White Matter Fiber Tracking Computation Based on Diffusion Tensor Imaging for Clinical Applications

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Fiber tracking allows the *in vivo* reconstruction of human brain white matter fiber trajectories based on magnetic resonance diffusion tensor imaging (MR-DTI), but its application in the clinical routine is still in its infancy. In this study, we present a new software for fiber tracking, developed on top of a general-purpose DICOM (digital imaging and communications in medicine) framework, which can be easily integrated into existing picture archiving and communication system (PACS) of radiological institutions. Images combining anatomical information and the localization of different fiber tract trajectories can be encoded and exported in DICOM and Analyze formats, which are valuable resources in the clinical applications of this method. Fiber tracking was implemented based on existing line propagation algorithms, but it includes a heuristic for fiber crossings in the case of disk-shaped diffusion tensors. We successfully performed fiber tracking on MR-DTI data sets from 26 patients with different types of brain lesions affecting the corticospinal tracts. In all cases, the trajectories of the central spinal tract (pyramidal tract) were reconstructed and could be applied at the planning phase of the surgery as well as in intraoperative neuronavigation.

KEY WORDS: Diffusion tensor imaging, fiber tracking, pyramidal tract, cortico-spinal tracts, neurosurgical planning and navigation, DICOM

BACKGROUND

Diffusion weighted magnetic resonance imaging (DW-MRI) is a technique of great value in the diagnosis of brain infarction and in further characterization of brain tissue, especially the white matter tracts based on diffusion-related parameters.¹ Because of their anisotropic water diffusion properties, white matter tracts can be imaged either by

using direction-specific diffusion gradients in one or more orthogonal directions² or by magnetic resonance diffusion tensor imaging (MR-DTI), which provides estimates of second-order diffusion tensors describing how the water molecules diffuse along neural tracts.³ Algorithmic, heuristically controlled fiber tracking techniques can then be applied for the reconstruction and visualization of the main fiber tract trajectories.^{4,5}

The state-of-the-practice application of DTI under clinical conditions, mainly in brain tumors, is mostly limited to relatively simple representations of the data, such as “color maps” representing a voxelwise color coding of the main direction of diffusion⁶ and not so often on results of a fiber tracking algorithm.^{7,8} This may occur as a result of some limitations of this new technique: (1) most line propagation algorithms do not recognize areas of fiber crossings or “kissings” where voxels contain two eigenvectors of similar magnitude, as occurs within the *centrum semiovale* with its

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mixture of callosal, association, and projection fibers; (2) because of vasogenic edema and/or invasive growth of the neoplasm, which complicates the tracking of white matter trajectories at the tumor surroundings due to decreasing diffusion anisotropy⁹ and increasing possibility of tracking artifacts,⁷ leading to incorrect results; (3) the correct position of the trajectories has been proven in humans by cortical stimulation only,¹⁰ but not within the white matter itself, thus further investigation about the correctness of the results given by fiber tracking algorithms is necessary, such as with the recently reported method of subcortical stimulation.¹¹

To support the integration of fiber tracking into the clinical routine, there is also a need for a software that is comfortable to use and fully integrated into the picture archiving and communication system (PACS) infrastructure of a hospital, transferring the task of performing fiber tracking procedures from the computer technician to the neuroradiologist.

We implemented a fiber tracking and visualization tool, embedded into a general-purpose DICOM (digital imaging and communications in medicine) framework that was developed earlier by our research group,¹² which allows fiber tracking to be executed in a transparent and integrated manner over DICOM data sets with MR-DTI images. The tool offers 2- and 3-dimensional visualization modes for the tracked trajectories, and images combining fiber tract trajectories with anatomical information can be encoded by using DICOM and sent to neuronavigation systems and visualization workstations through network transfer services. The fiber tracking algorithm we developed is based on existing line propagation implementation approaches^{4,13} and included a heuristic to overcome the limitations imposed by possible fiber crossings/kissings and by edema around tumors.

