White matter functional connectivity as an additional landmark for dominant temporal lobectomy

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ABSTRACT

Dominant temporal lobectomy is classically performed based on two criteria: a perfect knowledge of the temporo-mesial microsurgical anatomy and cortical landmarks laterally. However, the functional anatomy of the subcortical white matter tracts is taken into account less, despite the risk of inducing a permanent deficit (especially aphasia) if damaged. Even if Klinger's technique allows dissection of fibres on cadaveric specimens, the exact three dimensional geometry of these fasciculi remains poorly described. Tractography, based on diffusion tensor imaging (DTI), is a powerful tool to build three dimensional images of several fasciculi, helping neurosurgeons to create a mental representation of their relationships. Moreover, intraoperative subcortical electrostimulation enables mapping of the function of these pathways. Here we review the recent findings on the white matter anatomo-functional connectivity of the dominant temporal lobe, based on combined anatomical data provided by DTI and functional information provided by intraoperative stimulation. We then discuss their implications for temporal lobectomy, by using white matter functional connectivity as an additional landmark.

For many decades, neurosurgeons have performed temporal lobectomy in the dominant hemisphere, preserving the anterior part of the superior temporal gyrus as well as the mid part of the middle temporal gyrus, while resecting the anterior and mid part of the inferior temporal gyrus without any functional consequences, especially on language.[1] This usual view has been challenged as a major interindividual anatomo-functional variability for language has been demonstrated at the level of the lateral temporal cortex, using both intraoperative electrostimulation[2] and functional neuroimaging.[3] Indeed, the anterior part of the superior temporal gyrus and the mid part of the middle temporal gyrus may be involved in language. When evidenced intraoperatively, these areas have to be preserved.[2] In addition, temporobasal areas can also play a role in language, even if their resection does not systematically cause a definitive deficit.[4]

Thus preoperative as well as intraoperative cortical mapping techniques have been introduced in order to tailor the cortical resection of the dominant temporal lobe according to functional boundaries, initially for epilepsy surgery,[2] and then for glioma surgery.[5] However, because glioma spread along white matter fasciculi, intraoperative subcortical stimulation was proposed, about 10 years ago, in order to stop the resection as close as possible to eloquent subcortical pathways.[6] Similarly, in epilepsy surgery, resection of cortical foci is often associated with disconnection of white matter tracts.[1] However, functional damage during this disconnection must be avoided in order to preserve the quality of life.[7]

Thus the aim of this paper is not to describe the well known anatomical landmarks of a temporomesial lobectomy,[8 9] and neither to detail the limbic connectivity of temporo-mesial structures involved in memory processing. We will rather attempt to describe additional and reliable landmarks given by functional white matter pathways (with special emphasis on language) in order to make the resection of the dominant temporal lobe more reproducible and safer, not only for glioma surgery, but also for corticectomies in epilepsy surgery.

METHODOLOGICAL ADVANCES IN SUBCORTICAL MAPPING

Recent developments in diffusion tensor imaging (DTI) have enabled the non-invasive study of white matter bundles, in particular those thought to be involved in language.[10] However, DTI provides only anatomical information, and cannot give details regarding the function sustained by the fibres.

Interestingly, during brain surgery for resection of a tumour invading both cortical and subcortical structures, it is now common clinical practice to awaken the patient in order to assess the functional role of restricted brain regions, so that the surgeon can maximise the extent of the resection without generating motor, sensory or cognitive (especially language) impairment. Patients continuously perform functional tasks while the surgeon temporarily inactivates localised regions within the grey or white matter around the lesion, using electrical stimulations. If the patient stops speaking or produces incorrect responses, the surgeon does not remove the stimulated region. Indeed, it has been demonstrated that resection too close to structures that are considered as eloquent on the basis of electrical mapping induced postoperative deficit.[5] Therefore, intraoperative electrostimulation can identify, with great accuracy (5 mm) and reproducibility, the structures that are essential for brain function, not only at the cortical but also at the subcortical level.[11]

Moreover, combining the precise functional disturbances elicited by stimulations with the anatomical data provided by preoperative and postoperative MRI (in particular DTI), has enabled the performance of reliable anatomo-functional correlations, especially with regard to subcortical pathways.[12–14] In comparison with voxel based lesion–symptom mapping, which analyses the relationship between tissue damage and behaviour in patients with a neurological deficit,[15] electrical mapping offers the possibility to study the relationship between brain and behaviour in subjects with no or only very slight neurological disorders as stimulation generates the effects of a transient virtual lesion.[2 11]

On the basis of this methodological progress, it is now possible to integrate our improved knowledge of the subcortical connectivity into the surgical planning of temporal lobectomy within the dominant hemisphere. To this end, we describe successively the different fasciculi which are encountered during resection of the temporal lobe, from anterior to posterior (fig 1).

