High–Resolution Line–Scan Diffusion–Tensor MRI of White Matter Fiber Tract Anatomy

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Abstract

BACKGROUND AND PURPOSE: MR diffusion tensor imaging permits detailed visualization of white matter fiber tracts. This technique, unlike T2–weighted imaging, also provides information about fiber direction. We present normal white matter fiber tract anatomy at high–resolution using line scan diffusion tensor imaging.

METHODS: Diffusion tensor images in axial, coronal and sagittal sections covering the entire brain volume were obtained with line scan diffusion imaging in six normal volunteers. Images were acquired for b–factors 5 and 1,000 s/mm² at a scan resolution of 1.7x1.7x4 mm. For selected regions, images were scanned at a reduced field of view with a spatial resolution of 0.9x0.9x3 mm. For each pixel, the direction of maximum diffusivity was computed and used to display the course of white matter fibers.

RESULTS: Fiber directions derived from the diffusion tensor were consistent with known white matter fiber anatomy. The principal fiber tracts were well seen in all subjects. Namely visualized were: the arcuate fasciculus; the superior and inferior longitudinal fasciculus; the uncinate fasciculus; the cingulum; the external and extreme capsule; the internal capsule; the corona radiata; the auditory and optic radiation; the anterior commissure; the corpus callosum; the pyramidal tract; the gracile and cuneatus fasciculus; the medial longitudinal fasciculus; the rubrospinal, tectospinal, central tegmental, and dorsal trigeminothalamic tract; the superior, inferior, and middle cerebellar peduncle; the pallidonigral and strionigral fibers; as well as the root fibers of the oculomotor and trigeminal nerve.
CONCLUSION: We obtained a complete set of detailed white matter fiber anatomy maps of the normal brain by means of line scan diffusion tensor imaging at high resolution. Near large bone structures, line scan produces images with minimal susceptibility artifacts.

Key words: Brain, anatomy
Brain, diffusion
Brain, white matter
Brainstem, anatomy
Brainstem, MR
Magnetic resonance (MR), diffusion study
Introduction

Before the advent of advanced MR imaging techniques, the investigation of white matter anatomy had been limited to the evaluation of gross brain sections with myelin–specific stains or to the dissection of fibers of formalin fixed brains. Conventional T2–weighted MR imaging offers excellent contrast between white and gray matter, however, without providing any information about fiber orientation. A rat brain atlas has been acquired with two–dimensional thin–section MR imaging [1] and a mouse lemur atlas with three–dimensional microscopic MR imaging [2]. Fluid–attenuated inversion recovery T2–weighted imaging has been introduced to attain improved visualization of the white matter tracts within the brain stem [3]. Magnetization transfer MR imaging is another technique which has been applied to white matter imaging [4–6], however, with any of the MR techniques mentioned above, the direction of the fibers in white matter tracts cannot be demonstrated, and therefore they cannot provide complete anatomic information about white matter fiber tracts.

MR diffusion imaging reveals the diffusion of water molecules. The direction of highest diffusivity coincides with the white matter tissue’s fiber tract axis [7, 8]. Variation of the diffusion along different spatial directions provides information about diffusion anisotropy and ultimately about tissue structure [9, 10]. The principal diffusion direction and diffusion anisotropy can be assessed with diffusion tensor imaging.

The purpose of the present study was to obtain detailed white matter fiber tract anatomy of the whole brain with a diffusion tensor imaging technique that yields minimal distortion
artifacts near large bone structures and air cavities as well as unprecedented high spatial resolution. To attain this goal, we employed line scan diffusion imaging (LSDI) [11] in conjunction with high performance magnetic field gradients.

**Methods**

**Subjects and Imaging Protocol**

Six normal volunteers (four men and two women, age range 35–45 years old) entered this study. No subject had a neurological disorder, or any abnormality on T1 and T2–weighted images of the brain. All studies were conducted within the guidelines of the research committee of our institution. Written informed consent was obtained from all subjects.