METHODS

Requirements for the fiber tracking method to be developed were as follows: (1) it should be able to perform adequate trackings also on data sets from relatively low time-consuming DTI sequences acquired during clinical routine situations, typically in less than 10 min; (2) it should be robust in regions showing reduced anisotropy and possible fiber crossings; (3) it should have a reasonable computation time when running on a standard PC. Requirements for the tool incorporating this

fiber tracking method were as follows: (4) it should integrate all processing steps in a transparent and usable manner, allowing medical staff to comfortably perform fiber tracking procedures in their daily routine; (5) it should allow the user to select specific trajectories using *a priori* anatomical knowledge from the set of tracked tracts in an interactive manner; (6) it should interactively present the tracking results as navigable 2D and 3D representations, thereby allowing their combination with other coregistered radiological data, such as 3D magnetization prepared rapid gradient echo (MPRAGE) images; (7) it should export the results in a manner that is compatible with neuronavigation and neurosurgical planning tools; (8) it should be easily integrable into the DICOM PACS framework existing at a given hospital.

Image Data

All MRI examinations were performed on a 1.5-T system (Siemens Sonata) with high gradients (40 mT/m) and application of parallel imaging technique [eight-channel iPAT coil and a generalized autocalibrating partially parallel acquisitions (GRAPPA) reconstruction algorithm]. The image acquisition protocol included, apart from the routinely acquired T₁- and T₂-weighted images, high-resolution 3D MPRAGE data sets with T_E/T_R = 16/1,900 ms, 1-mm-thick slices in sagittal orientation, no interslice gap, with an in-plane resolution of 512 × 512 pixels and a pixel size equal to 0.5 × 0.5 mm. The DTI data sets were acquired by using a diffusion-weighted single-shot spin-echo echo-planar based sequence, with T_E/T_R = 105/8,000 ms, one nondiffusion-weighted image (*b* = 0 s/mm²), and six diffusion-weighted images (*b* = 1,000 s/mm²) corresponding to gradients applied along six noncollinear directions with six repetitions. The data sets were sampled in a matrix of 128 × 128 × 33 voxels, with a voxel size of 1.8 × 1.8 × 3.0 mm.

Fiber Tracking

From the measured DTI data sets, the six diffusion tensor (*D*) elements were determined on a voxel by voxel basis according to the method described by Basser et al.³ The discrete statistical approximation was converted to a continuous approximation/interpolation¹⁴ of the underlying 3-dimensional diffusion tensor field, *D*(*x*, *y*, *z*), where *x*, *y*, and *z* are coordinates of the chosen frame of reference. The decomposition of the diffusion tensor in eigenvalues and eigenvectors was accomplished by using a routine for symmetric bidiagonalization followed by QR reduction provided in the GNU Scientific Library.¹⁵

Fiber tracking was performed with the fourth-order Runge-Kutta (RK4) method to numerically integrate the 3D white matter trajectories^{13,16} from the diffusion tensor eigenvector system. The seeding points for the RK4-based algorithm were the center of all voxels from the DTI data set volume that satisfied a noise threshold [mean diffusivity (MD) ≥ 50 s/mm²] and a gray matter threshold [fractional anisotropy (FA) ≥ 0.15 units]. The step size used for the RK4 integration algorithm was equal to 0.5 units of the given frame of reference. The 3D space curves representing the white matter trajectories were stored as 3D polygons.

Heuristics for Linkage Criteria

One of the aims of our work was to improve the robustness of the tracking method in such a way that areas of possible fiber crossings and of reduced anisotropy do not interrupt the tracking process. For this purpose, we developed two heuristics for decision making during the integration of trajectories:

- (1) *Disk-shaped tensors.* When the two strongest eigenvectors of a tensor passing through a given voxel have similar eigenvalues, representing more than one preferential diffusion direction, the pathways at this point can be considered ambiguous and most approaches stop here. To cope with this, the algorithm rotates the normal vector computed at the prior integration step until it lies parallel to the plane given by the two main eigenvectors. This is then considered the preferential linkage trajectory plane and search for a plausible trajectory compatible with the previous step and one of the main eigenvectors is performed.
- (2) *Computation of plausible trajectories.* The computation of a given trajectory continues, while all of the following criteria are satisfied: (a) the current trajectory coordinate has not reached the image volume boundaries; (b) the current computed trajectory coordinate is still lying inside a region of white matter, which is verified against the FA threshold (0.15 units); (c) the angle between two consecutive computed normal vectors is inferior to a defined threshold (20°); (d) the length of the 3D space curve has not exceeded a threshold of 200 mm. The trajectories also have to satisfy a minimum length threshold of 5 mm.