TRACTOGRAPHY METHOD

Subject and acquisition parameters

A right-handed subject (36 years old) gave written informed consent to participate in the study, which was approved by the local ethics committee. No subject had radiological signs of cerebral lesions on conventional MRI. MRI data were acquired using echo planar imaging at 1.5 T (General Electric Healthcare Signa, Chalfont St Giles, UK) with a standard head coil for signal reception. DTI axial slices were obtained using the following parameters: repetition time 19 s; echo time 93 ms; flip angle 90°; voxel size 1.88×1.88×2 mm (isotropic voxels); diffusion weighting was performed along 200 independent directions, with a b value of 3000 s/mm^2.

Image processing

Raw diffusion weighted data were corrected for geometric distortion secondary to eddy currents using a registration technique based on the geometric model of distortions.[16] Brainvisa 3.0.2 (http://brainvisa.info/) software was used to calculate diffusion tensors and anisotropy data, to define regions of interest and to perform fibre tracking using a likelihood algorithm[17] on a diffusion tensor model with a fractional anisotropic threshold of 0.2 and a maximum angle of 45°.

WHITE MATTER (FUNCTIONAL) LANDMARKS IN TEMPORAL LOBECTOMY

Uncinate fasciculus

This pathway connects the anterior part of the temporal pole, the uncus, amygdale and hippocampal gyrus to the orbital and polar frontal cortex.[18] A reduced left-greater-than right asymmetry of the uncinate fasciculus has been linked to schizophrenia in an in vivo DTI study,[19 20] although postmortem studies failed to confirm this hypothesis.[21] Moreover, this tract is regularly sectioned in epilepsy surgery, without inducing major personality disorders. Thus, to date, the functional role of the dominant uncinate fasciculus remains speculative, and its resection is widely admitted.

Inferior longitudinal fasciculus

This tract, first described by KF Burdach in 1822, connects the anterior part of the temporal lobe to the occipital lobe, and runs laterally and inferiorly to the lateral wall of the temporal horn of the lateral ventricle. Recent DTI studies[22] have demonstrated the existence of both a direct and indirect pathway (constituted

