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Presurgical simulation for neuroendoscopic procedures: Virtual study of the integrity of neurological pathways using diffusion tensor imaging tractography

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Abstract

Background: White matter (WM) transgression is an unexplored concept in neuroendoscopy. Diffusion tensor image (DTI) tractography could be implemented as a planning and postoperative evaluation tool in functional disconnection procedures (FDPs), which are, currently, the subject of technological innovations. We intend to prove the usefulness of this planning method focused on the assessment of WM injury that is suitable for planning FDPs.

Methods: Ten cranial magnetic resonance studies (20 sides) without pathological findings were processed. Fascicles were defined by two regions of interest (ROIs) using the fiber assignment method by the continuous tracking approach. Using three-dimensional (3D) simulation and DTI tractography, we created an 8-mm virtual endoscope and an uninjured inferior fronto-occipital fasciculus (IFOF) from two ROIs. The injured tract was generated using a third ROI built from the 3D model of the intersection of the oriented trajectory of the endoscope with the fascicle. Data and images were quantitatively and qualitatively analyzed.

Results: The average percentage of the injured fibers was 32.0% (range: 12.4%–70%). The average intersected volume was 1.1 cm^3 (range: 0.3–2.3 cm^3). Qualitative analysis showed the inferior medial quadrant of the inferior fronto-occipital fasciculus (IFOF) as the most frequently injured region. No hemispherical asymmetry was found ($P > 0.5$).

Conclusion: DTI tractography is a useful surgical planning tool that could be implemented in several endoscopic procedures. Together with a functional atlas, the presented technique provides

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Conflicts of interest
There are no conflicts of interest.

a noninvasive method to assess the potential sequelae and thus to optimize the surgical route. The suggested method could be implemented to analyze pathological WM fascicles and to assess the surgical results of FDP such as hemispherotomy or amygdalohippocampectomy. More studies are needed to overcome the limitations of the tractography based information and to develop more anatomically and functionally reliable planning systems.

Keywords

Diffusion tensor imaging; endoscopy; epilepsy; simulation; transgression; white matter

Diffusion tensor magnetic resonance image (MRI) tractography is a useful imaging tool that allows the generation of three-dimensional (3D) maps of white matter (WM) fibers of the brain.[1,2] Understanding the structure, function, and pathways of WM is a key subject in the present and future of neurosurgery. Despite its limitations (e.g., low reliability, experimenter-expectancy effect, and confirmation bias), diffusion tensor image (DTI) tractography is the most widely used method to assess WM tracts in clinical practice. Tractography is nowadays used for preoperative planning and postoperative evaluation of functional and oncologic procedures.[3]

Neuroendoscopy has gained wide acceptance as a minimally invasive surgical technique in the treatment of many neurosurgical procedures. The ability to provide access to deep cerebral structures with minimal tissue disruption has expanded its applications. In this sense, there exists an increasing interest in discovering newer applications of neuroendoscopy, such as epilepsy surgery.[4,5] Although the technique is safe and well-validated, neuroendoscopy does lead to a variable degree of cerebral transgression that is often disregarded.

In the current preoperative assessment paradigm that provides a great availability of preoperative planning technologies (neuronavigation, virtual reality, and WM reconstruction), neurosurgeons are urged to anticipate the potential sequelae of surgical trajectories, including the disruption of subcortical connectivity. However, there is still a lack of clinical experience related to most of the classically defined neuroendoscopic trajectories, which rely mainly on avoidance of cortical function and surface vessel injury.[6]

In this study, we evaluate the utility of a DTI tractography method to assess the potential WM disruption provoked by an endoscope aimed at the temporal horn. We intend to optimize this recently described approach suggested for functional disconnection procedures (FDPs).[7] We describe a preoperative 3D planning and calculation process to quantify WM transgression and improve the surgical route selection.

Methods

Ten cranial magnetic resonance studies (20 sides/trajectories) were collected and anonymized from the database of the Department of Radiology at our institution. The inclusion criterion was the absence of structural abnormalities in the central nervous system. Right and left hemispheres were processed and analyzed by one of the authors (S.G.).

