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# Tractography of the amygdala and hippocampus: anatomical study and application to selective amygdalohippocampectomy

## Laboratory investigation

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*Object*. The aim of this study was to evaluate, using diffusion tensor tractography, the white matter fibers crossing the hippocampus and the amygdala, and to perform a volumetric analysis and an anatomical study of the connections of these 2 structures. As a second step, the authors studied the white matter tracts crossing a virtual volume of resection corresponding to a selective amygdalohippocampectomy.

*Methods*. Twenty healthy right-handed individuals underwent 3-T MR imaging. Volumetric regions of interest were manually created to delineate the amygdala, the hippocampus, and the volume of resection. White matter fiber tracts were parcellated using the fiber assignment for continuous tracking tractography algorithm. All fibers were registered with the anatomical volumes.

*Results*. In all participants, the authors identified fibers following the hippocampus toward the fornix, the splenium of the corpus callosum, and the dorsal hippocampal commissure. With respect to the fibers crossing the amygdala, the authors identified the stria terminalis and the uncinate fasciculus. The virtual resection disrupted part of the fornix, fibers connecting the 2 hippocampi, and fibers joining the orbitofrontal cortex. The approach created a theoretical frontotemporal disconnection and also interrupted fibers joining the temporal pole and the occipital area.

*Conclusions*. This diffusion tensor tractography study allowed for good visualization of some of the connections of the amygdala and hippocampus. The authors observed that the virtual selective amygdalohippocampectomy disconnected a large number of fibers connecting frontal, temporal, and occipital areas.
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**Key Words** • **diffusion tensor tractography** • **amygdala** • **hippocampus** • **epilepsy surgery**

The amygdala and hippocampus are involved in several neurological disorders including mesial temporal lobe epilepsy. Resection of these structures has come to be recognized as an effective and safe treatment for epilepsy.[36,45] Knowledge of the connections of the amygdala and hippocampus with the other brain structures allows for understanding the pattern of spreading of the seizures, the functional and cognitive outcome of the disease, and the possible consequences for surgical treatment. While much is known about these brain regions and their connections from classic anatomical studies in humans,[13,16,33] new techniques using brain imaging are emerging that may complement this knowledge. For example, quantitative MR imaging–based volumetric studies have begun to provide important data concerning the anatomy of the mesial temporal structures in normal and pathological conditions,[4,10] although the volumetric approach does not yield crucial information about the connections of specific brain structures.

Diffusion tensor tractography is a novel MR imaging method that provides 3D reconstructions of white matter tracts characterizing the diffusion properties of water.[3,30,31] A large number of papers have reported DTT studies of well-known anatomical tracts in healthy individuals[1,14,42] and also in pathological conditions.[19,27,29] Some studies have focused on the relationship between mesial temporal lobe structures and anatomical structures such as the temporal stem,[26] the optic radiations,[46] or the inferior temporooccipital fasciculus.[6] Concha et al.[10] used tractography to study the limbic system in healthy individuals, and Pugliese et al.[40] recently reported a study of the limbic system in pathological conditions. Tractography studies of the connections of the parahippocampal gyrus[37,52] have also been reported. However, to our knowledge, none of these studies have examined the global volume of all fiber tracts that innervate the amygdala and hippocampal structures. Inclusion of tracts that pass through these structures, in addition to the characterization of the

*Abbreviations used in this paper:* DTT = diffusion tensor tractography; MNI = Montreal Neurological Institute; ROI = region of interest; selAH = selective amygdalohippocampectomy.

afferent and efferent tracts, would provide a more complete evaluation of the possible anatomical connections. A comprehensive parcellation of all white matter tracts crossing the amygdala and hippocampus may provide for an evaluation of the possible disruptions that may occur following a specific surgical procedure, such as an selAH, to remove these structures. Using DTT, we aim to evaluate the volume of the fiber bundles crossing the amygdala and hippocampus in healthy individuals and to visually describe the major fasciculi in the system.

In this study, we will investigate the use of DTT to characterize the location and volume of white matter pathways of the amygdala and hippocampus in 20 right-handed healthy individuals. As a second step, we will study the white matter tracts crossing the corridor performed during a virtual lateral transcortical approach to mesial temporal lobe structures to visualize and estimate which tracts would be disrupted after an selAH.

## Methods

### *Study Participants*

Twenty healthy right-handed individuals, 12 men and 8 women, without any history of neurological or psychiatric disorders, were included in this study. The age range of the participants was 19–51 years (mean 25.15 ± 7.47 years [± SD]). Information regarding age and neurological and psychiatric conditions was obtained directly from the individuals. The study was approved by the MNI Research Ethics Board, and written informed consent was obtained for all participants.

### *Magnetic Resonance Imaging Acquisition Protocol*

All individuals underwent imaging using a 3-T Trio MR imaging system (Siemens Medical Systems) at the MNI. A 12-channel phased-array head coil was used for radiofrequency transmission and reception of the radiofrequency transmission and signal reception. For each participant, we obtained a 1-mm isotropic resolution T1-weighted anatomical volume using a 3D spoiled gradient echo acquisition sequence (TR 2.3 msec, TE 2.98 msec). A sequence involving 64 diffusion-encoding directions (b = 1000 seconds/$m^2$, TE 90 msec, TR 10 seconds, and GRAPPA [generalized autocalibrating partially parallel acquisitions] parallel reconstruction) was used to acquire 2 diffusion weighted volumes comprising 65 contiguous 2-mm slices each. Diffusion encoding was achieved using a single-shot spin echo planar imaging sequence with twice-refocused balanced diffusion-encoding gradients.

