Tractography of the optic radiation with diffusion compartment imaging and multi-fascicle modeling

Jolene M Singh[1]; Rory J Piper[2,3]; Vinay Jayaram[1]; Benoit Scherrer[1]; Maxime Taquet[1]; Xavier Tomas-Fernandez[1]; Onur Afacan[1]; Sean Clancy[1]; Simon K Warfield[1].

[1]Computational Radiology Laboratory, Boston Children's Hospital, USA
[2]College of Medicine and Veterinary Medicine, University of Edinburgh, Edinburgh, UK
[3]Muir Maxwell Epilepsy Centre, University of Edinburgh, Edinburgh, UK

Abstract:

Temporal lobe resection is a potentially curative intervention for temporal lobe epilepsy (TLE). Visual field defects may arise if a resection transects the optic radiation. The anatomic course of the optic radiation is known to have substantial inter-individual variability. Noninvasive localization of the precise course of the visual pathways in individual patients offers the possibility of improved assessments of the risks and benefits of a temporal lobe resection.

Diffusion weighted imaging is an excellent tool for localization of critical white matter pathways. However, methodological differences in acquisition protocols and modeling choices have led to substantial variation in the localization of the vision pathways, and the optimal approach for characterization of the optic radiation including Meyer's loop is unclear.

Here, we show the impact of high spatial resolution diffusion compartment imaging combined with either conventional single tensor diffusion modeling (DTI) or multi-fascicle modeling (MFM). In addition, we include a novel smoothing filter for multi-fascicle modeling which helps to resolve tensors in regions of fiber crossings. We conclude that spatial resolution, diffusion compartment imaging, choice of diffusion model, regularization constraint and use of super resolution reconstruction (SRR) imaging are all necessary to conduct optimal and clinically feasible imaging of the OpR in preparation for tractography as part of presurgical planning for anterior temporal lobe resection.

Description:

Anterior temporal lobectomy (ATL) is a well-established and effective treatment option for drug-resistant temporal lobe epilepsy (Wiebe 2001). However, this procedure poses risk of damage to the optic radiation (OpR), a white matter structure that carries visual information from the lateral geniculate nucleus (LGN) in the thalamus posteriorly to the calcarine sulcus in the occipital lobe. The anterior bundle of this structure, the Meyer's loop, which follows a 'plunging' course through the white matter of the temporal lobe, is particularly at risk (Meyer 1907). Visual field defects (VFD) may arise if a resection transects the OpR. Furthermore, the anatomic course of the OpR is well known to have substantial interindividual variability. Therefore, the design and application of noninvasive imaging techniques to localize the OpR before and during

ATL is desirable in order to reduce OpR damage and the subsequent risk of patients developing postoperative visual field defects (VFD).

Diffusion tensor imaging (DTI) is a widely accepted and employed method for localization of critical white matter pathways. Diffusion weighted imaging (DWI) is a magnetic resonance imaging (MRI) method that manipulates a signal derived from the anisotropic flow of water, which allows noninvasive imaging of the white matter tracts. Three-dimensional reconstruction of DTI data derived from the white matter is called tractography or fiber tracking. DTI and tractography have been extensively employed in order to reveal the OpR. A recent systematic review revealed 13 studies that employed DTI and/or tractography to demonstrate a relationship between the extent of OpR damage and the severity of postoperative VFD (Piper 2014). A further study by Winston et al investigating the outcomes of patients undergoing ATL showed favorable visual field outcome in patients whose surgery was compared to those whose surgery was not guided by tractography of the OpR (Winston 2014). Thus, there is an increasing research and clinical interest in the use of DTI for this purpose.

However, methodological differences in DTI acquisition protocols and modeling choices have led to substantial variations in the localization of the vision pathways. Thus the optimal approach for characterization of the OpR including Meyer's loop is unclear and many challenges remain (Mandelstam 2012). Variances exist between maximum tract angle, minimum fractional anisotropy, seeding and selection ROI. A combination of these techniques may be the most appropriate strategy. Another challenge of localizing the OpR with DTI is limitations in spatial resolution in DTI and consequent susceptibility to partial volume effect. Improvements in spatial resolution may allow tract selection to generate results that more accurately and selectively match the known anatomy of the OpR.