The technique currently being decribed has been recently developed by our team and is suitable for the conventional endoscopic procedures.[8] In this study, we sought to assess the transgression of WM tracts provoked by an endoscope that was utilized for the functional disconnection of mesial temporal (MT) structures. During the development of the reported technique, we tested different endoscopic trajectories (which were modifications of the trajectory implemented for endoscopic third ventriculostomy)[8] and WM fascicles such as the inferior fronto-occipital fasciculus (IFOF), the inferior longitudinal fasciculus, cingulum, corpus callosum, and corona radiata. Finally, we decided to fous upon in the study the disruption of the IFOF produced by an 8-mm endoscope with an occipitotemporal trajectory, aimed at the ipsilateral temporal horn.[7] The DTI reconstruction of other fascicles involved in MT circuits, such as the fornix or the cingulum, have also been studied by other authors.[8] However, as their tractographic rendering is still controversial,[9] we decided not to include them in our study.

Data acquisition and diffusion tensor imaging processing

Image data were acquired on a 3-Tesla magnetic resonance unit (Trio Tim, Siemens, Erlangen, Germany) with an eight-channel phase array coil. Sagittal 3D T1-weighted gradient echo sequence was acquired as an anatomical reference; TR (repetition time) 12 ms, TE (echo time) 4.68 ms, flip angle 15°, field of view (FOV) 354 × 256 mm, matrix size 256 × 256 mm, and voxel size 1 × 1 × 1 mm.

DTI was obtained with an echo planar imaging(EPI) two-dimensional sequence in the axial plane; TR 6900 ms, TE 90 ms, and flip angle 90°. Two b-values were obtained (0 and 1000 s/mm^2) in 30 directions. The FOV was 240 mm, matrix size 100 × 100, and voxel size 2.4 × 2.4 × 2.4 mm.

DTI data were processed using StealthViz (TM) Planning Station software (Medtronic®, Minneapolis, MN, USA). The DTI and T1 echo planar images were coregistered to create fractional anisotropy (FA) and directionally encoded color (DEC) maps merged with an MRI sequence showing clear anatomical references. To minimize the software limitations during the merging and coregistering process, every MRI sequence was acquired in the same session.

White matter tract reconstruction

The tractography parameters were defined by consensus[10] [Table 1]. Fascicles were generated using the deterministic method “fiber assignment by continuous tracking” (FACT). Fascicles were built defining voxels, or regions of interest (ROIs), that represented known points of unavoidable passage in the trajectory of the tract. Based on the atlas by Catani and Thiebaut de Schotten,[11] at least two ROIs were defined to create the fascicle.

The IFOF connects the inferior frontal cortex to the posterior–inferior part of the temporal lobe and to the part of occipital lobe above the calcarine sulcus. The frontal ROI was defined around the WM of the anterior floor of the extreme capsule, between the insula and the lenticular nucleus. The occipital ROI was defined around the WM tracts of the occipital lobe, near the joint of body of the corpus callosum with the splenium at the mid-sagittal line and posterior to the tip of the occipital horn.[11]

Creation of the endoscopic volumetric model

A 3D virtual model of an 8-mm endoscope (considering the maximal diameter of the endoscope's sheath) was created using segmentation tools from StealthViz (TM) Planning Station.[8] A diameter of 8 mm was set as the size of round-shaped brush tool in the segmentation window [Figure 1a and b]. This defined area was extended to all the slices in the axial plane to create a cylindrical object [Figure 1c] representing a virtual endoscope at 1:1 scale with the anatomical 3D model.

Coregistering the endoscope and the reference magnetic resonance image

After a preliminary study of the interaction of different tracts and trajectories, in this study, we decided to focus on a novel approach that could be useful in FDP: a transventricular endoscopic trajectory to the temporal horn of the lateral ventricle. As described by the authors, the rostral–caudal axis of the temporal horn defines the surgical trajectory from an entry point located 2.7 cm lateral and 5.6 cm superior to the inion[7] [Figure 1d]. This orientation was set prior to merging the anatomical MRI (sagittal 3D T1 echo planar image) with the MRI study containing the endoscope volume. Once the trajectory was manually adjusted, both MRI volumes were coregistered and merged. The same process was repeated for both hemispheres.

