years Hirai and Jones [6] presented a unified terminological concept of thalamic subdivision. It provides easy comparison of human thalamic organization with the wealth of information on thalamic organization available, for the most part, only in non-human primates. Classical descriptions are supplemented by more objective histochemical criteria (e.g. histochemical staining for acetylcholinesterase). Calcium-binding proteins like parvalbumin, calbindin D-28K, calretinin are especially suited for histochemical parcellation because there is evidence that their thalamic distribution pattern is related to distinct cell populations [7]. Craig et al. [8] demonstrated an association of calbindin with a posterolateral thalamic area relaying pain and temperature information.

2 Co-registration of Atlas and Patient Data in 3D MRI scans

2.1 Stereotaxic atlas data

The atlas presented by Morel et al. [9] is based on multiarchitectonic parcellation (Nissl, myelin, calcium-binding proteins) on sections parallel or perpendicular (frontal and sagittal) to the horizontal intercommissural (anterior commissure-posterior commissure, AC-PC) reference plane.

2.2 Digitization and co-registration of atlas data

Besides anatomical labels the atlas supplies closed contours of the histological entities. Thus it is well suited for digital 3D representation. From the sagittal atlas data (3.6 - 19.4 mm lateral to the interhemispheric plane) 55 anatomical structures were digitized. Apart from thalamic structures, the subthalamic nucleus, substantia nigra as well as the (incomplete) section profile of the caudate nucleus were

included. Data were interpolated in the direction of the cuts using an algorithm suggested by Akima [10, 11]. The data were manually re-edited after the interpolation so as to eliminate unwanted side effects of the interpolation and resolve ambiguities in the definition of bordering structures. The outcome is an isotropic 3D contour and volume representation with a resolution of .225 mm.
The atlas data are co-registered with the MRI scans and shown in superimposition. Atlas data may be subjected to rigid transformations (translation, rotation, and scaling) in a correlated triplanar display (axial, frontal, and sagittal sections, correlated cursor movements). Thus the morphological quality of the atlas-to-patient registration is interactively assessed and improved. Reference structures which are discernible both in the atlas and in the MR images (e.g. thalamic surface, section profiles of mamillothalamic tract, caudate nucleus, red nucleus) serve as control for the quality of the fit. Following a coarse-to-fine strategy, the initial transformation matrix for the co-registration of atlas and patient data is thus gradually refined under direct visual control [cf. 12]. After correct adjustment of the atlas [Fig. 1] the course of the planned trajectory is thoroughly checked and alternatives can be evaluated. Target and trajectory coordinates may then be transferred to the Radionics planning system.

2.3 Target determination

Target planning during the stereotactic intervention is performed with the MRI-related fiducial-based Radionics system coupled to the Cosman-Roberts-Wells (CRW) stereotactic frame. During MRI examination (T1-weighted images, Philips Gyroscan S 15 with MRI-compatible head ring fixed to the patient earlier under local anesthesia), a rapid series of 5 mm thick horizontal slices through the diencephalic area is acquired so as to determine the midsagittal plane. Then a series of 2 mm thick sagittal slices is performed which is centered on the midsagittal plane. The midsagittal scan allows for determination of AC and PC and thus for the definition of the intercommissural plane DV0 which is orthogonal to the midsagittal plane. From a series of 2 mm thick horizontal slices (with 0.2 mm interslice gap) planned parallel to DV0, one is centered on the dorso-ventral coordinate of the intended target. In the latter slice the other anterior-posterior (measured from the PC or mid-commissural point) and medial-lateral (measured from the ventricular border) target coordinates are determined. The final XYZ coordinates of the intended target are set on the CRW frame using the fiducial-related Radionics stereotactic program. The penetration angles are determined according to the pre-planned electrode trajectory on the atlas and the intended frontal precoronal approach.

3 Discussion

The advent of MRI-guided stereotaxy in conjunction with digital atlas representation enables the direct visual control of the atlas-to-patient transformation above. Arguments for fitting the thalamic contours from the atlas to the MRI data of the patient is superior to solely ACPC-based target determination can be extrapolated from the work of Brierley and Beck [13]. In 53 hemispheres they found a

proportional arrangement of the thalamic nuclei in the antero-posterior axis but failed to demonstrate a constant relationship of the thalamic nuclei to PC in frontal sections.