Therefore, we wished to test the impact of super resolution reconstruction (SRR) DWI (Scherrer Med Image Analysis 2012) to better capture the structure of the OpR. We also wanted to experiment with diffusion compartment imaging and a multi-fascicle model (MFM) (Scherrer PLoS One 2012) in order to overcome the limitations of previous DTI methods. Unlike the DTI model, the MFM provides a separate representation of each of the crossing fascicles within a voxel as well as the isotropic compartment of extracellular water molecules. We propose the MFM is a more accurate model in comparison to DTI, especially in the localization of crossing, fanning or kissing tracts (Scherrer PLoS One 2012). Finally, we wanted to experiment with a novel smoothing algorithm to optimize the tractography of the optic radiation.

Methods

Image acquisition

SRR was acquired on one healthy male, aged 23 years and two healthy females, aged 21-31 years. The diffusion weighted imaging acquisitions were performed as described in (Scherrer PLoS One 2012) and high resolution k-space sampling was achieved via super-resolution reconstruction (SRR) by acquiring three orthogonal (axial, coronal, and sagittal) anisotropic

1.2x1.2x2.4mm^3 images as described in Scherrer (Med Imag Analysis) 2012 and direct DW 1.2x1.2x1.2mm^3 isotropic images. Single-tensor and multi-fascicle models were used to generate whole-brain tractography.

To test the results from our SRR cases, we compared the findings against DTI from 25 healthy subjects (ages ranging from 5-18 years). MRI was carried out using a Siemens 3T Tim Trio scanner equipped with a 32 channel head coil. All subjects were imaged using the same sequences, and no subjects were imaged while under sedation. The magnetic resonance imaging protocol was based on guidelines for routine clinical imaging extended with diffusion imaging. An isotropic 1x1x1mm 3D T1-weighted MPRAGE, a high-resolution T2-weighted SPACE, and a 3D FLAIR sequence were all acquired for the purposes of quantitative volumetric analysis.

In both the SRR cases and the DTI series, high spatial resolution diffusion weighted images were acquired following the Cube and Sphere (CUSP) scheme (Scherrer PLoS One 2012), combining a conventional spherical HARDI acquisition with additional HARDI shells truncated to those directions, and with gradient strengths that remain inside the sphere at a constant TE. CUSP diffusion allows for the fitting of a full multiple tensor model, as well as the characterization of multiple white matter fascicles at each voxel.

Image processing

Using the CRKit pipeline processing modules (http://crl.med.harvard.edu) the diffusion weighted image (DWI) was registered to the masked T1W image.

Using the pipeline we generated whole brain connectivity (WBC) maps in the single tensor DTI and multi-tensor MFM cases. WBC maps were generated using seeding regions that are anatomically defined (described later) and then the streamlines that show the connections indicated by the model of the diffusion signal are built into tracts. By employing this exploratory tractography method, a DTI-based and an MFM-based whole brain connectivity were derived for all 25 clinical resolution cases and the 3 SRR cases. For the MFM-based tractography, the multi-tensor field was interpolated at each step using the method described in Taquet (IEEE Trans. Med. Imaging) 2014.

In DTI, a second-order diffusion tensor is estimated at each voxel. The color encoding of the DTI represents the direction of the primary eigenvector. MFM estimates three, two or one second-order tensors at each voxel, as necessary, as well as the relative fraction of each compartment to the diffusion signal. The color encoding of the MFM streamlines represents the diffusion of each of these tensors.

MFM Smoothing

MFM estimates were smoothed after the pipeline processing using a Gaussian mixture-model simplification approach (Taquet ISBI, 2012). In order to increase spatial continuity and reduce noise-based effects on the tractography a Gaussian window was used to filter the MFM estimate.