### *Image Processing*

The 2 diffusion weighted raw data sets were registered using a mutual information–based algorithm[28] to remove image misregistration from echo planar–induced image distortion and motion. The diffusion orientation distribution function was calculated using spherical deconvolution reconstruction[47] at 64 isotropically spaced directions generated using an electrostatic repulsion algorithm. The diffusion tensor was also calculated at each voxel to generate fractional anisotropy and mean diffusivity maps.

### *Tracking Algorithm*

Estimates of axonal projections were computed by fiber assignment with continuous tracking using the fiber assignment for continuous tracking algorithm.[30,44] Tracking was initialized at all voxels in the brain, and fibers that crossed the ROI were retained. Projections were initiated in the anterograde and retrograde directions according to the direction of the principal eigenvector in each voxel. We selectively tracked voxels with fractional anisotropy values that exceeded 0.25 and ensured that the line of propagation deviated no more than 60°. All ROIs were manually delineated on the coregistered native T1-weighted volume. Visualization of the fibers was completed using in-house software developed at the MNI Brain Imaging Center.

### *Volumetric ROIs*

Volumetric ROIs were manually created using the interactive visualization software package, DISPLAY, developed at the Brain Imaging Center of the MNI. This program allows simultaneous viewing of MR images in coronal, horizontal, and sagittal orientations, which is known to increase the accuracy for delineation of the mesial temporal structures.[39]

### *Anatomical Study*

For each study participant, the amygdala and hippocampus were delineated on the native-space T1-weighted MR image on a voxel-by-voxel basis by a trained expert, according to previous published studies.[4,48] Great care was taken not to include any voxels corresponding to white matter outside the ROI to increase the precision of the study by reducing the number of false-positive results. Thus, as an example, we carefully excluded voxels that could be classified as belonging to the hippocampus and also to the adjacent parahippocampal white matter. Using the same selection criteria, we took into account partial volume effects by removing voxels that could correspond to the very mesial part of the hippocampal head because of the proximity of the crus cerebri and the potential artifact of the pyramidal tract.

### *Surgical Study*

To visualize which fibers would be disrupted after an selAH we created a virtual lesion in the temporal lobe. Two ROIs were delineated: one corresponded to the volume of resection of the mesial structures and the other corresponded to the surgical lateral transcortical approach. The 2 ROIs were created in 1 individual according to the senior author's usual procedure for selAH.[35] The volume of resection included the amygdala and the anterior third of the hippocampus. The approach was lateral transcortical across the second temporal gyrus toward the temporal horn of the lateral ventricle and the mesial structures (Fig. 1).

### *Rating Reliability Assessment*

The MR volumes of 5 participants were randomly selected for analysis of interrater and intrarater reliability.[43]

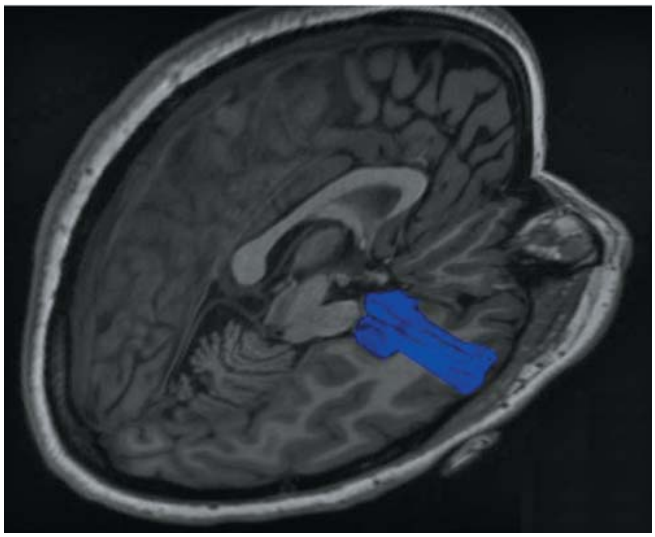

FIG. 1. Three-dimensional reconstruction of the virtual resection overlayed on an axial T1-weighted MR image. The *blue area* represents the surgical corridor across the second temporal gyrus in combination with the volume of resection that includes the amygdala and the anterior third of the hippocampus.

In these 5 volumes, the amygdala and the hippocampus were segmented by 2 trained raters (S.C. and K.M.). Interrater reliability coefficients were calculated assuming that the 2 raters were the only raters of interest. Intrarater reliability coefficients were calculated from 5 subsequent segmentations of the volume for one individual by one rater (S.C.). Both raters were blind with regard to age and sex of the individual, but not to hemisphere.