As there are hints that interindividual differences in the spatial arrangement of thalamic nuclei exist [9, 12, 13], digital representation of histological data from different brains is to our opinion a prerequisite for the consistent evaluation of the degree and nature of this variation.

Subsequently fuzzyfication [14] applied to the different histological data sets helps to overcome problems of interindividual variation. Recent advance in high-field MR imaging - yet at an experimental stage - [15,16] is expected to have a positive impact in this area because it enables a more specific discrimination of intrathalamic landmarks.

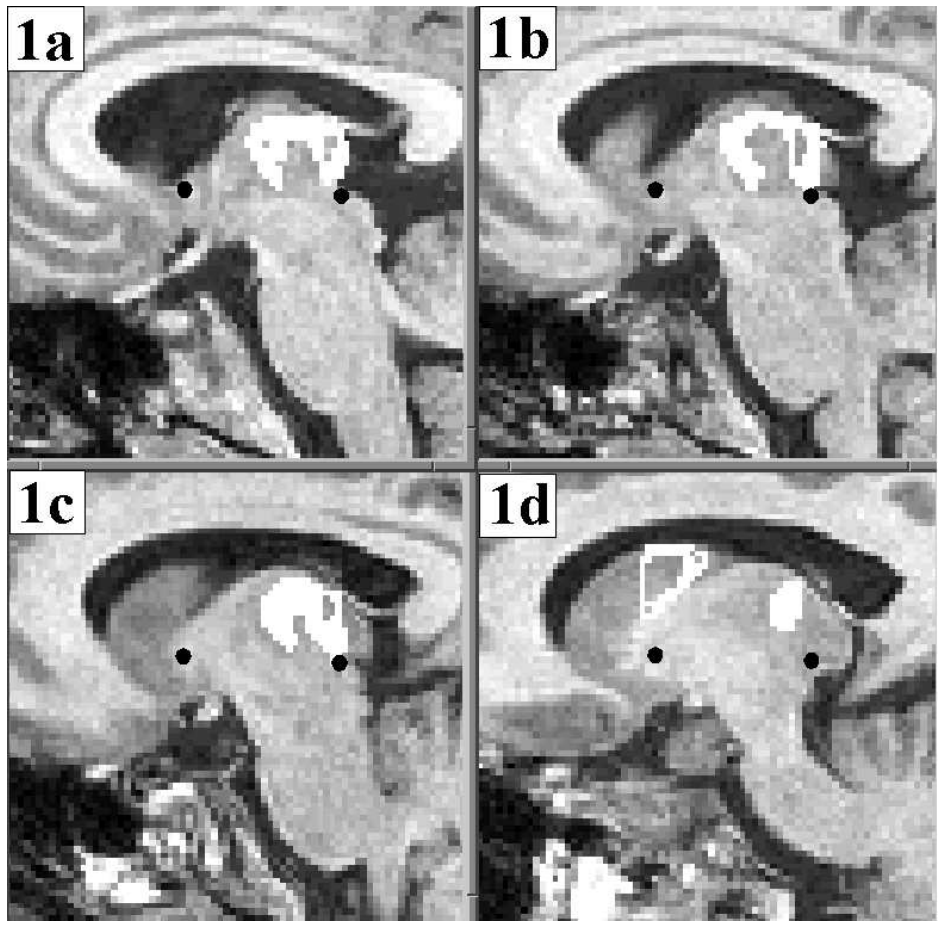

Figure 1. Central lateral nucleus of thalamus in superimposition with sagittal MRI scans after adjustment of atlas to patient. Slices are 5 mm (1a), 7 mm (1b), 9 mm (1c), 11 mm (1d) apart from the midsagittal plane. Central lateral nucleus shown in white. Section profile of caudate nucleus indicated in 1d serves as reference structure. AC and PC represented by black dots.

4 References

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