Multimodality Data Integration and Presentation of Results

The neurosurgical planning and navigation procedures routinely carried out for neurosurgery are based on 3D MPRAGE image data sets. These images characterize the patient's brain with a high level of anatomical details, and are hereafter referred to as *anatomical images*. To allow the neurosurgical planning and navigation procedures to include fiber tracking results, we developed a method to combine the fiber tracking results with these anatomical images.

First, the DTI data sets and the anatomical images were coregistered by using the mutual information normalization method,¹⁷ as implemented by the software Statistical Parametric Mapping, version 2 (SPM; Wellcome Department of Imaging Neuroscience, University College London). The FA maps volume, derived from the DTI data set, and the anatomical images volume were respectively inputted as "source" and "target" images into the coregistration program. All coregistrations were manually checked for alignment consistency, by using the tool supplied with SPM. Manual check of the alignment consistency took between 1 and 5 min, depending on the expertise of the person who performed the procedure. Finally, to combine the fiber tract trajectories with the anatomical images, the 12-component affine transformation resulting from the coregistration was applied to the collected fiber tract 3D polygons, which were transformed into 3D splines and directly plotted into the high-resolution anatomical

volume data sets. All the voxels lying under the coregistered trajectories were assigned with a special unique signal intensity value.

The Software Tool

To enable the integration of fiber tracking into the routine image workflow of the neuroradiological and neurosurgical departments in our clinic, it was important that the results produced by this new technique could be represented in a format common to all devices involved. Thus, we have chosen to implement the MR-DTI processing tool on top of a DICOM client/server software framework that we have previously implemented,¹² which allowed an easy development of routines to encode images combining fiber tracking results and anatomical information using the DICOM standard.

The DTI data sets and the anatomical images were retrieved from the clinic PACS by using our DICOM client software, and stored in a local database. The user selected the DICOM series containing the DTI data sets and started the MR-DTI processing tool (Fig. 1). The tool also offers the possibility to load DTI data sets in the Analyze format, allowing the use of third-party software for preprocessing steps, such as correction of movement artifacts.

Processing Alternatives and Possibilities

The tensors can be computed from the original measured DTI data set (1) directly, or (2) continuously approximated,¹⁴ allowing smoothed diffusion tensors, according to the scale factor (1.0 = interpolated, lower than 1.0 = approximated) (see also Fig. 1). The user may compute maps of several diffusion tensor based indices¹⁸ such as FA, FA Color Maps, and MD, in transversal, sagittal, and coronal orientations.

The fiber tracking algorithm numerically integrates curves representing the tract trajectories using, as seeding points, the center of a given set of voxels satisfying the noise and white matter thresholds (see above). The seeding points can be defined as (1) all the voxels from the data set or (2) the voxels lying inside regions of interest (ROIs) placed by the user along the data set, in the transversal, sagittal, or coronal orientations. Before starting to track fibers trajectories, the user can also change the parameters that control the algorithm behavior, as described in "Computation of plausible trajectories."

The tracked trajectories can be stored into a local PACS. For this purpose, we developed a new private DICOM information object definition (IOD) called "White Matter IOD," and the results are stored as SOP (DICOM Service-Object Pair) instances of it. Later, the user has the option to load the trajectories stored on the database.