*Statistical Analysis*

The nonparametric Mann-Whitney U-test was used to evaluate left and right symmetry of the volumes of the amygdala and the hippocampus and their corresponding fibers. A Spearman correlation analysis was performed to show if the volumes of amygdala and/or hippocampus correlated with their efferent fibers on each side. A probability value $< 0.05$ was considered statistically significant (SPSS version 14.0, SPSS, Inc.).

## Results

As shown in Table 1, the results of the calculations for reliability assessment revealed high coefficients of agreement, ranging from 0.88 to 0.94.

*Volumetric Analysis*

*Volume of the Structures and Fibers*. The mean values of the volume of the amygdala, hippocampus, and their related fibers tracts are shown in Table 2. Comparison between corresponding left and right volumes of the 2 structures and their related tracts did not demonstrate any statistical difference (Table 3).

*Correlations Between Volume of Structures and Volume of Fibers*

Correlations Between the Volumes of Structures. Left and right amygdala volumes were correlated ($r = 0.471$; $p = 0.03$; 20 individuals) as were left and right hippocampal volumes ($r = 0.874$; $p \leq 0.001$; 20 individuals). None of the selected ROI volumes were correlated with cerebral volume.

TABLE 1: Interrater and intrarater intraclass reliability coefficient*

| | Intraclass Reliability Coefficient | | | |
|---|---|---|---|---|
| Rater | LA | RA | LH | RH |
| intrarater | 0.94 | 0.92 | 0.89 | 0.90 |
| interrater | 0.92 | 0.90 | 0.91 | 0.88 |

* LA = left amygdala; LH = left hippocampus; RA = right amygdala; RH = right hippocampus.

Correlations Between the Volumes of Structures and Their Related Fibers. A strong correlation was found between the volume of the amygdala and the volume of fibers crossing the amygdala, both on the right ($r = 0.565$; $p = 0.009$; 20 individuals) and on the left ($r = 0.609$; $p = 0.004$; 20 individuals) sides. By contrast, no correlation was observed for the hippocampus and its related fibers, neither on the left nor on the right side.

Correlations Between the Volumes of Fibers. The volume of fibers crossing the right amygdala was correlated with the volume of fibers crossing the left amygdala ($r = 0.620$; $p = 0.04$; 20 individuals). In the same way the volume of fibers crossing the right hippocampus was correlated with the volume of fibers crossing the left hippocampus ($r = 0.826$; $p \leq 0.001$; 20 individuals) (Table 4).

*Anatomical Study*

*Tractography of Hippocampus*. We observed a common pattern of fibers crossing the hippocampus in which the shape was constant in every participant (Fig. 2). Those fibers followed the hippocampus itself toward the crus fornicis and the body of the fornix in the internal part of the lateral ventricle (Fig. 3). The connections between the 2 hippocampi appear to follow 2 main pathways: the splenium of the corpus callosum (Fig. 4) and the dorsal hippocampal commissure located inferiorly to the callosal fibers (Fig. 5). In some individuals, callosal fibers coming from the right and left hippocampus seem to originate predominantly from one side (Fig. 2). Corticohippocampal connections are not consistently observed in each patient. We mainly identified fibers joining the occipital areas (Fig. 2), and we did not identify any fibers joining the neocortical temporal areas or the frontal area. We also observed fibers directly connecting the hippocampus to the brainstem in the region of the mesencephalon and pons (Fig. 3).

*Tractography of Amygdala*. We observed fiber bundles crossing the amygdala and connecting the orbitofrontal cortex to the anterior temporopolar cortex with a hook shape consistent with the uncinate fasciculus (Fig. 6). Fi-

TABLE 2: Volume of ROI and fiber tracts

| | ROI | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Vol ($mm^3$) | LA | RA | LH | RH | LA Tracts | RA Tracts | LH Tracts | RH Tracts | Cerebral Vol |
| mean | 1638 | 1645 | 2825 | 2858 | 1214 | 1336 | 2247 | 2290 | 1,321,650 |
| SD | 254 | 300 | 417 | 309 | 224 | 366 | 468 | 565 | 110,007 |

bers crossing the midline through the anterior commissure were observed in only 1 patient, and they originated from both sides (Fig. 7). We also identified efferent fibers going upward and backward above the thalamus, which we believe could correspond to the stria terminalis (Fig. 8). Fibers connecting the amygdala to the hippocampus were seen on both sides.

*Surgical Approach*

To assess the fiber tracts affected by a resection, we first studied the fibers that crossed the virtual volume of resection and then studied the fibers crossing the volume of resection in conjunction with the corridor corresponding to the surgical approach. The resection of the amygdalohippocampal volume involves fibers going to the fornix, some connecting callosal fibers, and also some of the orbitofrontal connections (Fig. 9). When we added the volume corresponding to the surgical approach, we observed that the surgical corridor disrupts additional orbitofrontal fibers. Moreover, temporal fibers connecting the anterolateral neocortex and the temporal pole were also involved as well as temporooccipital fibers (Fig. 10).

## Discussion

Many authors have reported volumetric studies of the mesial temporal structures.[4,5,12,39] However, to our knowledge, none of these have looked especially at fibers that cross the amygdala and the hippocampus. Using deterministic tractography, we demonstrated in this study that in the right and the left hemispheres, the volume of fibers crossing the amygdala correlates with the volume of the amygdala.