Assessment of fascicle transgression

Our main goal was to calculate the absolute number, percentage, and volume of fibers that could be damaged in a specific endoscopic approach. The merged volume containing the anatomical study and the oriented endoscope were displayed in the fusion mode within the DEC study harboring the IFOF [Figure 1e]. The 3D model of the fascicle and the endoscope were activated by clicking on the multiplanar reconstruction and surface boxes. Then, the endoscope volume was selected as a gray image in the *segmentation* window. Surfing through the images of this study, we found the fascicle mask overlapping the endoscope mask. Using the *magic wand* tool, after adjusting the threshold, we were able to select the areas where the endoscope passed across the fascicle [Figure 1f]. Thus, a new 3D volume *intersection* was created. The following rendering options, *all slices*, *absolute values*, *fill interior* (creates an area within the defined shape), and *same 3D object only* (creates a volume from a given area), were activated.

Back on the *view* window, IFOF was generated, as described in previous reports.[8,11] Next, the IFOF was modified with a third ROI, the *intersection*, defined by the volume of the endoscope intersecting the uninjured fascicle. Thus, a new fascicle (injured fibers) representing the fibers crossing the frontal ROI, the *intersection*, and the occipital ROI was obtained [Figure 2a–f].

The software provides statistical information for every fascicle or object selected: the number of fibers, as well as their area, volume, voxels, and so on [Figure 3a]. Quantitative analysis was conducted and expressed in the number of fibers, volume of 3D objects (cm^3), and percentages. Percentages or relative values were prefered to avoid the potential bias intrinsic to the fiber tracking process. The same process was used to calculate the volume transgressed by the endoscope. Images were analyzed to correlate the relative location of the damaged fibers within the uninjured fascicle. The original fascicles were divided into coronal-section quarters to consensually define which quarter was mainly damaged.

To determine statistically significant differences between both hemispheres in terms of the number of fibers or their volume, Wilcoxon matched pair test was implemented. An equal distribution of probabilities in both hemispheres was set as the null hypothesis.

Results

The simulation process was successfully conducted in every subject. The mean time to complete the whole presurgical planning was 11.5 min. The average percentage of injured fibers and intersected volume was 32% (range: 12.4%–70%) and 1.1 cm^3 (range: 0.3–2.3 cm^3), respectively. The qualitative analysis of fascicle transgression revealed that the most frequent region disrupted by the endoscope was the inferior medial quadrant, as expected by anatomical coherence. No significant hemispheric asymmetry was found ($P > 0.5$). Complete statistical assessment is presented in Table 2.

Discussion

In this article, we provide a thorough and stepwise method for assessing WM transgression provoked by a surgical instrument advanced in a given trajectory. We sought to provide a planning and estimation method, focused on the maintenance of WM integrity and the preservation of eloquent areas of the brain, that is suitable for FDPs and for removal of deep seated lesions of the brain. The suggested procedure allowed us to quantify the dimension of the injury and its relative location within a defined fascicle [Figure 3b and c].

There exists a growing interest in the performance of minimally invasive procedures in neurosurgery. Among them, neuroendoscopy plays a paramount role. Regarding complications related to neuroendoscopy, a strong emphasis has been made on planning trajectories to evacuate intraventricular hemorrhages and to resect lesions in periventricular locations, often ignoring the WM transgression that accompanies the procedure.[12,13] Nonetheless, the widespread adoption of more complex presurgical planning methods lead to a better understanding of the intraoperative difficulties and potential risks that are likely to be encountered.

Nowadays, the use of surgical simulation methods in training and planning procedures is becoming widely accepted.[14–18] The main goal of these techniques is to virtually recreate the surgical environment that closely resembles the real-life situation, allowing the surgeon to anticipate future situations in the operating room.[19] The DTI information is currently being integrated in such simulation procedures, mainly to check the extent of resection of different lesions.[20] Our method contributes to enhancing the possibilities of designing minimal-impact surgical trajectories that use ports or endoscopes, by adding objective quantitative information.[8,21] DTI-based tractography is experiencing a great resurgence in the clinical, teaching, and experimental fields.[22–24] Different fiber tracking methods have been validated to assess the anatomical, surgical, and neuropsychiatric disorders that arise due to the WM structural changes.[25–29] In addition, DTI fiber tracking is currently used as a virtual dissector of WM with globally accepted reliability.[30] In this sense, the fascicle integrity, determined by DTI tractography, is considered as a predictor of the preservation of motor function[25] and cerebral connectivity.[31] However, many authors have warned of the superiority of neurophysiologic monitoring, as well as of the need for completing the visual information obtained by DTI with other diffusion parameters such as fractional anisotropy (FA), mean diffusivity, and apparent diffusion coefficient (ADC).[25,32]