Subsets of the tracked trajectories can be selected also by placing ROIs along the transversal, sagittal, or coronal projections of the DTI data set. Specific white matter fiber tracts can then be selected by using *a priori* anatomical knowledge—the selected ROIs are placed at the areas where the tracts are expected to cross. The Boolean operands OR, AND, NOT, and XOR can be used to combine different ROIs. For example, to select the computed trajectories belonging to a tract that is known to cross both regions A and B, two ROIs should be placed, one at A and another at B, and both can be

Fig 1. Screenshot showing some of the interface windows of the developed MR-DTI and fiber tracking processing software: The Cyclops MIB (Medical Images Browser, background window) is the radiological workstation used to retrieve and send data as well to start applications such as the MR-DTI Fiber Tracking software. The front-plane window is the main interface of the fiber tracking tool, which resembles the interface of a radiological images viewer. The images displayed are FA color maps computed from the MR-DTI dataset, color-encoding the main orientation of diffusion (red = left-right, green = anterior-posterior, blue = cranio-caudal). The interface in the foreground (bottom right) is used to enter information about the diffusion gradients and to start the computation of the diffusion tensors. At the top-right window MR-DTI sequence parameters are displayed.

combined in a Boolean AND operation. All trajectories crossing the ROI placed at A and all trajectories crossing the ROI placed at B are then selected (Fig. 2).

The corticospinal tracts were selected via two ROIs, one of them placed into the cerebral peduncles and the other one into the pre- and postcentral gyrus.

Visualization Possibilities

The tool offers several trajectory visualization possibilities: (1) intratool 2D and 3D projections; (2) export of an image volume in Analyze format, containing the trajectories to be used as an overlay for anatomical images; and (3) export of a DICOM series combining anatomical images and the fiber tracking results selected by the user. The 2D and 3D projections are directly visualized within the tool, and can be frozen and exported in JPEG (joint photographic experts group) format.

All generated images and data sets can be stored into a DICOM PACS, allowing the user to permanently retain all the results

obtained with the fiber tracking tool. The DICOM storage server to be used should support the White Matter IOD mentioned above and its related SOP classes. For this purpose, we specifically extended our in-house-developed DICOM archiving server; however, any DICOM PACS server could be extended to support this SOP class.

Patients

For the test and refinement of this tool and in order to adapt it to routine examination requirements, fiber tracking was performed on DTI data sets acquired from 10 healthy volunteers (5 females and 5 males) and 26 patients (15 females and 11 males, age range 16–80 years) with brain tumors and other focal lesions (7 low-grade gliomas, 7 glioblastomas, 3 meningiomas, 6 metastases, 1 ganglioglioma, 1 cavernoma, 1 tuberculoma). The study was carried out over 18 months and has been approved by the local ethics committee. Informed consent was obtained prior to patients' participation. Only patients with lesions displacing the

Fig 2. An illustration of how the selection of trajectories by placement of ROIs and its combination with Boolean operators works. (a) A single ROI was placed at the bottom and all the trajectories crossing at that region were selected. (b) Combination of two ROIs through a Boolean AND operation is shown, and only the trajectories crossing both ROIs were selected (thick lines). (c) Two ROIs were combined with a Boolean OR operation, and all the trajectories crossing one or the other ROI were selected. (d) All trajectories crossing the ROI at the bottom and NOT crossing the ROI placed at the top were selected, exemplifying the combination of an ROI with the boolean operator NOT.

corticospinal tracts were included in the study. Fiber tracking was executed for every patient and the trajectories corresponding to the central corticospinal tract (pyramidal tract) were used for neurosurgical planning and navigation according to our method.

Neurosurgical Planning and Intraoperative Navigation

The DICOM series with images combining anatomical information (3D MPRAGE) and corticospinal tracts localization were transferred to a neurosurgical planning system (Dextroscope from Volume Interactions/Singapore) and to neuronavigation systems (VectorVision® from BrainLab, Germany and SonoWand® from MISON, Norway).

RESULTS

MR-DTI-based fiber tracking was performed in all 26 patients who participated in this study. The duration of the protocol for acquisition of images for neurosurgical planning and navigation has been increased by approximately 8 min, after

inclusion of the DTI sequence. The data sets with DTI and anatomical images were retrieved into a Linux Workstation (AMD Athlon, 1.2 GHz, 1 Gb RAM). Fiber tracking, using the center of all voxels inside the volume that satisfied the noise and white matter thresholds (see above) as seeding points, lasted about 20 min. When we include the time necessary for interactive selection of the corticospinal tract trajectories, coregistration of DTI images to the anatomical images, and generation of images combining anatomy and the selected trajectories, the time for complete processing of images for neuroplanning/neuronavigation lasted about 2 h.