We identified some of the major known connections of the amygdala and hippocampus, and we also created a virtual model of selAH in which we demonstrated that this surgical procedure disrupts some crucial connections of the mesial temporal structures toward the frontal lobe, the occipital lobe, the temporal pole, and the temporal neocortex.

The mean amygdala and hippocampal volumes reported in this study are consistent with previously described reports,[5,12] although there are some discrepancies in the literature concerning the mean volume of the hippocampus. This deviation, however, could be attributed to differences in methodological approaches used to delineate this structure. In particular, acquisition variables such as magnetic field strength, slice thickness, and dimensionality,[32,39] are known to modify image resolution. Accordingly, differences in image resolution are likely to result in variations in volumetric segmentation. In this study, our protocol involved the acquisition of a T1-weighted anatomical volume using a 3-T MR imaging system to obtain 1-mm isotropic resolution. The resulting reconstructed volume provided a high contrast-to-noise ratio between white matter, gray matter, and CSF and a good discrimination of the hippocampal boundaries.

TABLE 3: Left versus right comparison for volume and fiber tracts

| Value | LA vs RA | LH vs RH | LA vs RA Tracts | LH vs RH |
|---|---|---|---|---|
| Z | −0.257 | −0.582 | 1.339 | 0.122 |
| p | 0.797 | 0.561 | 0.181 | 0.903 |

Very few published reports have investigated the volume of amygdala and hippocampal tracts, but our observations are in keeping with their findings. We have failed to demonstrate any difference between the left and right hemisphere in volume of fiber bundles related to the amygdala and the hippocampus. Yogarajah et al.[52] studied the volume of fibers connecting the parahippocampal gyrus in 10 healthy individuals and did not find any difference between the left and right hemispheres. In the same way, Concha et al.[10] reported a tractography study of the limbic system in which they did not find interhemispheric asymmetry.

Many articles have reported DTT-based anatomical studies of major fiber tracts, including those in relation to temporal lobe structures.[6,19,26,42] In our DTT study of the fiber bundles crossing the amygdala and the hippocampus, we further reveal the dorsal hippocampal commissure, which, to our knowledge, has never been visualized using tractography. This tract has previously been described by Déjerine and Déjerine-Klumpke[13] as the Ammon horn commissure, a bundle of transverse fibers coming from both crura of the fornices, located at the anterior and inferior part of the splenium of the corpus callosum, which joins the 2 Ammon horns. Those authors made a distinction between this commissure and the psalterium, also called David's lyre, which is composed of oblique fibers located in the triangular space delimited anteriorly by the body of fornix and posteriorly by the anterior part of the splenium of the corpus callosum. Gloor et al.[17] reported that whereas the ventral hippocampal commissure is a vestigial structure in humans, the dorsal hippocampal commissure is more developed and represents a sizeable tract. Using depth electrode recordings, they also demonstrated that some patterns of seizure spread seem to involve this tract.

Interestingly, we did not observe any connection between the 2 amygdalae, except in one individual in whom

TABLE 4: Correlations between volume of structures and volume of fibers

| Variable | Value | RA | LA | RH | LH | RA Tracts | LA Tracts | RH Tracts | LH Tracts | Cerebral Vol |
|---|---|---|---|---|---|---|---|---|---|---|
| RA | r | | 0.471 | 0.588 | 0.445 | 0.565 | 0.344 | 0.042 | 0.147 | 0.308 |
| | p | | 0.036 | 0.006 | 0.049 | 0.009 | 0.137 | 0.860 | 0.535 | 0.186 |
| LA | r | 0.471 | | 0.248 | 0.170 | 0.475 | 0.609 | 0.095 | 0.069 | 0.311 |
| | p | 0.036 | | 0.292 | 0.474 | 0.034 | 0.004 | 0.691 | 0.772 | 0.182 |
| RH | r | 0.588 | 0.248 | | 0.874 | 0.365 | 0.205 | 0.161 | 0.355 | −0.011 |
| | p | 0.006 | 0.292 | | 0.000 | 0.113 | 0.387 | 0.498 | 0.125 | 0.965 |
| LH | r | 0.445 | 0.170 | 0.874 | | 0.235 | 0.114 | 0.086 | 0.421 | 0.158 |
| | p | 0.049 | 0.474 | 0.000 | | 0.319 | 0.631 | 0.719 | 0.064 | 0.506 |
| RA tracts | r | 0.565 | 0.475 | 0.365 | 0.235 | | 0.620 | 0.541 | 0.621 | 0.256 |
| | p | 0.009 | 0.034 | 0.113 | 0.319 | | 0.004 | 0.014 | 0.003 | 0.277 |
| LA tracts | r | 0.344 | 0.609 | 0.205 | 0.114 | 0.620 | | 0.561 | 0.519 | 0.323 |
| | p | 0.137 | 0.004 | 0.387 | 0.631 | 0.004 | | 0.010 | 0.019 | 0.164 |
| RH tracts | r | 0.042 | 0.095 | 0.161 | 0.086 | 0.541 | 0.561 | | 0.826 | −0.062 |
| | p | 0.860 | 0.691 | 0.498 | 0.719 | 0.014 | 0.010 | | 0.000 | 0.796 |
| LH tracts | r | 0.147 | 0.069 | 0.355 | 0.421 | 0.621 | 0.519 | 0.826 | | 0.098 |
| | p | 0.535 | 0.772 | 0.125 | 0.064 | 0.003 | 0.019 | 0.000 | | 0.682 |
| cerebral vol | r | 0.308 | 0.311 | −0.011 | 0.158 | 0.256 | 0.323 | −0.062 | 0.098 | |
| | p | 0.186 | 0.182 | 0.965 | 0.506 | 0.277 | 0.164 | 0.796 | 0.682 | |