Region-of-interest approach

Instead of stochastically initializing streamlines in the white matter near the LGN, the OpR was extracted by using two regions-of-interest (ROIs) in order to isolate relevant streamlines in the WBC. A seeding ROI was placed at the white matter adjacent to the lateral geniculate nucleus (LGN) and a waypoint (selection ROI) was placed in the stratum sagittal, as demonstrated in our previous study (Benjamin 2014). To eliminate spurious tracts – either true anatomical structures captured accidentally, or false spurious tracts that did not correspond to the tracts expected to form the OpR – we employed exclusion ROI. Tracts that came into contact with these ROI were removed. On the basis of previous ex-vivo studies (Ebeling & Reulen 1988) we set exclusion ROI that removed tracts extending anteriorly to the frontal lobe, superiorly to the cortex and inferiorly to the brainstem.

Results

In Figure 1, we compare clinical resolution color FA images to high-resolution DWI CUSP color FA images. Here it can be seen that the white matter near the LGN is more distinct and bilaterally more symmetric in the higher resolution imaging. This enables better delineation of seeding ROI.

SRR enabled high resolution in less time and required fewer repeat images to achieve equivalent SNR compared to direct DW imaging. Therefore SRR is a more clinically feasible protocol for high-resolution DW imaging.

In addition to showing the impact of high-resolution image acquisition, we tested the contribution of diffusion modelling to visualization of the OpR. In Figure 2 we demonstrate the differences between DTI and MFM with and without smoothing. It can be seen that in DTI the posterior extensions of the OpR are more limited than that seen in MFM and there are fibers more inferior than would be indicated by the known anatomy. MFM without smoothing produces many sparse fibers branching out from the sheet-like OpR structure. However, imposing regularization through smoothing filter produces tracts that are more extensive and consistent with the anatomy of the OpR.

In Figure 3 we show the underlying tensor orientation in the ROI for seeding the OpR. In axial and coronal views we show that smoothing produces a representation of crossing fibers whereas MFM without smoothing produces areas of conflicting orientation. As a result without smoothing streamlines veer off in many directions and leave sparse areas whereas with regularization it is possible to produce fuller tracts representing the OpR with fewer regions of sparsity. In addition, unlike DTI, MFM fails to produce spurious tracts inferior to the OpR that constitute a kissing pathway.

New or breakthrough work to be presented:

- Super resolution reconstruction (SRR) image data for high-resolution DWI and OpR tractography
- Direct diffusion at high-spatial resolution (1.2x1.2x1.2mm,^{3} isotropic)
- Multi-fascicle model (MFM) for OpR tractography
- Novel smoothing filter for MFM

Conclusions:
The OpR can be separated from nearby crossing and/or kissing fibres through high-spatial resolution diffusion compartment image acquisition (i.e. CUSP) combined with a multi-fascicle (MFM) diffusion model and regularization constraint (smoothing filter).

Prior/Concurrent Submissions:
None.