In all 26 cases, the corticospinal tracts of only one of the brain hemispheres were affected by the lesions, either by displacement resulting from its mass size and/or by the extent of the peritumoral edema, enabling us to compare the fiber tracking results between the affected and the nonaffected brain hemispheres. The corticospinal tracts, spe-

Fig 3. Screenshot of the neuronavigation system (SonoWand® from MISON, Norway) while the surgeon navigates through the brain and the tumor cavity (glioblastoma) to determine the limits of the tumor resection and its spatial relation to the tracked trajectories. The top-right image is a 3D MPRAGE combined with the tracked trajectories (indicated by white arrows). Ultrasound images at the top left and at the bottom indicate the tumor cavity during resection. The oblique line, with a mark on its end, shows the relative position of a surgical instrument used by the surgeon during the surgery in relation to the anatomical structures and the reconstructed fiber tract trajectories.

cifically the central fibers containing the pyramidal tract, could be tracked in all patients, and usually a larger number of trajectories was found in the nonaffected hemisphere than in the affected one. We also checked for intrarater reproducibility of tracking the corticospinal tracts by repeating the tracking procedure three times from newly placed ROIs in 10 cases, determining the number of voxels hit by all three procedures. There was a mean accordance rate of $p_{\text{obs}} = 0.793 \pm 0.108$, corresponding to a variation coefficient of 13.6%.

In cases where the corticospinal tracts were lying in regions with peritumoral edema, as seen on T₂-weighted or FLAIR images, tracking with the routinely applied parameters produced anatomically reliable trajectories, although the number of identified trajectories was reduced.

The combination of anatomical information usually contained in T₁-weighted images and the trajectories of the pyramidal tract allowed the

demonstration of its position in relation to the lesion both during operation planning and surgery. Based on the information from the reconstructed pyramidal tract, the surgeon compared the possible surgical approaches of lesion removal, allowing him to elaborate an operation plan that minimizes possible pyramidal tract damages. Neuronavigation combining anatomical information and the trajectories of the pyramidal tract were used by surgeons during surgery to determine at which extent intrinsic brain lesions could be treated, which was helpful in estimating the limits of tumor removal (Fig. 3).

DISCUSSION

When performing MR-DTI in patients, measurement time must be as short as possible. By applying PAT combined with GRAPPA,¹⁹ which

makes use of less phase-encoding steps, susceptibility artifacts and spatial distortion inherent to DTI sequences based on echo planar imaging could be reduced, while the time necessary to acquire one DTI data set was kept around 8 min. This allowed the inclusion of MR-DTI in the MR examination protocol used for surgical planning and neuronavigation. Obvious spatial distortions, which are expected to occur in EPI-based MR sequences and specially in DTI, were not severe and did not disturb the coregistration of DTI to anatomical images (Fig. 4).

The low spatial resolution at which the measured diffusion tensor field was sampled introduced several problems for the RK4-based tracking algorithm, such as a higher susceptibility to noise and lower precision while integrating the fiber tract trajectories. Thus we used a continuous tensor field approximation,¹⁴ which provided a means to interpolate/approximate the original sampled data and, consequently, compute smoother trajectories in a more noise-robust way. Although the number of repetitions used while acquiring DTI data sets

in our study was reduced, compared to other studies, the signal-to-noise ratio was sufficiently high and, combined with the improvements given by the tensor interpolation, allowed the tracking of major white matter tracts (Fig. 5), apart from the corticospinal fibers.

We based our fiber tracking algorithm on the line propagation method as originally described by Mori et al.⁴ and Basser et al.¹³, and developed a new heuristic to solve the preferential orientation of diffusion in the case of disk-shaped tensors, where more than one preferential orientation of the diffusion is present. This allowed fiber-tracking results to include trajectories possibly crossing along the plane of the 3D ellipse given by the main and medium diffusion tensor eigenvectors, although this increases the algorithm susceptibility to noise and may produce more aberrant trajectories. Our validation study has shown that, with the parameters we have chosen, this susceptibility could be managed and trajectories corresponding to the anatomical localization of the corticospinal tracts could be computed.