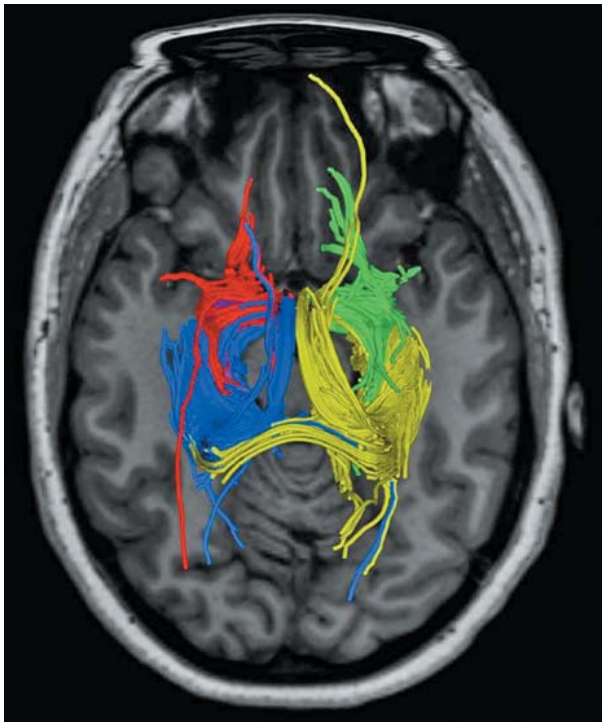

FIG. 2. Three-dimensional reconstruction of the fiber tracts crossing the amygdala and the hippocampus overlayed on an axial T1-weighted MR image. The *red* and *green fibers* represent those crossing the left and the right amygdala, respectively. These fibers join the orbitofrontal cortex and the temporal lobe on both sides. The *blue* and *yellow fibers* represent those that cross the left and the right hippocampus, respectively, and follow the shape of the fornix. Some fibers join the 2 hippocampi across the splenium of the corpus callosum and, in this individual, these fibers predominantly come from the left side. In both hemispheres, we observed some fibers joining the occipital area.

we revealed a connection through the anterior commissure. This finding is consistent with previous physiological and clinical data concerning the pattern of spreading of temporal seizures.[2] Three commissures are potentially involved, but it seems that the anterior commissure is in-

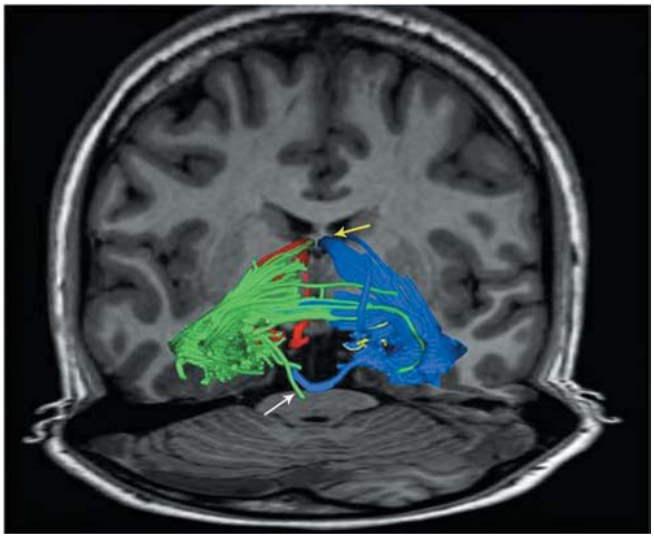

FIG. 3. Three-dimensional reconstruction of the fiber tracts crossing the amygdala and the hippocampus overlayed on a coronal T1-weighted MR image. The *green* and *blue fibers*, respectively, represent the fibers that cross the left and the right hippocampus. These fibers pass through the body of the fornix *(yellow arrow)*. We observed some fibers joining the anterior part of the brainstem *(white arrow)*. *Red fibers* and partially visible *yellow fibers* represent those that cross the left and the right amygdala, respectively.