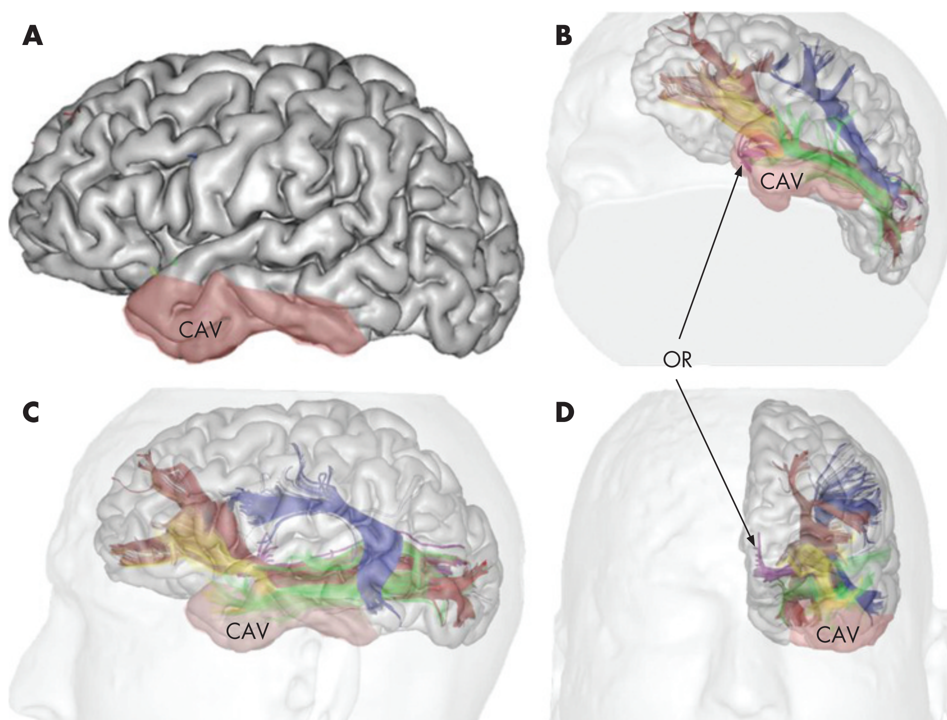

Figure 1 Fibre tracking of the superior longitudinal fasciculus (blue), inferior longitudinal fasciculus (green), inferior fronto-occipital fasciculus (red), uncinate (yellow) and optic radiation (OR) was performed using the regions of interest (ROIs) described by Catani and colleagues.[25] A ''two regions of interest'' approach was used for each fasciculus tracking. The procedure, described by Basser,[44] consisted of defining a second ROI, at a distance from the first ROI, such that it contained at least a section of the desired fasciculus but did not contain any fibres of the undesired fasciculus that passed through the first ROI. Diffusion tensor imaging and high resolution three dimensional anatomical images (B–D) were registered using Brainvisa 3.0.2. Displaying of derived tracts was performed using Anatomist 3.0.2 (http://brainvisa.info). We have drawn a virtual resection cavity (CAV) according to essential subcortical pathways (inferior fronto-occipital fasciculus and arcuate fasciculus), while removing the ''non-essential'' tracts (uncinate, inferior longitudinal fasciculus and anterior part of the OR). By reporting this cavity on the three dimensional surface reconstruction (A), we have obtained a resection similar to those classically reported in the literature, according to cortical boundaries.

by U shaped fibres of the occipito-temporal projection system). Interestingly, while the inferior longitudinal fasciculus was supposed to play a role in emotional processing—likely through a wide network also involving the uncinate fasciculus—a recent brain stimulation study has demonstrated that this tract was not essential for cognitive function, especially for language.[23] As a consequence, its disconnection or resection can be performed with no functional consequence on quality of life, even in the dominant hemisphere, as for the uncinate fasciculus. These findings are in accordance with the classical view concerning temporal lobectomy (ie, that it is possible to remove the inferior temporal gyrus and the fusiform gyrus (in addition to the temporal pole), without generating a permanent deficit). Interestingly, some studies have also proposed that this resection may be performed very posteriorly, even if the existence of cortical eloquent areas have been suspected—namely, that language disturbances have been elicited by cortical electrostimulation at the level of the so-called postero-basal temporal areas.[4]

Inferior occipito-frontal fasciculus

This tract comes from the occipital lobe and postero-lateral temporal areas, then runs laterally and superiorly to the lateral wall of the temporal horn of the lateral ventricle, and continues antero-superiorly to the orbito-frontal and dorso-lateral pre-frontal cortices via the anterior floor of the external capsule under the insular lobe.[24 25] Recently, using intraoperative subcortical mapping, it has been demonstrated that direct electrostimulation of this pathway induced semantic paraphasias (ie, errors with regard to the meaning of the word target) with a high reproducibility.[26] These observations have provided strong arguments in favour of the fact that the inferior occipito-frontal fasciculus was a subcortical pathway underlying the "ventral stream", crucial for language semantic processing, and able to compensate the inferior longitudinal fasciculus, thus explaining why this latter can be removed without deficit.[23]

As a consequence, the inferior occipito-frontal fasciculus has to be preserved at the end of surgical resection at the depth of the dominant temporal lobe.[26] Interestingly, in the anterior floor of the external capsule, this pathway is located immediately medially and above the uncinate fasciculus.[24] Therefore, as the uncinate fasciculus can be resected, the inferior occipito-frontal fasciculus represents the postero-superior and deep limit of the resection of the temporal pole, at the level of the "pli falciforme de Broca". More posteriorly, the temporal part of this pathway represents the supero-mesial and deep boundary of the resection, above the roof of the temporal horn of the ventricle.[26] Indeed, the roof of the ventricle is a good anatomical landmark to define the inferior lateral fasciculus (below) and the inferior occipito-temporal fasciculus (above).