The protocol included T1–weighted imaging for localization and line scan diffusion tensor imaging of the entire brain in axial, sagittal and/or coronal sections. Thin–section, high–resolution line scan diffusion tensor images of the brain stem were also obtained in axial, sagittal and/or coronal orientations. LSDI uses multiple diffusion weighted spin–echo column excitations to form a two–dimensional image. The basic sequence is composed of a selective $\pi/2$ pulse and a selective $\pi$ pulse with diffusion gradients on both sides of the refocusing $\pi$ pulse, followed by a standard frequency encoding readout along the selected column. The sequential collection of this line data in independent acquisitions makes the sequence largely insensitive to bulk motion artifacts. Spatial interleaving of the
column excitation allows for uniform sampling with overlapping column cross-sections and minimal T1 weighting. Multiple slices can be obtained in sequential scans and the scan time, therefore, is proportional to the number of slices acquired. Since no phase encoding is applied, chemical shift and susceptibility artifacts are only present in the frequency encoding direction and like chemical shift and susceptibility artifacts in conventional spin-echo imaging, determined by the applied bandwidth.

All studies were performed on a 1.5 Tesla whole-body MR system (LX Echospeed Cvi; General Electric Medical System, Milwaukee, WI) with version 8.2.5 software. The scanner is equipped with magnetic field gradients that permit up to 40 mT/m amplitude. A quadrature bird cage head coil was used for all scans with the exception of scans performed with a surface coil to demonstrate subcortical U-fibers.

T1-weighted imaging for localization was performed with a standard spin-echo sequence: TR/TE, 750/14 ms; FOV, 220 mm; slice thickness, 5 mm; slice gap, 1 mm; matrix size, 256 x 256; bandwidth, +/- 15.6 kHz; excitation, 1. Axial and coronal slices for diffusion tensor imaging were planned orthogonal to a midline sagittal T1-weighted image. The axial slices were slightly oblique, parallel to the anterior–posterior commissure line and the coronal slices were angulated perpendicular to the anterior–posterior commissure line. The orientation of sagittal slices was planned on axial localizing images. Depending on subject and slice orientation, 24 to 34 slices were sufficient to cover the entire brain.

Line scan diffusion images were obtained with the following scan parameters: TR_{Eff}(effective TR relevant for T1 weighting [11])/TR(interval between column
excitations)/TE, 2560/80/66 ms; rectangular FOV, 220x165 mm; effective slice thickness, 4 mm [11]; slice gap, 1 mm; matrix size, 128x96 (frequency x column); bandwidth, +/− 3.91 kHz; excitation, 1. In order to measure the apparent diffusion coefficient (ADC),
images were scanned at two different diffusion weightings (b−factors, 5 and 1,000 s/mm²;
gradient pulse duration δ, 21.2 ms; separation Δ between first and second gradient pulse, 33 ms; gradient amplitude, 40 mT/m, i.e., two gradient main directions applied
simultaneously at 70 % of the maximal attainable amplitude). Diffusion weighting for the
high b−factor was applied along six non−collinear directions [8, 9] (relative amplitudes,
(Gₓ, Gᵧ, Gz)=(1,1,0), (0,1,1), (1,0,1), (0,1−1), (1,−1,0), (−1,0,1)), whereas for the low b−
factor, diffusion weighting was applied along two directions only. Collection of image data
for all gradient configurations at low diffusion weighting is not necessary, since the
directionally dependent, diffusion related signal attenuation is minimal. A minimal
diffusion encoding of 5 s/mm² is required, because with the present sequence
implementation the diffusion encoding gradients also act as spin echo crusher gradients.
Two diffusion−weighted images instead of only one are acquired for various reasons, such
as reduction of average gradient load and optimal cancellation of secondary echoes. The
scan time was 61 seconds per slice, i.e., the time required for complete coverage of the
brain along one orientation was between 25 and 35 minutes. Shorter TE, TR, and scan time
would have been possible, had gradient heating not been a concern. Scans of the brain stem
and subcortical U−fibers were obtained with the same diffusion gradient configuration at a
reduced slice thickness of 3 mm and a slice gap of 0 mm. Other scan parameters were:
TR\textsubscript{eff}/TR/TE, 2178/99/76 ms; rectangular FOV, 220x55 mm; matrix size, 256x64 (frequency x column); bandwidth, +/-3.91 kHz. For optimal SNR, 4 averages were acquired for head coil scans and 1 average only for surface coil scans.

