Anatomy of brain-stem white-matter tracts shown by diffusion-weighted imaging

Abstract We acquired high-resolution MRI and anisotropically diffusion-weighted images (DWI) with direction-selective gradients of the brain stem in 20 healthy volunteers, to identify brain-stem structures such as white-matter tracts and nuclei which show diffusion anisotropy. After averaging and superposition of individual cuts, the images were projected onto appropriate plates of the Schaltenbrand and Wahren anatomical atlas. We identified 20 structures – white-matter tracts and some nuclei – with high contrast. The direction of fibres could be determined as areas of increased (parallel to) or decreased diffusion (perpendicular to the gradient). This study may contribute to understanding of the functional anatomy of the brain stem.

Keywords Brain stem · Fibre tracts · Diffusion-weighted imaging

Introduction

Since its first description by Stejskal and Tanner [1] and clinical application by Le Bihan et al. [2], diffusion-weighted MRI (DWI) has been developed into a tool for noninvasive characterisation of normal and pathological tissue [3, 4, 5]. Now echo-planar (EPI) DWI is established in diagnostic procedures, being used for early detection of ischaemic stroke or tumour differentiation [6, 7, 8].

The anisotropy of DWI, sometimes regarded as a handicap in stroke imaging, can be used to demonstrate fibre tracts according to their major direction of diffusion, which is restricted laterally and unrestricted along the fibres [9, 10, 11]. The method has been used for imaging of supratentorial white matter, including the cor-
pus callosum and pyramidal tract [10, 12, 13, 14, 15, 16, 17, 18, 19]. We have used anisotropic DWI with digital image processing methods in 20 healthy volunteers, to identify white-matter tracts in the brain stem quickly and reliably with a sequence which also shows acute infarctions; this may help differentiate fibre tracts from ischaemic lesions.

**Materials and methods**

We examined 20 healthy volunteers, who gave informed consent; the study was approved by our local ethic committee. We studied 11 men and nine women, mean age of 27 ± 15 years (range 21–75 years).

MRI was performed on a clinical 1.5 tesla imager. We obtained T2-weighted fast spin-echo (TR 3810 TE 90 ms, 512 × 512 matrix, slice thickness 3 mm), T1-weighted spin-echo (TR 600 TE 14 ms, 256 × 256 matrix, slice thickness 3 mm), and EPI DWI (TR 4000 TE 103 ms) with separately applied diffusion gradients in the three spatial axes (b 1164 s/mm², 128 × 128 matrix, 250 ms per slice, 20 slices, thickness 3 mm, 8 acquisitions). The axial sections were perpendicular to the sagittal brain-stem sections of the Schaltenbrand and Wahren atlas [20]. In contrast to the usual DWI postprocessing, we did not average the images with direction-selective gradients, but used the images separately as images with transverse (tDWI), sagittal (sDWI) and longitudinal (zDWI) diffusion gradients.

The 8 acquisitions were averaged for each individual on the imager console. The averaged axial slices were normalised (Fig. 1) and projected on one of the levels of the anatomical atlas [20]. According to the atlas, a zero point was set one section above the pontomesencephalic junction (Fig. 2) and the number of the level represents the distance in mm from the zero point. We also used sagittal sections for the best fit to the atlas in the z axis. Sagittal and coronal normalisation was checked by setting the exit zone of the cranial nerves on the anatomical plates. The axial plates were used for normalisation in-plane. The normalised images of one level were electronically superimposed on each other. The white-matter tracts were identified according to the major direction of diffusion, using several anatomical atlases [20, 21, 22, 23] and postmortem MRI. For postprocessing we used commercial workstations and software.

**Results**

We were able to differentiate 20 white-matter tracts and nuclei (Fig. 1). The direction of fibres is shown by decreased (parallel to) or increased intensity (perpendicular to the gradient). The pyramidal tract and medial lemniscus were identified in every slice. Important landmarks for mesencephalic stroke imaging are the superior cerebellar peduncles, and their decussation, which is seen as high signal in images with craniocaudal diffusion gradients (zDWI). The central tracts of the reticular formation, tectal tract and the main cranial nerve fibres can be identified in the upper part of the pons and mesencephalon, whereas the medial longitudinal bundle was visible on individual cuts, but not on the superimposed images as a separate structure.

In the lateral part of the quadrigeminal plate, the brachium of the colliculi is seen. In the central and the lower pons the horizontal pontine fibres and the middle and lower cerebellar peduncles can be differentiated from the medullary trigeminal tract. Between these tracts, some iron-containing nuclei such as the substantia nigra, red, dentate and inferior olivary nuclei (the last of these due to its hilar fibres) are identified as dark structures, whereas most cranial nerve nuclei, the reticular formation and the stratum griseum give intermediate signal on DWI with each of the three gradient directions. Six representative sections will be described in detail:

**Mid-medulla oblongata, level + 33 (Fig. 1a)**

This section cuts through the inferior olivary nucleus (17) which is dark on tDWI and sDWI according to its oblique hilar fibres. The bright structures on tDWI and sDWI medial and rostral to the nucleus are the medial lemniscus (5) and the pyramids, containing the corticospinal tract (1) which appears dark on zDWI. The same applies to the inferior cerebellar peduncle (16) which occupies the dorsolateral part of the medulla. The floor of the 4th ventricle contains the dorsal-column nuclei (2) laterally and the nuclei of the lower cranial nerves more medially. The structure dark on sDWI between these nuclei and the inferior cerebellar peduncle laterally internal arcuate fibres and the olivocerebellar tracts, which both decussate obliquely in the midline to join the medial lemniscus and inferior cerebellar peduncle, respectively. The anterolateral fascicle containing the spinothalamic (6) and the anterior spinocerebellar tracts at the lateral border of the medulla and can be differentiated from the rostral pole of the superior cerebellar peduncle at level + 27 on tDWI (Fig. 1c) as a high-signal area between the peduncle (16) and the olivary nucleus (17). The spinal trigeminal tract is in a more medial position and can be identified only on some images.

**Pontomedullary junction, level + 24 (Fig. 1d)**

The long white-matter tracts (1, 16) give the same signal as on the preceding level and lie in a similar position within the section, apart from the medial lemniscus (5) which is now in the rostral part of the tegmentum. The nuclei of the floor of the 4th ventricle (2) give intermediate signal. The anterolateral fascicle (6) is identified as dark on zDWI. At the lateral border of the medulla, adjacent to its junction with the pons, and dorsal to the upper part of the olivary nucleus (17), the prominent