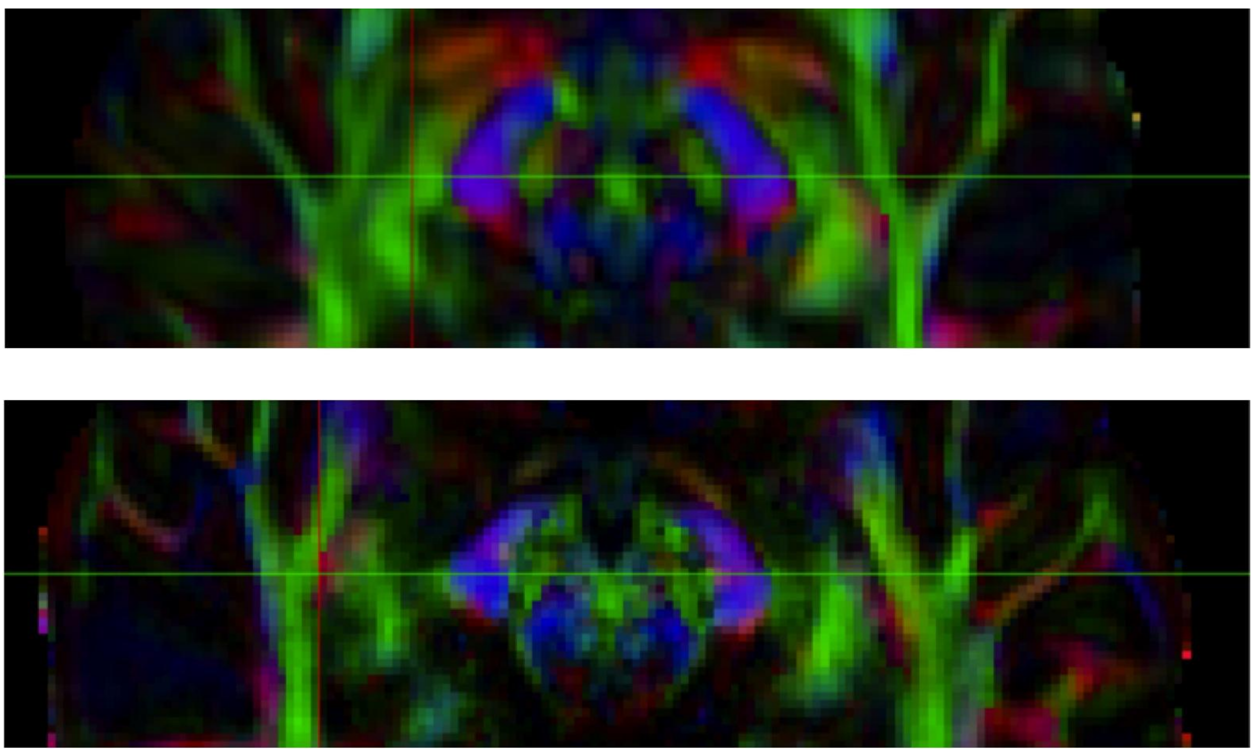
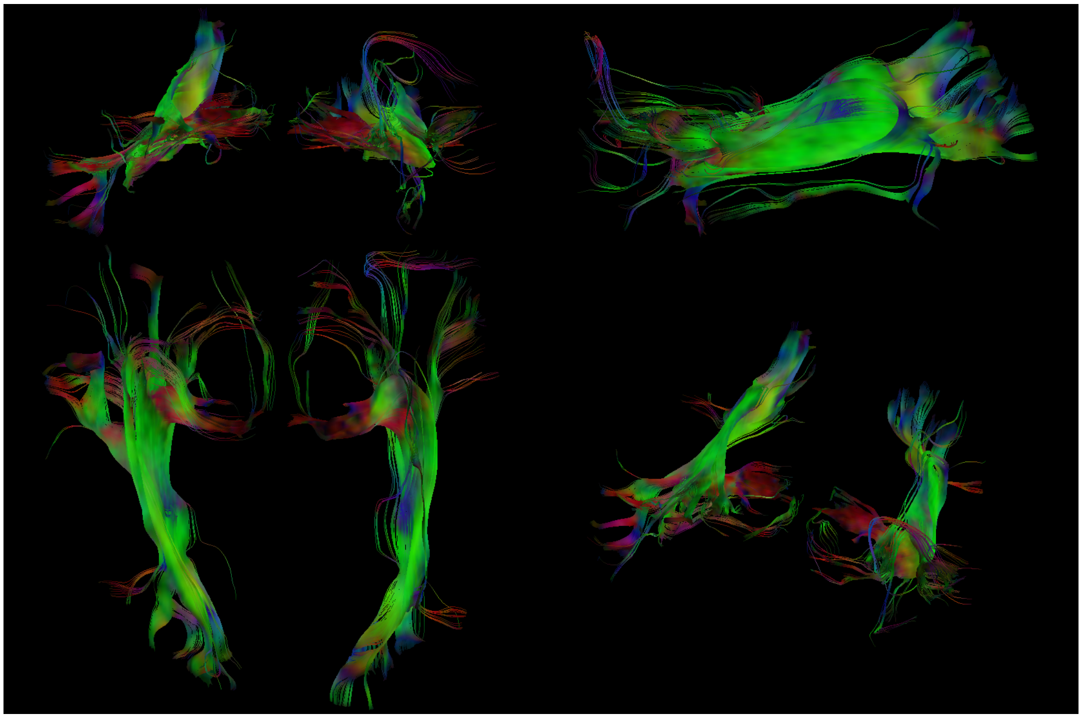