The seeding points for the fiber tracking algorithm were the center of all voxels inside the measured volume where the noise and white matter thresholds (see above) were satisfied. This approach produces trajectories that give the impression of fiber tract branchings, which are anatomically correct but cannot be represented by a single 3D curve, and enabled the tracking of unusual branchings of the corticospinal tract, as it is occasionally induced by the tumor mass effect with deviation of some fibers only. This approach can produce hundreds of thousands of trajectories, and thus a method to select the trajectories of interest must be available. Using *a priori* anatomical knowledge, a number of criteria can be defined by the user and only the trajectories satisfying these criteria are selected. Knowing that corticospinal fibers cross the cerebral peduncles, a ROI was placed there and all the trajectories that crossed this region were selected. By placing a second ROI into the ventral part of the pons, we tried to differentiate the central corticospinal ("pyramidal") tract from the parallel running fibers of the fronto-pontine and fronto-occipito-pontine tracts. By eliminating the ROI placed at the level of the cerebral peduncles, and by placing a new ROI at the level of the pre- and postcentral gyrus, the central corticospinal tracts could then be selected (Fig. 6). The intrarater reproducibility of our method

Fig 4. T₁ MR weighted images showing a meningioma (asterisk) and the FA maps computed from the MR-DTI dataset from a patient aligned after coregistration, with correct spatial adjustment.

Fig 5. 3D projections of fiber tracking results including color-coded fractional anisotropy values between 0 (red) to 1 (blue). Top left: commissura anterior (axial view). Bottom left: commissura anterior and the cingulum including its parahippocampal extension (lateral view). Top right and bottom right: axial and lateral views of the anterior and posterior radiations of the corpus callosum.

shows a mean accordance rate of $p_{\text{obs}} = 0.793 \pm 0.108$, and is just slightly below the results obtained by Stieltjes et al.²⁰ in healthy volunteers.

FA can be interpreted as a measure of white matter integrity, being higher in areas not affected by the lesions. The FA threshold of 0.15 units used in the present study corresponds to the “border” between gray and white matter and is in accordance with the value used by Nimsky et al.⁸ In the tumor surrounding region, in areas with preserved or increased (edematous) T_2 signal, but with only moderately reduced FA, we were able to find trajectories being displaced by the tumor. However, in peritumoral regions where the anisotropy was severely reduced, lying under the specified FA threshold, fiber tracking was severely impaired. This might have been attributable to tract infiltration or disruption, and it can also result from partial volume effects caused by the low image/signal resolution. Similar difficulties were reported by Yamada et al.⁷ who found interruptions of the continuity at the tumor level in 10 major tracts in

23 patients with brain tumors. However, the reappearance of the tract after successful tumor removal in one of their patients clearly demonstrates that tracts can be masked, and the non-visibility of trajectories within a tumor-surrounding area does not necessarily mean that they are destroyed. Bammer et al.²¹ reported on three patients from other institutions (2 glioblastomas, 1 ganglioglioma) in whom tracts within edematous areas retained their anisotropy and could be recognized by the algorithm.

To include the fiber tracking system into the neurosurgical and neuroradiological clinical routine, the workflow was changed so that (1) a DTI sequence was acquired together with the already existing MR imaging protocol for neurosurgical interventions, (2) a neuroradiologist (P.R.W.) or a computer scientist (P.R.D.) was asked to perform fiber tracking, and (3) the images combining anatomical information and the fiber tract trajectories were sent back to the PACS central archive or directly to neurosurgical planning and navigation

Fig 6. T_{2w} image, FA color map (second column), and coronal sections of a 3D MPRAGE image volume over which the trajectories corresponding to the central corticospinal white matter tracts were projected. This figure illustrates how the ROIs were placed to select only the trajectories corresponding to the corticospinal tracts, mainly the pyramidal tract. Two ROIs, combined with a boolean AND operator, were placed at every brain hemisphere into the pre- and postcentral gyrus (upper row, first and second columns), and into the ventral part of the pons (lower row, first and second columns).

systems. Because the MR imaging protocol ran at least 1 day before the surgical intervention, the average 2 h necessary to process the images for neuroplanning/neuronavigation were not a prohibitive factor and the fiber tracking system could be successfully inserted into the clinical workflow.