**Post–Processing**

The term "tensor" originates from the physics and engineering field, where it was introduced to describe tension forces in solid bodies with an array of three–dimensional vectors. The particular tensors used to describe diffusion can be further conceptualized and visualized as ellipsoids. The longest of the three orthogonal main axes of the diffusion ellipsoid represents the value (eigenvalue) and direction (eigenvector) of maximum diffusion, whereas the shortest axis denotes the value and direction of minimum diffusion. If the length of the three axes is equal, then the diffusion is said to be isotropic and the diffusion tensor can be visualized as a sphere. For example in the case of cerebrospinal fluid (CSF) or gray matter, the diffusion tensor is best characterized by spherical, or isotropic, diffusion. If the length of the three axes differs, then the diffusion is said to be anisotropic. The diffusion tensor data was processed off–line. For each slice, a T2–weighted map (average of the two images obtained at low diffusion weighting), a trace diffusion–weighted map, a trace ADC map, and a relative anisotropy map was calculated. In addition, maps of the principal effective diffusivities (eigenvalues \(\lambda_1, \lambda_2,\) and \(\lambda_3\)) as well as the eigenvector components x, y, and z of the largest eigenvalue
\( \lambda_1 \) were computed. Dedicated software was used to visualize fiber directions with the
eigenvector of the largest eigenvalue superposed on an anatomical background image\(^{12} \). In
order to highlight gray and white matter areas, T2–weighted images were used as
background maps. The eigenvector of the largest eigenvalue (first eigenvector) is believed
to represent the fiber direction \([7, 13] \). For each pixel, a line representing the in–plane
component of the measured fiber direction is drawn. The length of the line is proportional
to the relative anisotropy. Gray, yellow dots on color images, respectively, represent pixels
where the through–plane component (vertical to the plane) of the scaled first eigenvector
reaches a predefined threshold. Masks, based on signal thresholds in images with high
diffusion weighting, were used to limit the representation of the eigenvectors to areas with
brain tissue. For some images, masks were defined manually to exclude areas with fatty
tissue in the skull and skin.

**Characterization of White Matter Fiber Anatomy**

The eigenvector maps were compared to histologic cross sections found in anatomy
books \([14, 15] \). The search for white matter tracts on these eigenvector maps was focused
on *association fibers* (cingulum, arcuate fasciculus, superior and inferior longitudinal
fasciculus, uncinate fasciculus, pallidonigral and strionigral fibers, U–fibers), *projection
fibers* (corona radiata, internal capsule, auditory and optic radiation), and *commissural
fibers* (corpus callosum and anterior commissure). The following structures were also
studied: root fibers of the oculomotor nerve; optic tract; pyramidal (corticospinal) tract in
the cerebral peduncle; the decussation of the superior cerebellar peduncle; rubrospinal tract; medial longitudinal fasciculus; tectospinal tract; central tegmental tract; dorsal trigeminothalamic tract; spinothalamic tract; pyramidal tract in the pons and frontopontine tract; superior, inferior and middle cerebellar peduncle; root fibers of trigeminal nerve; the pyramidal decussation; and pontocerebellar fibers.

**Results**

The description of the findings follow the traditional anatomic separation into association fibers, projection fibers, commissural fibers, and fibers of brain stem and cerebellum. The image examples originate from different subjects, however, the tracts described were seen throughout all subjects.

**Association Fibers**

The best gross view of the association fibers is demonstrated on sagittal images (Fig. 1, 2). The course of these fibers, however, cannot be followed in a single slice. When viewed in multiple sections, the appearance of the association fibers on the principal eigenvector maps is consistent with known anatomy. The main bundle of the cingulum is observed in a medial sagittal slice (Fig. 1A). The posterolateral branching bundle of the cingulum that connects with the parahippocampal area, is observed on more lateral slices. The middle part of the arcuate fasciculus and almost the entire course of the superior longitudinal fasciculus are observed on a lateral slice through the insula (Fig. 1B). The inferior longitudinal fasciculus connecting to the temporal lobe may be seen on the same section.
Moreover, this particular slice also shows the portion of the uncinate fasciculus that radiates into the temporal lobe. The main bundle of the uncinate fasciculus can be seen in a slice more medial to the one shown in Fig. 1B. In coronal images, all of these association fibers are demonstrated running vertical to the plane (Fig. 1C). The strionigral and pallidonigral fibers are observed in coronal image sections through the basal ganglia (Fig.1D). U–fibers connecting different cortical areas can be seen on multiple slice locations. Figure 1E shows U–fibers in the occipital subcortex.