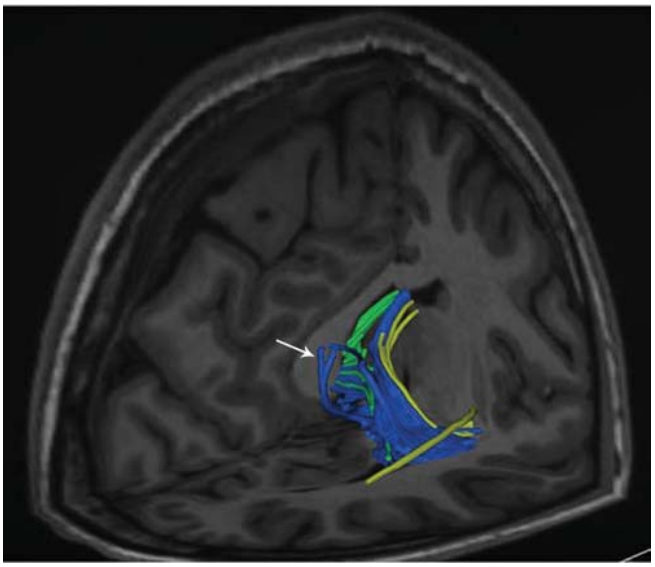

Fig. 4. Three-dimensional reconstruction of the fiber tracts crossing the amygdala and the hippocampus overlayed on a sagittal T1-weighted MR image. The *green* and *blue fibers* represent those that cross the left and the right hippocampus, respectively. Fibers originating in the right hippocampus cross the midline through the splenium of the corpus callosum toward the left hippocampus *(arrow)*. The *yellow fibers* correspond to those that cross the right amygdala.

volved in the propagation of the seizure activity emerging from paralimbic regions. Several recent articles have highlighted the connections between the hippocampus and the dopaminergic circuitry of the midbrain in the region of the ventral tegmental area.[20,51] Classic anatomical literature also reported that the hippocampal formation receives some afferents from monoaminergic cell groups in the brainstem.[16,33] Our results are consistent with this body of work, although the fibers that we observed are

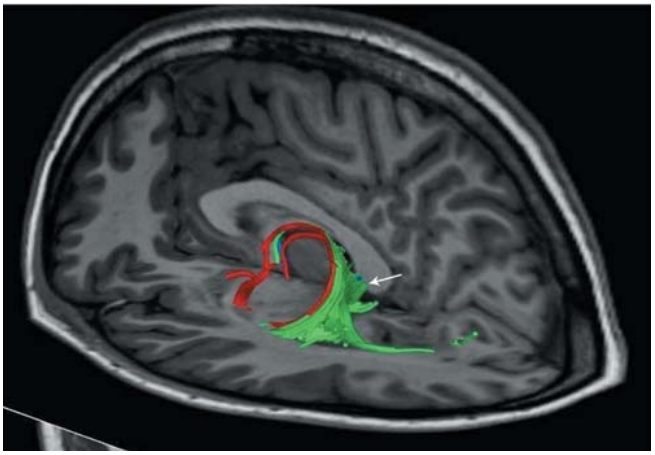

Fig. 5. Three-dimensional reconstruction of the fiber tracts crossing the amygdala and the hippocampus overlayed on a sagittal T1-weighted MR image. The *green fibers* represent those that originate from the left hippocampus that cross the midline through the dorsal hippocampal commissure *(arrow)* at the anterior and inferior part of the splenium of the corpus callosum. The *red fibers* represent those that cross the left amygdala.

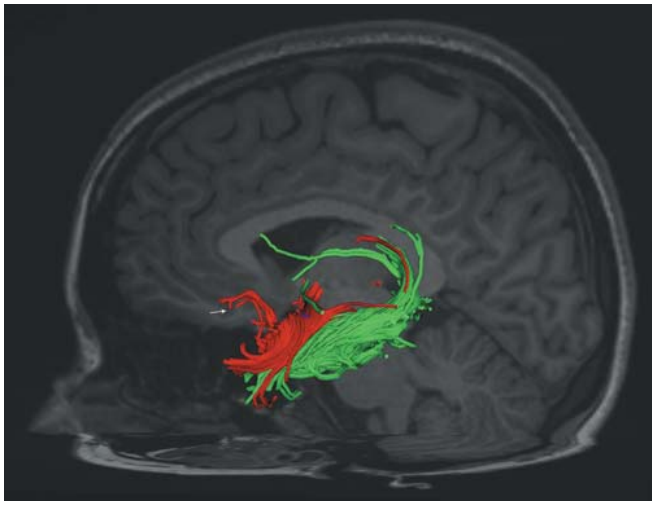

Fig. 6. Three-dimensional reconstruction of the fiber tracts crossing the amygdala and the hippocampus overlayed on a sagittal T1-weighted MR image. The *red* and *green fibers* represent those that cross the right amygdala and the right hippocampus, respectively. The fibers that cross the amygdala join the orbitofrontal area and the anterior temporal area through the uncinate fasciculus *(arrow)*.

located in the anterior part of the pons and the mesencephalon. It is well known that, in such areas, the complexity of the white matter architecture may lead to the generation of spurious tracts in diffusion tractography.[31] It is therefore not clear whether these fiber bundles correspond to an artifact due to the selection of the tracking parameters[24] or to real fiber tracts.