Recently, neuroendoscopy has been utilized for carrying out functional disconnection procedures for the treatment of epilepsy.[33] The feasibility, potential efficacy, and safety of endoscopic hemispherotomy, callosotomy, hippocampectomy, amygdalectomy, and other functional disconnection procedures have been anatomically assessed.[4,33–36] Nowadays, tractography is being implemented as a preoperative planning and postoperative evaluation tool in epilepsy surgery.[28,37] Thus, the information provided by DTI maps is used to approach those cases in whom epilepsy recurs or persists after a hemispherotomy.[31] However, no previous method has permited the qualitative and quantitatively assessment of the location of a defined target and the extent of disruption needed to treat a drug-resistant epileptic syndrome. The currently suggested method enables this dual evaluation and might be adapted for several surgical approaches. As shown in Figure 4, the lesion provoked by the endoscope in IFOF was spatially rendered to be analyzed and located within the virtual structures created. The IFOF is related to speech, reading, visual recognition, and picture naming.[38–40] Combining qualitative and quantitative analyses together with the information contained in the functional atlases, it is possible to anticipate potential sequelae with a reasonably reliable noninvasive system. The suggested method allowed the quantitative data to be statistically compared. Relying on the collected information, we could redefine our trajectory to avoid areas of maximal eloquence and minimize WM transgression, maintaining the same target.

The information provided by the software varied appreciably from patient to patient [Table 2]. This wide range of variation might be due to the sum of the following factors: Changes in MRI acquisition, data processing, brain atrophy, differences in anatomical landmarks, morphological differences (size of the ventricles, direction of the rostral–caudal axis of the temporal horn), and so on. In our study, we sought to alleviate the impact of these factors by presenting relative results. Nonetheless, many efforts are being made to address the limitations of DTI fiber tracking by fiber assignment by continuous tracking (FACT).[41,42]

Among the main conceptual DTI limitations is the assumption that the direction of the principal axis of a diffusion ellipsoid aligns with the orientation of a single fiber. The high angular resolution diffusion and constrained spherical deconvolution might contribute to improving the precision of DTI information.[43,44] In addition, techniques such as the streamsurface[45] and the tensorline[46] might offer more biologically reliable fiber patterns.

Probabilistic fiber tracking algorithms are aimed to reduce the effects of noise, partial volume effect, and subjectivity attributable to FACT.[44] The main limitation of the probabilistic method is the long image acquisition time. This fact might preclude its clinical use in general neurosurgery departments.[10] Based on residual resampling or bootstrapping, some authors have achieved less biased DTI data with more reasonable acquisition times. Thus, Mandelli *et al*., assessed the reliability of DTI tractography compared with the intraoperative electrophysiological data.[32] However, due to better availability, reproducibility, and reasonable reliability, the deterministic FACT process enhanced by anatomical knowledge, and a multiple ROI approach, as used in our procedure, remain the most mainstream tractography methods.[19]

In this study, we have assumed a reasonable accuracy of the rendering and merging tools of the software. However, though widely used for clinical or investigational purposes,[26,47] this software harbors some limitations: 3D rendering is constrained by the size of voxels, and precision errors of the merging process might accrue throughout the simulation process. 3D rendering could be improved upon by implementing more sophisticated softwares. Merging limitations were addressed by acquiring anatomical and DTI sequences in the same MRI device and session.

The described technique should be understood as a virtual simulation method suitable for many neurosurgical procedures and available for many departments worldwide. The suggested technique might allow the simulation of different instruments, trajectories, and 3D targets. However, the presented method still requires validation either through anatomical dissection using Klinger's WM preparation,[48] postoperative DTI, or by means of more cumbersome techniques such as MRI elastography.[49]

Conclusion

WM tractography is a useful tool to improve the neuroendoscopic preoperative planning. The proposed technique allows the simulation of different trajectories tailored to a specific patient, and permits the utilization of different sized endoscopes or ports. This signifies a step further in personalized medicine and neurosurgical simulation. Indeed, this kind of assessment should become mandatory to evaluate the safety profile of a novel approach, such as the use of neuroendoscopy in functional neurosurgery. Further studies using postsurgical DTI should be implemented to confirm the predicted grade of injury of the involved tracts. Increasing the availability and applications of presurgical planning methods that help to preserve the WM tracts will improve the reliability and understanding of the procedure.