**Projection fibers**

The fan–shaped appearance of the corona radiata which connects the internal capsule with subcortical areas is observed on multiple lateral sagittal views (Fig. 2A). An axial view of the upper portion of the corona radiata is shown in Fig. 2B. Figure 2C shows an axial view of the internal capsule at the level of the basal ganglia. On this axial image, the anterior limb of the internal capsule is demonstrated as a bundle of dense in–plane fibers, while in the posterior limb the fibers run predominantly through plane. A coronal view of the posterior limb of the internal capsule is shown in Fig. 1C. On axial images, parts of the optic (Fig. 1D and 2C) and auditory (Fig. 2C) radiation can be seen. On a coronal image through the posterior horn of the lateral ventricle (Fig. 2D), the geniculocalcarine tract of the optic radiation is observed.

**Commissural Fibers**

The commissural fibers of the corpus callosum are observed on sections near the lateral
ventricle. On the particular slice shown in Fig. 2C, the genu of the corpus callosum contains mainly the fibers that interconnect the medial parts of the frontal lobes. The body of the corpus callosum with fibers originating from the posterior part of the frontal lobe and the parietal lobe can be seen in Fig. 1C and 3A. The splenium, shown on an axial view in Fig. 2C and on a coronal view in Fig. 2D, contains the fibers that interconnect corresponding areas of the temporal and the occipital lobes. The fibers crossing within the anterior commissure are well observed on the coronal section depicted in Fig. 3B. On the adjacent coronal section (Fig. 3A), the fibers of the anterior commissure can be seen radiating toward the temporal lobes. The frontal part of the anterior commissure is known to be a very thin, small bundle of fibers interconnecting the olfactory bulbs. We failed to demonstrate this bundle of fibers on any sections in this study.

Fibers of Brain Stem and Cerebellum

Small fiber bundles, that pass through and around the red nucleus and converge to the rootlets of the oculomotor nerve, can be observed on an axial section through the midbrain (Fig. 4A). The cerebral peduncles are easily separated from surrounding fiber tracts due to their cranio-caudal direction component which is represented as white dots on the axial plane maps (Fig. 4A and 4B). On the slice shown in Fig. 4A, the optic tracts are demonstrated coursing anterior to the cerebral peduncles. Their connection to the lateral geniculate bodies can be found on more cephalad sections (Fig. 4C). In the center of a more caudal axial section of the midbrain, the decussation of the superior cerebellar peduncle is demonstrated (Fig. 4B). Ventral to the decussation of the superior cerebellar
peduncle, the rubrospinal tract with fibers in cranio-caudal direction (dots) is observed.

Dots dorsal to the decussation as seen in Fig. 4B, represent the cranio-caudal fibers of the medial longitudinal fasciculus as well as the tectospinal, central tegmental, and dorsal trigeminothalamic tract. Visual separation of these tracts, however, based on either fiber direction or anisotropy, is not possible. At the level of the pons (axial slice in Fig. 4D), cranio-caudal fibers belonging to the superior cerebellar peduncle, medial longitudinal fasciculus, tectospinal tract, dorsal and ventral trigeminothalamic tracts, central tegmental tract, spinothalamic tract, as well as the rubrospinal tract can be seen in the dorsal part, anterior to the fourth ventricle. Again, visual separation of the individual tracts with diffusion-weighted imaging seems not feasible. Along the cisternal side of the pons, fibers of the middle cerebellar peduncles traverse between each cerebellar hemisphere. Moreover, the axial section presented in Fig. 4D, demonstrates the bilateral roots of the trigeminal nerve emerging from the pons into the pre-pontine cistern. Posterior to the middle cerebellar peduncle fibers, the frontopontine tract and the pyramidal tract can be seen coursing in cranio-caudal direction (Fig. 4D).