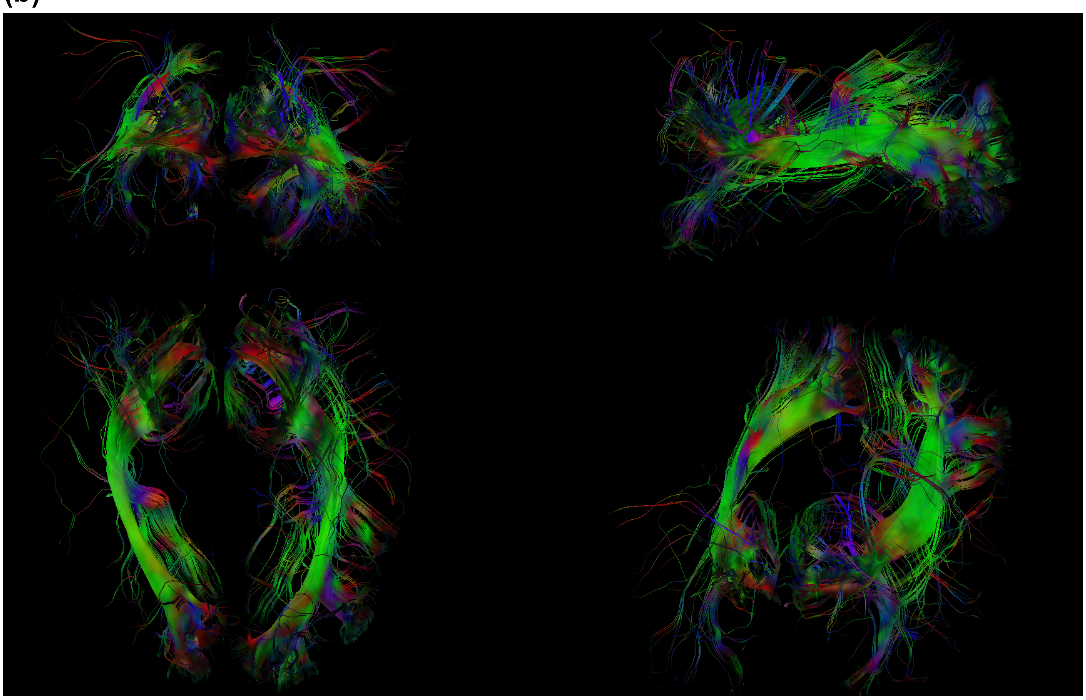