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Key Messages:

Usual neuroendoscopic trajectories were initially designed on the basis of cortical eloquence and superficial vasculature. White matter connectivity has often been disregarded as a major element to consider when assessing neuroendoscopy’s safety. The trajectory of surgical instruments and white matter fascicles can be simulated to evaluate their interaction. Modern neuronavigation and DTI softwares allow the evaluation of white matter transgression both quantitatively and qualitatively. The presented method and results require clinical and/or neurophysiological validation.

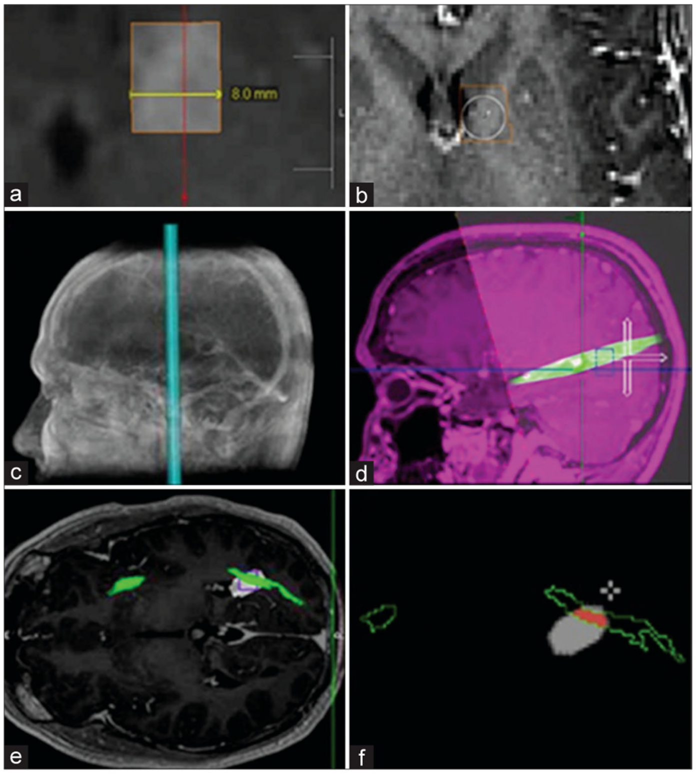


Figure 1:

(a and b) An 8-mm circular shape model of the virtual endoscope section was created in any random anatomical location of the simulation system. (c) Projection of circular shape to generate a cylinder. (d) Coregisteration with baseline magnetic resonance image, diffusion tensor imaging study, and oriented virtual endoscope. (e) Axial view of the inferior fronto-occipital fascicle and virtual endoscope. (f) Segmentation of the intersection object that will be used as intermediate region of interest to define the fibers injured by the virtual endoscope