On a coronal slice through the ventral medulla (Fig. 5A), a long section of the pyramidal tract, from the posterior limb of the internal capsule via the cerebral peduncles down to the decussation within the lower medulla, can be seen concurrently. An axial view of the motor decussation is shown in Fig. 5B. The corticospinal pathway of the pyramidal tract along the ventral portion of the medulla is demonstrated on a midsagittal slice (Fig. 5C) of the brain stem. Moreover, the corticobulbar pathway of the pyramidal tract can be seen passing along the posterior portion of the pons. On the same slice following the base of the
fourth ventricle towards midbrain, the medial longitudinal fasciculus can be observed. Furthermore, ponto–cerebellar fibers running orthogonal to the plane are readily distinguished. On a sagittal section through the fornix (Fig. 5D), the internal arcuate fibers of the sensory decussation can be seen coursing in antero–posterior direction. On an axial image of the medulla illustrated in Fig. 5B, an area with low anisotropy (short lines) is recognized dorsal to the motor decussation. This area corresponds to the central gray matter and the bilateral nucleus cuneatus.

On a coronal image through the fourth ventricle floor in Fig. 6A, fibers of the superior and inferior cerebellar peduncles can be seen passing along the fourth ventricle wall in cranio–caudal direction. In the same section, the middle cerebellar peduncle runs in antero–posterior direction in this section. On a more posterior coronal section (Fig. 6B), the fibers of the cerebellar peduncles can be seen branching out towards the cerebellar cortex.

**Discussion**

In the present study, LSDI was applied to collect diffusion tensor data of the human brain. LSDI was used, since it offers excellent image quality and spatial resolution. Moreover, LSDI is insensitive to bulk motion. Chemical shift and magnetic field susceptibility artifacts are minimal [11, 16, 17]. Echo–planer imaging (EPI), which also available at our institution, is equally robust to bulk motion, but requires fat suppression and suffers from susceptibility related image distortions in areas close to bone and air–
filled structures [18, 19]. With the massive skull base bone structure and air–filled spaces, susceptibility related image distortions become a critical issue in imaging brain stem. LSDI is almost free of such artifacts and therefore particularly suited to demonstrate detailed white matter fiber anatomy in these areas. LSDI compared with EPI, requires longer scan times. Nevertheless, complete brain coverage at high spatial resolution is feasible in approximately half an hour. Even though, missregistration within this scan time is not an issue: slices are acquired sequentially, each slice in less time than with an interleaved multislice EPI diffusion tensor scan. Shorter scan time and improved signal to noise ratio result with a reduced resolution along the column direction. On the other hand, at the expense of scan time or volume coverage, thin slice, sub–millimeter spatial in–plane resolution can be achieved. Reduction of the bandwidth does increase the signal–to–noise ratio, however, at very low bandwidths, chemical shift and susceptibility artifacts may become an important issue. Other techniques, that yield diffusion–weighted images with low susceptibility artifacts are available: for example, multi–shot navigated EPI [20], fast spin echo [21], magnitude back–projection imaging [22], and single–shot EPI with SENSE [23] have been used in conjunction with diffusion–weighted imaging. However, these techniques are either sensitive to motion and require cardiac gating or suffer from low signal–to–noise ratio.