Finally, it is worth noting that since this tract connects the frontal lobe to the postero-lateral temporal cortex, the posterior limit of the resection at the cortical level (superior and middle temporal cortices) depends on the individual distribution of the language sites detected using brain mapping techniques. However, the subcortical postero-lateral boundary of the resection has also to be determined. The temporal part of the superior longitudinal fasciculus may represent this limit.

Superior longitudinal fasciculus

The superior longitudinal fasciculus (or arcuate fasciculus) is a fibre tract stemming from the caudal part of the posterior and superior temporal cortex (mainly Wernicke's area) that arches around the insula and projects forward to end within the frontal lobe (mainly prefrontal and premotor gyri, especially Broca's area).[27] With regard to functional aspects, Wernicke and then later Geschwind postulated that lesions of this tract would produce conduction aphasia. Recently, the different parts of the superior longitudinal fasciculus have been identified using intraoperative subcortical stimulations, by eliciting reproducible phonemic paraphasias, namely disorders that affect the phonological form of the words.[28] As a consequence, it is mandatory to preserve this pathway, which subserves the "dorsal phonological stream". Thus the anterior wall of the temporal part of the superior longitudinal fasciculus, running vertically at the outer surface of the ventricle, represents the subcortical postero-lateral boundary of the resection.[28]

Optic radiations

The optic pathways are located just medially and above the inferior longitudinal fasciculus, whereas the inferior occipito-frontal fasciculus runs medially and above them.[24 29–31] Interestingly, it was recently demonstrated that it was possible to identify these visual tracts intraoperatively, by eliciting transient shadow during their direct electrostimulation.[32] It is very important to preserve the optic radiations at this level, to avoid a permanent postoperative hemianopsia, a deficit which prevents leading a normal life (eg, driving), conversely to a single quadrantanopsia, frequently induced following temporal lobectomy, but which has no functional consequence on quality of life. As a consequence, this tract has to represent the postero-superior and deep limit of temporal lobectomy.

Finally, in the depth, the pyramidal pathway,[33] running within the posterior limb of the internal capsule, and easily detectable using intraoperative stimulation, has to be preserved; this tract constitutes the most posterior mesial boundary of the resection.

Application to language deficit analysis after dominant temporal lobectomy

Since the seminal paper of Langfitt and Rausch,[34] it is now widely agreed that naming decline is a common adverse consequence of dominant temporal lobectomy. Based on retrospective as well as prospective studies, the severity of the deficit has been correlated to individual functional organisation,[35 36] to factors related to epilepsy[36–38] or to the surgical technique.[39 40] We propose that functional outcome after temporal lobectomy could be analysed statistically in terms of damaged fasciculus. It is indeed expected that severe naming decline would be observed when the resection involved some part of either the inferior occipito-frontal or arcuate fasciculus. Careful comparison of preoperative and postoperative DTI tracking, combined with data provided by intraoperative subcortical mapping, could thus provide important information about mechanisms underlying language deficit after dominant temporal lobectomy.

CONCLUSION

Greater knowledge of the anatomo-functional organisation of the subcortical pathways may provide additional and reliable landmarks to perform temporal lobectomy in the dominant hemisphere. Indeed, while it is currently well known that a slow growing lesion may induce functional cortical reshaping, due to cerebral plasticity mechanisms,[41] such reorganisation is negligible within the white matter.[6] As a consequence, the subcortical landmarks detailed here are very reproducible, and can be useful to optimise the benefit/risk ratio of temporal

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lobectomy—that is, to perform a large resection of pathological tissue (during glioma as well as epilepsy surgery) without postoperative impairment of language function. Intraoperative stimulation is still the gold standard to map these functional pathways, but in the near future, intraoperative MRI combined with preoperative DTI could allow intraoperative identification with great accuracy.[42 43]