From the point of view of data format integration, we followed two different philosophies for the export of results for external usage and for the storage of fiber tracking results for further usage by the tool itself. MR volumes combining anatomical images and coregistered selected trajectories were exported in DICOM format, allowing their easy loading into any DICOM-compatible application, such as visualization tools or the neuroplanning and navigation systems described above and used in this study. Image volumes of selected trajectories were exported in the Analyze format, which allows the combination of fiber tracking results with functional magnetic resonance imaging (fMRI) or positron emission tomography (PET) results after their coregistration to a common anatomical image. For the storage of the results, however, we developed our own extension to the DICOM standard, a

privately defined IOD, the White Matter IOD. To allow the storage of White Matter SOP instances on a PACS, we extended a DICOM server developed by our group to allow communication and storage of this privately defined IOD. This philosophy limits compatibility, because it requires that a PACS system should be able to store “native” postprocessed fiber tracking data and has to implement the White Matter IOD and its SOPs, a fact that does not apply to commercial DICOM servers. We decided to follow this philosophy because the obvious DICOM IODs for the storage of the fiber tracking results, either the MR IOD or the SC IOD, did not support the tract curve data that we considered necessary to be stored. On the other hand, Analyze is a medical image data interchange format for files used in complex image analysis tasks and not a PACS data standard, and is not supported by most PACS. The DICOM standard, through its conception scheme, allows its easy extension through new data object definitions in an elegant fashion. This makes an extension of the DICOM standard the natural choice for the storage of data generated during a fiber tracking procedure.

CONCLUSIONS

DTI-based fiber tracking is a promising technique to demonstrate deviations and involvement of white matter tracts by brain tumors, and it may contribute to minimal invasive neurosurgery. DTI sequences that can be performed under normal clinical conditions are useful for fiber tracking if the tracking algorithm is robust and can solve ambiguities. Improvement of peritumoral anisotropy contrast is an important issue to allow a more reliable identification of white matter tracts in this critical area and to differentiate between edematous affection that might resolve after successful operation, and true neoplastic invasion or disruption, which both have important implications on neurosurgical strategies. Further investigation about the effects produced by the modification of our fiber tracking algorithm in regions with peritumoral edema is still necessary and will be published elsewhere.

A usable and integrated fiber tracking software tool can be successfully inserted into the PACS infrastructure of a clinic and medical staff trained to use it. End users can also be trained and motivated to export the resulting data to the neuronavigation and neurosurgical planning systems and use them in their routine. A freely downloadable distribution of the fiber tracking software as well as instructions on how to use it are available at <http://www.staff.uni-mainz.de/dellani/ft>.