Anatomical studies are crucial for planning an approach in temporal epilepsy surgery[9,11] as they may allow us to understand the relationship between different white matter tracts in the temporal lobe.[41] In our study we show that it is also possible to use diffusion tractography as a tool to visualize the global volume of fibers that could be disrupted after a lateral transcortical selAH. It is also possible to use DTT to focus on one specific white matter tract to visualize its relationship with, for instance, a given surgical approach. Thus, several authors have reported DTT studies of the anterior limb of the optic radiation to assess the risk of visual field defect after temporal lobectomy,[34,38,46] or to demonstrate the wallerian degeneration of the optic tract after temporal lobectomy.[50] In our study, we chose to focus on the lateral transtemporal approach to the mesial temporal structures, but other approaches, such as the transsylvian[49] or subtemporal approaches,[23] could also be evaluated and compared in terms of potential fiber tract disruption. According to the DTT anatomical study of the temporal stem reported by Kier et al.,[26] one can assume that the transsylvian approach that passes through this structure would disrupt part of the uncinate fasciculus, the inferior occipitofrontal fasciculus, and the Meyer loop of the optic radiations. Diffusion tensor tractography images can also be integrated into the neuronavigation system to provide additional data for the intraoperative guidance. In addition, Duffau et al.[14] suggested that combining pre- and postoperative DTT data with intraoperative cortical and subcortical stimulation

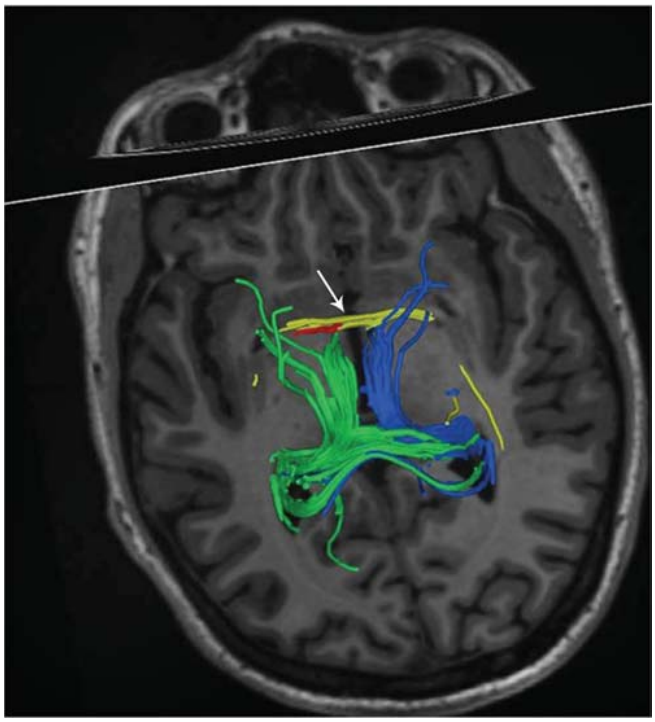

Fig. 7. Three-dimensional reconstruction of the fiber tracts crossing the amygdala and the hippocampus overlayed on an axial T1-weighted MR image. The *green* and *blue fibers* represent those that cross the left and the right hippocampus, respectively. The *yellow* and *red fibers* represent those that cross the right and left amygdala, respectively. Some fibers cross the midline through the anterior commissure *(arrow),* predominantly from the right side.

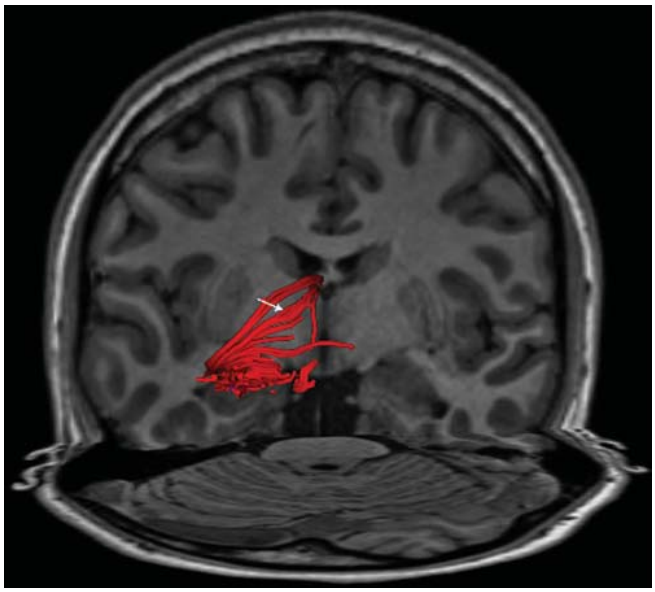

Fig. 8. Three-dimensional reconstruction of the fiber tracts *(red)* crossing the left amygdala overlayed on a coronal T1-weighted MR image. Some fibers are located between the thalamus and the head of the caudate nucleus on the floor of the lateral ventricle and correspond to the stria terminalis *(arrow)*.

may provide for a better understanding of the anatomofunctional correlations of subcortical pathways.