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REFERENCES

1. **Spencer DD,** Spencer SS, Mattson RH, *et al*. Access to the posterior medial temporal lobe structures in the surgical treatment of temporal lobe epilepsy. *Neurosurgery* 1984;**15**:667–71.
2. **Ojemann G,** Ojemann J, Lettich E, *et al*. Cortical language localization in left, dominant hemisphere. An electrical stimulation mapping investigation in 117 patients. *J Neurosurg* 1989;**71**:316–26.
3. **Vigneau M,** Beaucousin V, Herve PY, *et al*. Meta-analyzing left hemisphere language areas: phonology, semantics, and sentence processing. *Neuroimage* 2006;**30**:1414–32.
4. **Luders H,** Lesser RP, Hahn J, *et al*. Basal temporal language area. *Brain* 1991;**114**(Pt 2):743–54.
5. **Haglund MM,** Berger MS, Shamseldin M, *et al*. Cortical localization of temporal lobe language sites in patients with gliomas. *Neurosurgery* 1994;**34**:567–76.
6. **Duffau H.** Intraoperative cortico-subcortical stimulations in surgery of low-grade gliomas. *Expert Rev Neurother* 2005;**5**:473–85.
7. **Smith JR,** VanderGriff A, Fountas K. Temporal lobotomy in the surgical management of epilepsy: technical report. *Neurosurgery* 2004;**54**:1531–4.
8. **Sindou M,** Guenot M. Surgical anatomy of the temporal lobe for epilepsy surgery. *Adv Tech Stand Neurosurg* 2003;**28**:315–43.
9. **Wen HT,** Rhoton AL Jr, de Oliveira E, *et al*. Microsurgical anatomy of the temporal lobe: part 1: mesial temporal lobe anatomy and its vascular relationships as applied to amygdalohippocampectomy. *Neurosurgery* 1999;**45**:549–91.
10. **Catani M,** Jones DK, ffytche DH. Perisylvian language networks of the human brain. *Ann Neurol* 2005;**57**:8–16.
11. **Duffau H.** Lessons from brain mapping in surgery for low-grade glioma: insights into associations between tumour and brain plasticity. *Lancet Neurol* 2005;**4**:476–86.
12. **Kamada K,** Todo T, Masutani Y, *et al*. Visualization of the frontotemporal language fibers by tractography combined with functional magnetic resonance imaging and magnetoencephalography. *J Neurosurg* 2007;**106**:90–8.
13. **Thiebaut de Schotten M,** Urbanski M, Duffau H, *et al*. Direct evidence for a parietal-frontal pathway subserving spatial awareness in humans. *Science* 2005;**309**:2226–8.
14. **Henry RG,** Berman JI, Nagarajan SS, *et al*. Subcortical pathways serving cortical language sites: initial experience with diffusion tensor imaging fiber tracking combined with intraoperative language mapping. *Neuroimage* 2004;**21**:616–22.
15. **Bates E,** Wilson SM, Saygin AP, *et al*. Voxel-based lesion-symptom mapping. *Nat Neurosci* 2003;**6**:448–50.
16. **Mangin JF,** Clark C, Le Bihan D, *et al*. Distortion and robust tensor estimation for MR diffusion imaging. *Med Image Anal* 2002;**6**:191–8.
17. **Mangin JF,** Poupon C, Cointepas Y, *et al*. A framework based on spin glass models for the interference of anatomical connectivity from diffusion-weighted MR data—a technical review. *NMR Biomed* 2002;**15**:481–92.
18. **Crossby EC,** Humphrey T, EW L. *Correlative anatomy of the nervous system*. New York: MacMillian, 1962.
19. **Burns J,** Job D, Bastin ME, *et al*. Structural disconnectivity in schizophrenia: a diffusion tensor magnetic resonance imaging study. *Br J Psychiatry* 2003;**182**:439–43.
20. **Kubicki M,** Westin CF, Maier SE, *et al*. Uncinate fasciculus findings in schizophrenia: a magnetic resonance diffusion tensor imaging study. *Am J Psychiatry* 2002;**159**:813–20.
21. **Highley JR,** Walker MA, Esiri MM, *et al*. Asymmetry of the uncinate fasciculus: a post-mortem study of normal subjects and patients with schizophrenia. *Cereb Cortex* 2002;**12**:1218–24.
22. **Catani M,** Jones DK, Donato R, *et al*. Occipito-temporal connections in the human brain. *Brain* 2003;**126**(Pt 9):2093–107.
23. **Mandonnet E,** Nouet A, Gatignol P, *et al*. Does the left inferior longitudinal fasciculus play a role in language? A brain stimulation study. *Brain* 2007;**130**(Pt 3):623–9.