To visualize the white matter fiber direction using diffusion tensor data, several methods have been proposed. Display of the diffusion ellipsoid, including three–dimensional rendering of diffusion ellipsoids [10], directionally encoded color maps [13, 24], and mapping of the first eigenvectors [12, 16, 25–27] has been suggested previously. In order
to visualize eigenvectors for each pixel, however, three–dimensional volume rendering and shading of the diffusion ellipsoids require very high resolution and fast computer displays. In directionally encoded color maps, it is difficult to follow in–plane connectivity of the same fiber tract group. For optimal visualization, eigenvector directions should be displayed in three dimensions. For example in an axial plane, fibers in the posterior limb of the internal capsule point out of the plane, while the anterior limb fibers run parallel to the plane (Fig.4). Displaying directions in three dimensions with color encoding [13] is, however, not very intuitive, since without referring to the definition of the color encoded direction in a look–up table, the viewer has no clue about the true direction. Our maps of the first eigenvector demonstrate fibers running out of plane as dots. The introduction of dots for eigenvectors pointing out of the plane simulates an ideal cut surface of longitudinal fiber bundles. Therefore, one can easily understand the directional differences not only between in–plane and through–plane, but also among different in–plane fiber directions. Moreover, the display of the first eigenvectors presents pictures extremely similar to those shown in anatomy atlas books [14, 15]. For good visual impression, the lines need to have a certain length. This may result in lines which exceed the pixel boundaries and for that reason it may be less quantitative than a color encoded map. In recent studies of diffusion tensor imaging, diffusion tracking techniques in human [28–31] have been introduced. Such techniques are very useful for following white matter fibers from a certain area to another in three dimensions. Connectivity of white matter fibers passing through the entire brain can be visualized with this technique.

Dense and compact white matter pathways, such as the anterior commissure, the corpus
callosum, the superior fronto–occipital fasciculus, the cingulum, the fornix, the mammillothalamic tract, the uncinate fasciculus, the superior and inferior longitudinal fasciculus, have been identified on conventional and fast spin–echo T2–weighted images by their relative short T2 relaxation time[32, 33]. The large bundles of white matter fiber tracts including pyramidal tract (internal capsule to corona radiata) [34], corpus callosum, cingulum [13, 24, 35–37], and optic tract [25] have been demonstrated by other authors previously. The course of the pyramidal tract within the brain stem has not shown with diffusion tensor imaging before. Other small nerve structures, hitherto not observed with diffusion tensor imaging, are the strionigral and pallidonigral fibers, the root fibers of the oculomotor nerve, the arcuate fibers of the sensory decussation, and the superior part of the anterior commissure.

Within the nuclei and deep gray matter, preferred diffusion directions were observed. Diffusion anisotropy in these areas, however, was not as high as in white matter tracts. This anisotropy may be explained by partial volume effects of fibers passing adjacent to the slice section, but it may also result from smaller radiation fibers connecting to the nucleus, e.g., strionigral and pallidonigral fibers. For example, in the coronal image of the mid thalamus, we observe well organized eigenvectors in the area of the thalamic nuclei, i.e., an area where partial volume effects of white matter in an adjacent slice is unlikely (Fig. 2C).

Diffusion tensor images in this study were obtained at high resolution. Even though, it is not sufficient to resolve all known anatomic structures of the brain. For example, the internucleus fibers could not be distinguished from radiation fibers extending to the larger
bundles. The visualization of the tracts varied among subjects. However, we attribute this variation not only to individual differences among subjects, but also to slice orientation and position.

Diffusion imaging has been used to diagnose stroke [17, 38, 39] and to investigate brain tumors [40] and multiple sclerosis [41] lesions. To better understand the functional consequences of such lesions, detailed knowledge of the fibers surrounding the lesions is needed. In planning of brain tumor surgery, the spatial relation between a lesion and major fiber structures, such as the pyramidal tract can be very important. Disruption of the normal white matter fibers adjacent to the lesions can be visualized with maps or tracking of the principal diffusion direction. Moreover, there is potential to distinguish preserved white matter fibers within edema from actually disrupted fibers.

**Conclusions**

We have demonstrated high-resolution white matter fiber anatomy in the human adult brain using maps of the first diffusion eigenvector. The direction of the first diffusion eigenvector appears to represent the fiber structures shown in anatomy atlantes. Unlike directionally encoded color maps, the directional information was displayed with lines drawn on top of conventional images. With LSDI, high resolution diffusion tensor images with minimal susceptibility artifacts were collected. Particularly, near large bone structures, e.g., skull base, the low sensitivity to susceptibility variations is important to obtain artifact-free images.
References


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Figure legends

Fig. 1. A, Sagittal 110x110 mm subimage close to the midline, passing through the cingulum. Note that the fibers of the corpus callosum run at a slight angle are through the plane (blue dots with short lines). B, More lateral sagittal section through the arcuate fasciculus (green), the inferior longitudinal fasciculus (pink), and the uncinate fasciculus (orange). C, Coronal section at the level of the posterior limb of the internal capsule. Fibers of the cingulum (pink), the arcuate fasciculus (green), and the uncinate fasciculus (orange) pass through the section (dots). Fibers of the posterior limb of the internal capsule (yellow lines) are running in–plane. D, High-resolution 55x55 mm coronal subimage of the thalamic region. The strionigral and pallidonigral fibers are shown in yellow. E, High-resolution axial surface coil image of the calcarine area at a 120x60 mm FOV. U–fibers connecting visual cortices are well demonstrated.