REFERENCES

1. Moseley ME, Kucharczyk J, Mintorovic J, Cohen Y, Kurhanewicz J, Derugin N, Asgari H, Norman D: Diffusion-weighted MR imaging of acute stroke: correlation with T₂-weighted and susceptibility-enhanced MR imaging in cats. *Am J Neuroradiol* 11:423–429, 1990
2. Fitzek C, Weissmann M, Speckter H, Fitzek S, Hopf HC, Schulte E, Stoeter P: Anatomy of brain-stem white-matter tracts shown by diffusion-weighted imaging. *Neuroradiology* 43: 953–960, 2001
3. Basser PJ, Mattiello J, LeBihan D: Estimation of the effective self-diffusion tensor from the NMR spin echo. *J Magn Reson B* 103:247–254, 1994
4. Mori S, Crain BJ, Chacko VP, van Zijl PCM: Three-dimensional tracking of axonal projections in the brain by magnetic resonance imaging. *Ann Neurol* 45:265–269, 1999
5. Mori S, van Zijl PCM: Fiber tracking: principles and strategies—a technical review. *NMR Biomed* 15:468–480, 2002
6. Tamura H, Takahashi S, Kurihara N, Yamada S, Hatazawa J, Okudera T: Practical visualization of internal structure of white matter for image interpretation: staining a spin-echo T₂-weighted image with three echo-planar diffusion-weighted images. *Am J Neuroradiol* 24:401–409, 2003
7. Yamada K, Kizu O, Mori S, Ito H, Nakamura H, Yuen S, Kubota T, Tanaka O, Akada W, Sasajima H, Mineura K, Nishimura T: Brain fiber tracking with clinically feasible diffusion tensor MR imaging: Initial experience. *Radiology* 227:295–301, 2003
8. Nimsch C, Ganslandt O, Hastreiter P, Wang R, Benner T, Sorensen AG, Fahlbusch R: Intraoperative diffusion-tensor MR imaging: shifting of white matter tracts during neurosurgical procedures – initial experience. *Radiology* 234:218–225, 2005
9. Tropine A, Vucurevic G, Hunsche S, Boor S, Hopf N, Bohl J, Stoeter P: Contribution of diffusion tensor imaging (DTI) to delineation of cerebral gliomas. *J Magn Reson Imaging* 20: 905–912, 2004
10. Coenen VA, Krings T, Axer H, Weidemann J, Kranzlein H, Hans FJ, Thron A, Gilsbach JM, Rohde V: Intraoperative three-dimensional visualization of the pyramidal tract in a neuronavigation system (PTV) reliably predicts true position of principal motor pathways. *Surg Neurol* 60:381–390, 2003
11. Duffau H, Capelle L, Denvil D, Sichez N, Gatignol P, Taillandier L, Lopes M, Mitchell MC, Roche S, Muller JC, Bitar A, Sichez JP, van Effenterre R: Usefulness of intraoperative subcortical mapping during surgery for low-grade gliomas located within eloquent brain regions: functional results in a consecutive series of 103 patients. *J Neurosurg* 98:764–778, 2003
12. Krechel D, Faber K, von Wangenheim A, Sampaio SC: Object-Oriented Implementation of a DICOM Network Client in Smalltalk. In 12th IEEE Symposium on Computer Based Medical Systems. Stamford, CT, USA, 1999
13. Basser PJ, Pajevic S, Pierpaoli C, Aldroubi A: Fiber tract following in the human brain using DT-MRI data. *IEICE Trans Inf Syst* E85-D (1):15–21, 2002
14. Pajevic S, Aldroubi A, Basser PJ: A continuous tensor field approximation of discrete DT-MRI data for extracting microstructural and architectural features of tissue. *J Magn Reson* 154:85–100, 2002
15. Galassi M, Davies J, Theiler J, Gough B, Jungman G, Booth M, Rossi F: Gnu Scientific Library: Reference Manual, 2nd edition. Network Theory Ltd., 2003
16. Dellani P, Glaser M, Tropine A, Vucurevic G, Bauermann T, Wille P, Strecker U, Stadie A, Perneczky A, Stoeter P: Intraoperative Neuronavigation von Hirntumoren unter Einschluss des Tractus Corticospinalis mit Hilfe von Diffusion Tensor Imaging und Fiber Tracking. *Klin Neuroradiol* 14:244–251, 2004
17. Ashburner J, Friston KJ: Multimodal image coregistration and partitioning—a unified framework. *NeuroImage* 6(3): 209–217, 1997
18. Pajevic S, Pierpaoli C: Colour schemes to represent the orientation of anisotropic tissue from diffusion tensor data: application to white matter fiber tract mapping in the human brain. *Magn Reson Med* 42:526–540, 1999
19. Griswold MA, Jakob PM, Heidemann RM, Nittka M, Jellus V, Wang J, Kiefer B, Haase A: Generalized autocalibrating partially parallel acquisitions (GRAPPA). *Magn Reson Med* 47:1202–1210, 2002
20. Stieltjes B, Kaufmann WE, van Zijl PCM, Fredericksen K, Pearson GD, Solaiyappan M, Mori S: Diffusion tensor imaging and axonal tracking in the human brainstem. *NeuroImage* 14:723–735, 2001
21. Bammer R, Acar B, Moseley ME: *In vivo* MR tractography using diffusion imaging. *Eur J Radiol* 45:223–234, 2003