24. **Kier EL,** Staib LH, Davis LM, *et al*. MR imaging of the temporal stem: anatomic dissection tractography of the uncinate fasciculus, inferior occipitofrontal fasciculus, and Meyer's loop of the optic radiation. *AJNR Am J Neuroradiol* 2004;**25**:677–91.
25. **Catani M,** Howard RJ, Pajevic S, *et al*. Virtual in vivo interactive dissection of white matter fasciculi in the human brain. *Neuroimage* 2002;**17**:77–94.
26. **Duffau H,** Gatignol P, Mandonnet E, *et al*. New insights into the anatomo-functional connectivity of the semantic system: a study using cortico-subcortical electrostimulations. *Brain* 2005;**128**(Pt 4):797–810.
27. **Nieuwenhuys R,** Voogd J, van Huijzen C. *The human central nervous system*. Berlin: Springer-Verlag, 1988.
28. **Duffau H,** Capelle L, Sichez N, *et al*. Intraoperative mapping of the subcortical language pathways using direct stimulations. An anatomo-functional study. *Brain* 2002;**125**(Pt 1):199–214.
29. **Sincoff EH,** Tan Y, Abdulrauf SI, White matter fiber dissection of the optic radiations of the temporal lobe and implications for surgical approaches to the temporal horn. *J Neurosurg* 2004;**101**:739–46.
30. **Rubino PA,** Rhoton AL Jr, Tong X, *et al*. Three-dimensional relationships of the optic radiation. *Neurosurgery* 2005;**57**(4 Suppl):219–27.
31. **Ebeling U,** Reulen HJ. Neurosurgical topography of the optic radiation in the temporal lobe. *Acta Neurochir* (*Wien*) 1988;**92**:29–36.
32. **Duffau H,** Velut S, Mitchell MC, *et al*. Intraoperative mapping of the subcortical visual pathways using direct electrical stimulations. *Acta Neurochirur* (*Wien*) 2004;**146**:265–70.
33. **Ebeling U,** Reulen HJ. Subcortical topography and proportions of the pyramidal tract. *Acta Neurochir* (*Wien*) 1992;**118**:164–71.
34. **Langfitt JT,** Rausch R. Word-finding deficits persist after left anterotemporal lobectomy. *Arch Neurol* 1996;**53**:72–6.
35. **Sabsevitz DS,** Swanson SJ, Hammeke TA, *et al*. Use of preoperative functional neuroimaging to predict language deficits from epilepsy surgery. *Neurology* 2003;**60**:1788–92.
36. **Schwartz TH,** Devinsky O, Doyle W, *et al*. Preoperative predictors of anterior temporal language areas. *J Neurosurg* 1998;**89**:962–70.
37. **Davies KG,** Bell BD, Bush AJ, *et al*. Naming decline after left anterior temporal lobectomy correlates with pathological status of resected hippocampus. *Epilepsia* 1998;**39**:407–19.
38. **Saykin AJ,** Stafiniak P, Robinson LJ, *et al*. Language before and after temporal lobectomy: specificity of acute changes and relation to early risk factors. *Epilepsia* 1995;**36**:1071–7.
39. **Hermann B,** Davies K, Foley K, *et al*. Visual confrontation naming outcome after standard left anterior temporal lobectomy with sparing versus resection of the superior temporal gyrus: a randomized prospective clinical trial. *Epilepsia* 1999;**40**:1070–6.
40. **Hermann BP,** Perrine K, Chelune GJ, *et al*. Visual confrontation naming following left anterior temporal lobectomy: a comparison of surgical approaches. *Neuropsychology* 1999;**13**:3–9.
41. **Desmurget M,** Bonnetblanc F, Duffau H. Contrasting acute and slow-growing lesions: a new door to brain plasticity. *Brain* 2007;**130**(Pt 4):898–914.
42. **Nimsky C,** Ganslandt O, Fahlbusch R. Implementation of fiber tract navigation. *Neurosurgery* 2006;**58**(4 Suppl 2):ONS-292–303.
43. **Nimsky C,** Ganslandt O, Merhof D, *et al*. Intraoperative visualization of the pyramidal tract by diffusion-tensor-imaging-based fiber tracking. *Neuroimage* 2006;**30**:1219–29.
44. **Basser PJ.** Fiber-tractography via diffusion tensor MRI (DT-MRI). Sixth Annual Meeting of the International Society for Magnetic Resonance in Medicine (ISMRM). Sydney, Australia, 18–24 April 1998.

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