We observed that a virtual transcortical selAH disrupts a large number of fibers joining the temporal, the frontal, and the occipital lobes, which may suggest that selAH is not selective from a functional point of view. In the same way, Dupont et al.[15] reported a PET study in which they demonstrated that selAH induced a postoperative hypometabolism in the polar temporal lobe structures that were spared by the surgery. Moreover, this extended disconnection is probably responsible for the favorable seizure outcome after the procedure for it has been demonstrated that the temporal pole, the temporal neocortex, and the orbitofrontal cortex are involved in the propagation of the temporal seizures.[7,8] In our study, we also observed that some temporooccipital fibers cross the surgical corridor, which is in keeping with postoperative studies showing impairment of visuospatial memory after selAH on the nondominant side.[18,21,25] However, it is important to note that the surgical corridor is thin and therefore is not responsible for a complete disconnection of the temporal structures. Moreover, as DTT does not provide functional data, it does not predict every potential deficit. As an example, although the uncinate fasciculus is involved in psychiatric diseases such as schizophrenia,[22] its surgical disruption is generally not responsible for psychiatric symptoms.[14]

Our study examined tractography in healthy individuals, but it is unclear whether our results apply to pathological conditions that could modify the diffusion of water along white matter tracts. Recently published DTT studies have demonstrated decreased fractional anisotropy in 4 major white matter tracts in patients with temporal lobe epilepsy[19] as well as abnormal integrity of the frontotemporal white matter tracts.[27] It would therefore

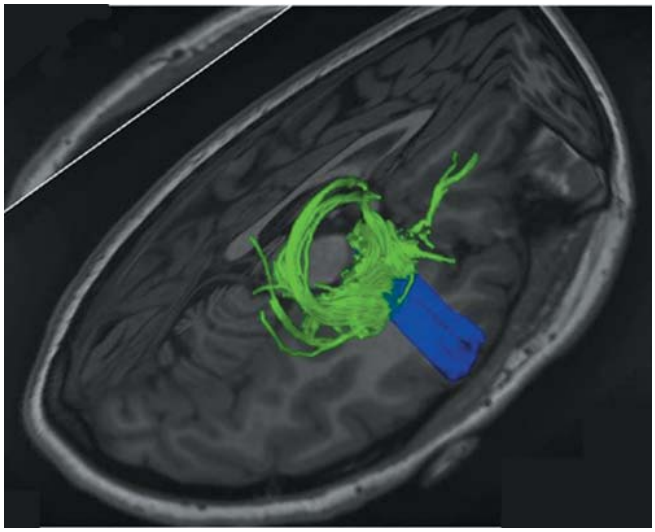

Fig. 9. Three-dimensional reconstruction of the fiber tracts crossing the volume of the virtual resection. The *blue area* corresponds to the surgical corridor. The fibers crossing the virtual resection *(green)* join the orbitofrontal cortex, the fornix, and the splenium of the corpus callosum.

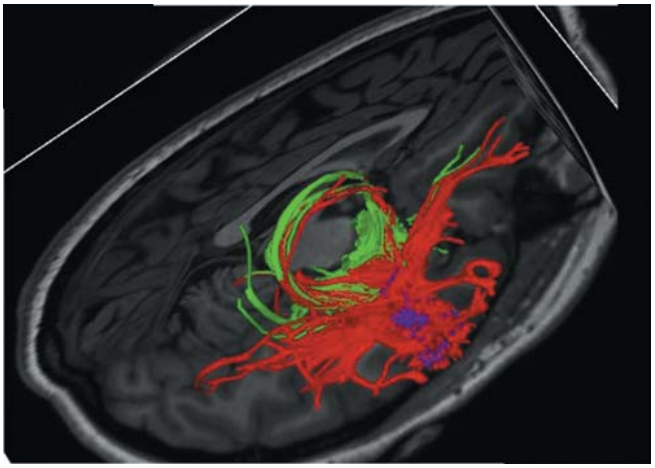

FIG. 10. Three-dimensional reconstruction of the fiber tracts crossing the volume of resection in conjunction with the corridor corresponding to the surgical approach. The fibers crossing to the amygdalohippocampal volume are *green*. The fibers crossing the surgical corridor are *red*. The approach disrupts additional orbitofrontal fibers and also fibers joining the anterolateral temporal cortex, the temporal pole, and the occipital area.

be of interest, in a future study, to verify our results from our virtual operation with a prospective DTT study on epileptic patients before and after selAH and to compare the imaging data with the seizure and neuropsychological outcomes.

## Conclusions

Diffusion tensor tractography is a method that is in its infancy and while the merits of such a methodology are being assessed, tractography images should be carefully interpreted in the context of well-established anatomical data. Nevertheless, in this study we demonstrated that DTT can be used as a useful tool to visualize the basic and surgical anatomy of the mesial temporal structures and to assist in planning a surgical procedure. Diffusion tensor tractography may also provide additional insights for understanding the impact on tracts affected by a surgical procedure such as selAH. Further DTT studies in epileptic patients are necessary to confirm our findings.

### Disclosure

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Author contributions to the study and manuscript preparation include the following. Conception and design: Colnat-Coulbois, Mok, Olivier. Acquisition of data: Colnat-Coulbois, Mok, Penicaud. Analysis and interpretation of data: Colnat-Coulbois, Tanriverdi. Drafting the article: Colnat-Coulbois. Critically revising the article: Klein, Tanriverdi. Reviewed final version of the manuscript and approved it for submission: all authors. Statistical analysis: Mok, Tanriverdi. Administrative/technical/material support: Klein. Study supervision: Olivier.

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