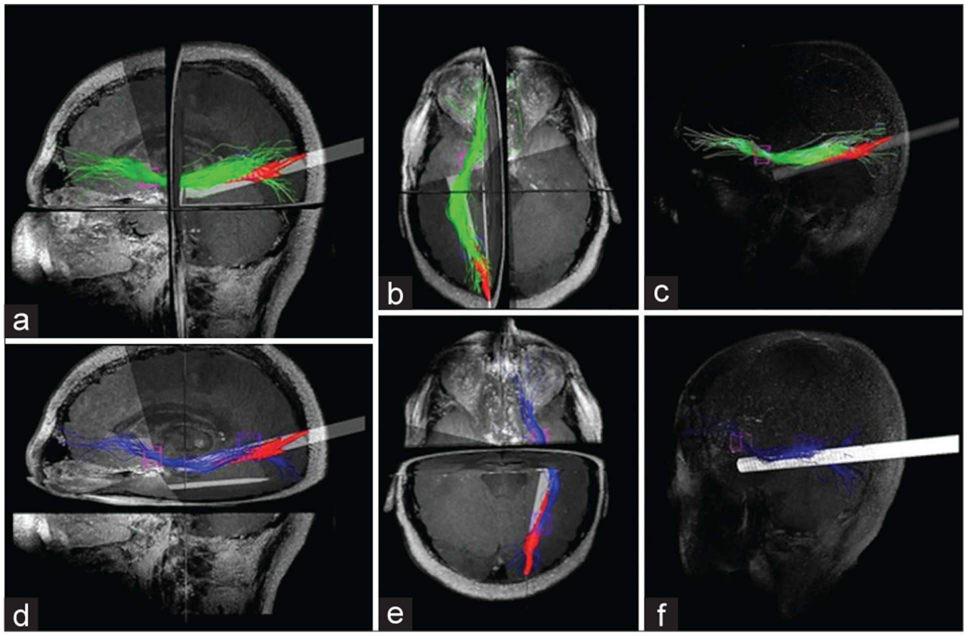
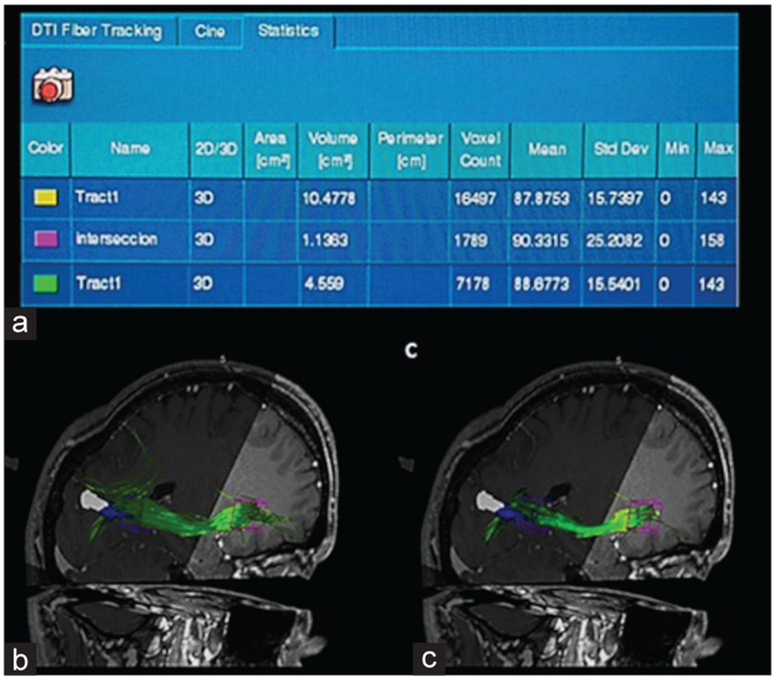


Figure 2:

(a-c) Left-side triplanar view of the whole inferior fronto-occipital fascicle fibers (green) and intersected fibers (red). (d-f) Right side triplanar view of the whole inferior fronto-occipital fascicle fibers (blue) and intersected fibers (red). Qualitative analysis



Color	Name	2D/3D	Area [cm²]	Volume [cm³]	Perimeter [cm]	Voxel Count	Mean	Std Dev	Min	Max
🟨	Tract1	3D		10.4778		16497	87.8753	15.7397	0	143
🟪	Interseccion	3D		1.1363		1789	90.3315	25.2082	0	158
🟩	Tract1	3D		4.559		7178	88.6773	15.5401	0	143

Figure 3:

(a) Statistical information provided by the workstation. (b) Anterolateral view, multiplanar reconstruction of the uninjured inferior fronto-occipital fascicle generated with two regions of interests, frontal and occipital. (c) Same view depicting the injured fibers. Fascicle built after adding a third region of interest, the intersection, represented in both pictures in blue