Fig. 2. Subimages (110x110 mm FOV) of the projection fibers. A, Lateral sagittal section passing through the corona radiata (yellow lines). B, Axial section through genu and splenium of the corpus callosum. Corona radiata fibers within the posterior limb (yellow) of the internal capsule can be distinguished by their strong through–plane component (dots), while fibers within the anterior limb (orange) of the corpus callosum run in–plane (lines). C, Axial section at the level of the basal ganglia. Fibers in the anterior limb of the internal capsule (orange) are running in–plane (lines), whereas in the posterior limb of the internal capsule (yellow) the fibers run through–plane (dots). Parts of the optic (pink) and auditory (green) radiation can also be seen. D, Coronal section through the trigon of the
lateral ventricles. Pink dots indicate through–plane fibers that are part of the optic radiation.

Fig. 3. A, Coronal section through the insula (110x110 mm subimage). In this section, fibers (blue) interconnecting the frontoparietal cortices of each hemisphere with the corpus callosum can be seen. The fbers of the anterior commissure (green) radiate into the temporal lobes. B, High–resolution coronal section (55x55 mm subimage) at the level of the anterior commissure (green).

Fig. 4. Subimages (55x55 mm FOV) of the brain stem. A, Axial section at the level of the upper midbrain. Very fine fbers that originate from the oculomotor nucleus, run through and around the red nucleus and converge to the roots of the oculomotor nerves (green). Note that fbers of the cerebral peduncles are running at a slight angle through the plane (yellow dots with lines). B, Axial section at the level of the lower midbrain. The arrow points at the decussation of the superior cerebellar peduncle. C, Axial section (110x110 mm FOV) at the level of the midbrain–cerebrum junction. The fbers of the optic tract (arrows) connect to the lateral geniculate bodies. Fibers of the optic radiation (pink) pass lateral to the optic tract. D, Axial section at the level of the pons, through the roots of the trigeminal nerve (green). Fibers of the cranio–caudal tracts (superior cerebellar peduncle, medial longitudinal fasciculus, tectospinal tract, dorsal and ventral trigeminothalamic tracts, central tegmental tract, spinothalamic tract, and rubrospinal tract) can be seen in the posterior part of the pons (pink). The yellow dots indicate fbers of the pyramidal and the
frontopontine tracts.

Fig. 5. A, Coronal section (110x55 mm subimage) of the brain stem at the level of the motor decussation. Fibers of the motor tract cross to the contralateral side at the level of the lower medulla. B, Axial subimage (27.5x27.5 mm FOV) of the medulla at the level of the motor decussation. Fibers of the motor tract cross to the contralateral side. C, Midsagittal subimage (55x55 mm FOV) of the brain stem. The pyramidal tract is shown in yellow and the medial longitudinal fasciculus in pink. D, Sagittal section (55x55 mm FOV subimage) of the brain stem at a lateral position. Fibers of the pyramidal tract (yellow) enter the pons. The arrow heads point to fine fibers of the sensory decussation (internal arcuate fibers), running in antero–posterior direction.

Fig. 6. Subimages (55x55 mm FOV) of the cerebellum. A, Coronal section at the level of the 4th ventricle floor. Fibers of the superior (green) and inferior (pink) cerebellar peduncles pass in cranio–caudal direction towards the cerebellar hemisphere, and fibers of the middle cerebellar peduncle (yellow) pass at an oblique angle through the slice (dots with lines). B, More posterior coronal section of the cerebellum. Fibers from the cerebellar peduncles branch out towards the cerebellar cortices.