Figure 1: Comparison of seeding region-of-interest (ROI) in the lateral geniculate nucleus (LGN) between standard resolution (top image) and high resolution images. In each image, the right LGN is indicated by cross-hairs.

(a)



(b)



(c)

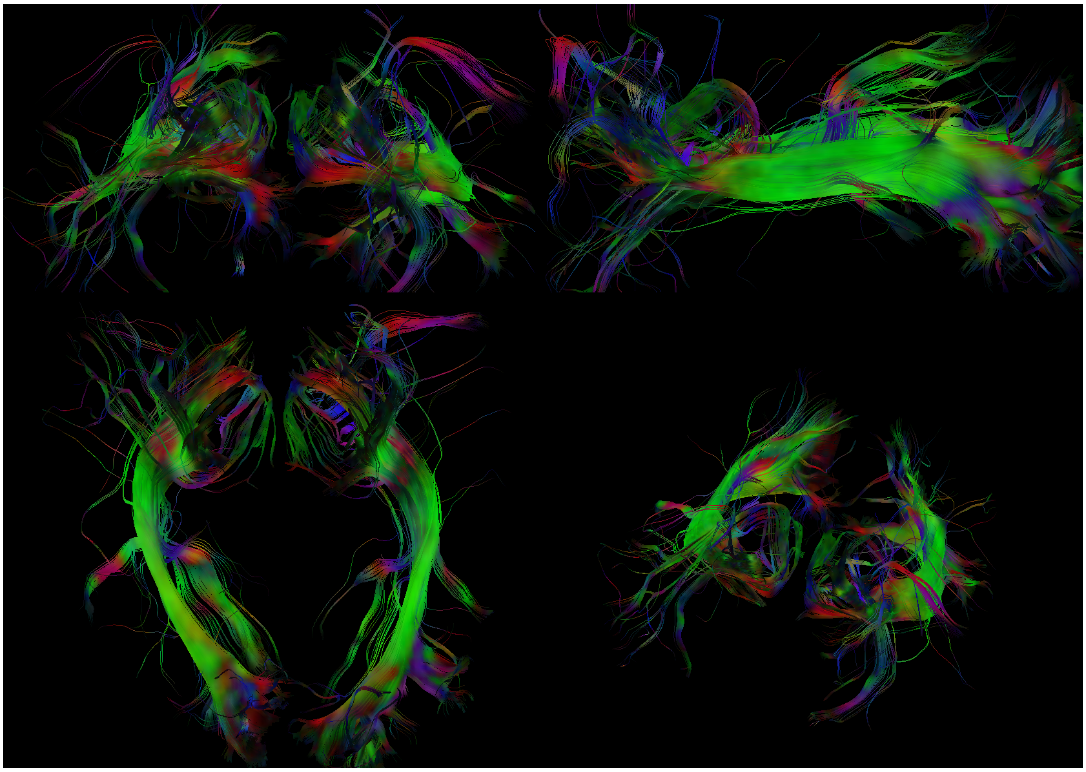
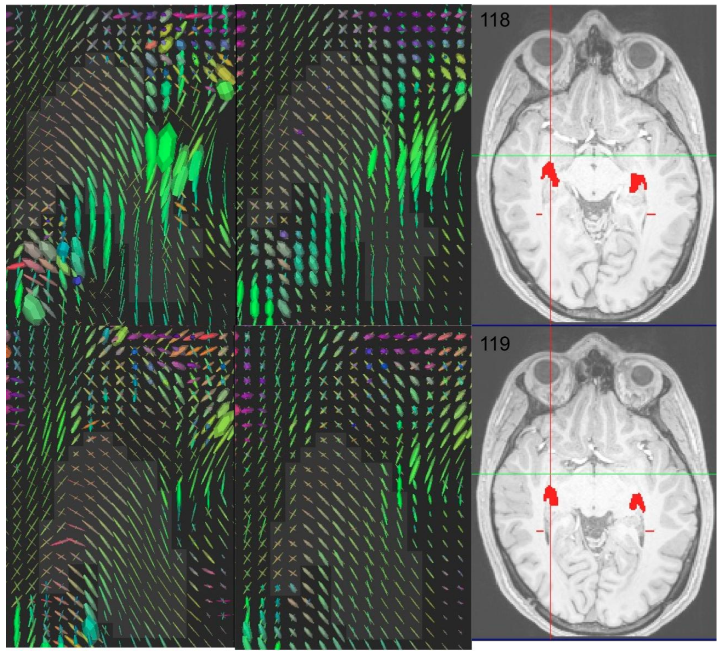


Figure 2: Tractography results in one subject with super resolution reconstruction (SRR) on (a) diffusion tensor imaging (DTI); (b) standard multi-fascicle model (MFM); and (c) MFM after smoothing.

(a)



(b)