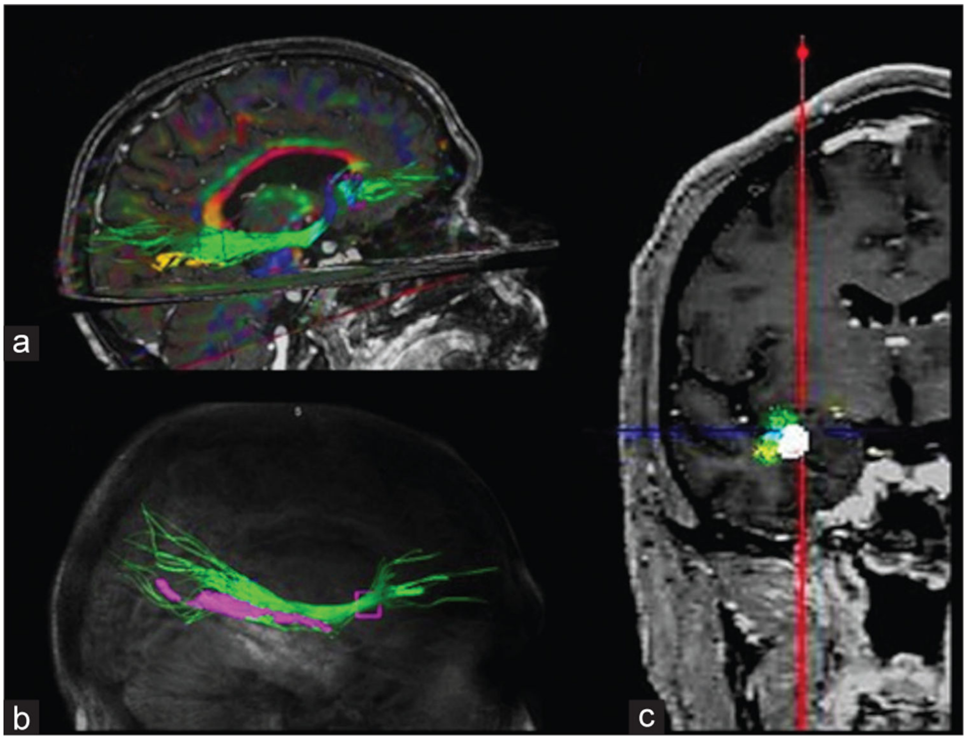


Figure 4:

(a) Multiplanar reconstruction representing the inferior fronto-occipital fascicle and the volume corresponding to the intersection (yellow).

(b) Three-dimensional reconstruction depicting the inferior fronto-occipital fascicle and its intersection with the endoscope in pink. (c) Coronal view showing how the endoscope injures the inferior fronto-occipital fascicle in its inferior medial aspect

Table 1:

Parameters used for tractography and three-dimensional model criterion used for building the fascicles

Tractography parameters	
Item	**Value**
Maximum deviation angle	45°
FA threshold	0.1
Seed density	1.00
Minimal fiber length	10
3D model bundle building criterion	
3D object distance	1.00
MPR line depth	3

FA=Fractional anisotropy; 3D=Three-dimensional; MPR=Multiplanar reconstruction

Table 2:

Results, in terms of fibers and volume, of transgression of the inferior fronto-occipital fascicle

Patient	Side	Fibers UT	V. UT	V. IT	Fibers DT	VD_t	Percentage fibers DT	Percentage V. DT	Injured area
60 y F	R	256	19.8	1.2	40	5.4	15.6	27.2	IM
	L	232	17.9	1.1	36	5.1	15.5	28.5	IM
66 y F	R	100	16.4	2.3	70	13.8	70	84	Medial
	L	104	17.1	1.9	58	12.5	55.8	73.1	IM
63 y F	R	104	14.6	1.2	50	9.6	48.1	65.7	IM
	L	115	15.4	1.1	48	9.1	41.7	59.1	IM
62 y M	R	112	14.9	0.3	14	4.8	12.5	32.2	IM
	L	105	12.3	0.4	13	4.7	12.4	38.2	Medial
52 y M	R	73	11.9	1.7	30	4.9	41.1	54.5	IM
	L	78	11.2	1.5	26	5.1	33.3	45.5	IM
32 y M	R	75	11.4	0.9	34	5.1	45.3	44.7	Inferior
	L	82	11.8	0.7	30	5.4	36.6	45.7	IM
37 y M	R	84	10.5	1.1	21	4.6	25	43.8	IM
	L	75	10.1	1.2	20	4.8	26.6	47.5	IM
54 y F	R	107	16.5	0.9	32	7.5	29.9	45.5	IM
	L	100	14.9	1.1	29	7.2	29	48.3	Medial
50 y M	R	56	10.9	0.3	14	4.3	25	39.4	IM
	L	58	10.7	0.5	16	4.6	27.6	43	Inferior
33 y F	R	111	19.2	0.5	29	8.4	26.1	43.8	IM
	L	115	19.6	0.7	31	8.6	27	43.9	IM
						Average			
51 y		107.1	14.3	1.1	32.0	6.8	32.2	47.7	

DT=Damaged tract; F=Female; M=Male; IM=Inferior medial; It=Intersection; L=Left; R=Right; UT=Uninjured tract; V=Volume; y=Years