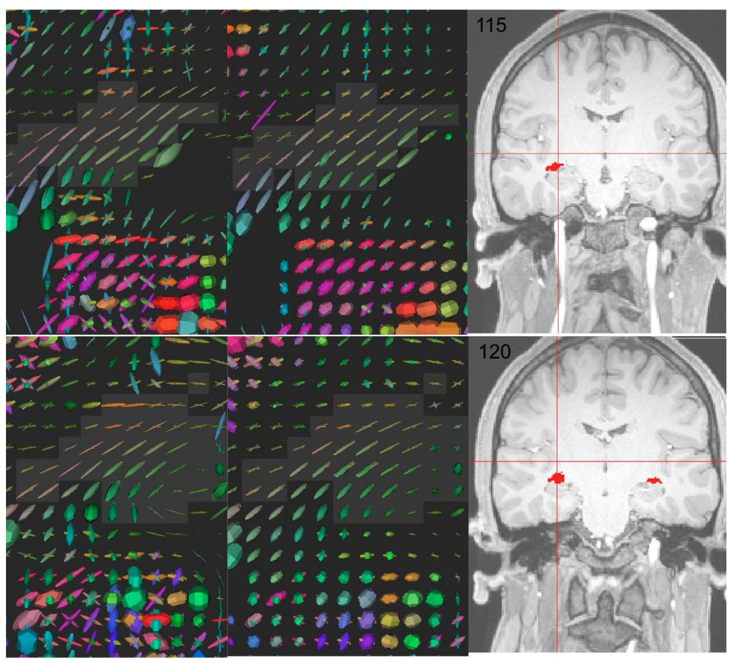


Figure 3: Visual comparison of multi-fascicle model (MFM) estimates before and after Gaussian smoothing in the region-of-interest (ROI) of the lateral geniculate nucleus (LGN), shown in an **(a)** axial and **(b)** coronal plane. Left, axial slices before smoothing. Center, axial slices after smoothing. Right, location on T1W image, with LGN ROI overlaid. Number in top left corner of T1W image indicates slice number in the volume.

References

Benjamin CF, Singh JM, Prabhu SP, Warfield SK. Optimization of tractography of the optic radiations. Hum Brain Mapp. 2014 Feb;35(2):683-97.

Ebeling U, Reulen HJ. Neurosurgical topography of the optic radiation in the temporal lobe. Acta Neurochirurgica. 1988;92:29-36.

Hofer S, Karaus A, Frahm J. Reconstruction and dissection of the entire human visual pathway using diffusion tensor MRI. Front Neuroanat. 2010; 4:15.

Mandelstam SA. Challenges of the anatomy and diffusion tensor tractography of the Meyer loop. AJNR Am J Neuroradiol. 2012;33:1204–1210.

Meyer A. The connections of the occipital lobes and the present status of the cerebral visual affections. Trans Assoc Am Physicians. 1907; 22:7-16.

Piper RJ, Yoong MM, Kandasamy J, Chin RF. Application of diffusion tensor imaging and tractography of the optic radiation in anterior temporal lobe resection for epilepsy: A systematic review. Clin Neurol Neurosurg. 2014;124C:59-65.

Scherrer B, Gholipour A, Warfield SK. Super-resolution reconstruction to increase the spatial resolution of diffusion weighted images from orthogonal anisotropic acquisitions. Med Image Anal. 2012;16(7):1465–1476.

Scherrer B, Warfield SK. Parametric representation of multiple white matter fascicles from cube and sphere diffusion MRI. PLoS One. 2012;7(11):e48232.

Taquet, M., Scherrer, B., Benjamin, C., Prabhu, S., Macq, B., & Warfield, S. K. (2012, May). Interpolating multi-fiber models by Gaussian mixture simplification. In Biomedical Imaging (ISBI), 2012 9th IEEE International Symposium on (pp. 928-931). IEEE.

Taquet, M., Scherrer, B., Commowick, O., Peters, J. M., Sahin, M., Macq, B., & Warfield, S. K. (2014). A mathematical framework for the registration and analysis of multi-fascicle models for population studies of the brain microstructure. Medical Imaging, IEEE Transactions on, 33(2), 504-517.

Wiebe S, Blume WT, Girvin JP, Eliasziw M. A randomized, controlled trial of surgery for temporal-lobe epilepsy. N Engl J Med. 2001;345:311–318

Winston GP, Daga P, White MJ, Micallef C, Miserocchi A, Mancini L, Modat M, Stretton J, Sidhu MK, Symms MR, Lythgoe DJ, Thornton J, Yousry TA, Ourselin S, Duncan JS, McEvoy AW. Preventing visual field deficits from neurosurgery. Neurology. 2014. pii: 10.1212/WNL.0000000000000685. [Epub ahead of print]

Wu W, Rigolo L, O'Donnell LJ, Norton I, Shriver S, Golby AJ. Visual pathway study using in vivo diffusion tensor imaging tractography to complement classic neuroanatomy. Neurosurgery. 2012;70(OPERATIVE):ons145–ons156.

Yogarajah M, Focke NK, Bonelli S, Cercignani M, Acheson J, Parker GJM, Alexander DC, McEvoy AW, Symms MR, Koepp MJ, Duncan JS. Defining Meyer's loop-temporal lobe resections, visual field deficits and diffusion tensor tractography. Brain. 2009;132(6): 1656–1668.