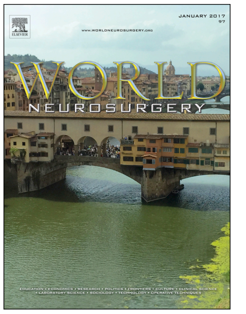
Journal Pre-proof



Transcortico-subcortical approach for left posterior mediobasal temporal region gliomas: a case series and anatomical review of relevant white matter tracts

Desmond A. Brown;, Sahin Hanalioglu, MD, PhD;, Kaisorn Chaichana, MD, Hugues Duffau, MD, PhD

PII: S1878-8750(20)30854-8

DOI: https://doi.org/10.1016/j.wneu.2020.04.147

Reference: WNEU 14832

To appear in: *World Neurosurgery*

Received Date: 10 February 2020

Revised Date: 15 April 2020

Accepted Date: 17 April 2020

Please cite this article as: Brown; DA, Hanalioglu S, Chaichana K, Duffau H, Transcortico-subcortical approach for left posterior mediobasal temporal region gliomas: a case series and anatomical review of relevant white matter tracts, *World Neurosurgery* (2020), doi: https://doi.org/10.1016/j.wneu.2020.04.147.

Transcortico-subcortical approach for left posterior mediobasal temporal region gliomas: a case series and anatomical review of relevant white matter tracts

Desmond A. Brown;[a*] Sahin Hanalioglu, MD, PhD;[b] Kaisorn Chaichana, MD,[c] & Hugues Duffau, MD, PhD[d]

[a]Department of Neurosurgery, Mayo Clinic, Rochester, MN, USA;
[b]Department of Neurosurgery, Health Sciences University, Diskapi Yildirim Beyazit Training and Research Hospital, Ankara, Turkey;
[c]Department of Neurosurgery, Mayo Clinic, Jacksonville, Florida, USA;
[d]Department of Neurosurgery and INSERM U1051, Montpellier University Medical Center, Montpellier, France

Highest Academic Degrees:

Desmond A. Brown, MD, PhD

Sahin Hanlioglu, MD, PhD

Kaisorn Chaichana, MD

Hugues Duffau, MD, PhD

[*]Corresponding author

Desmond A. Brown, M.D., Ph.D.,

Department of Neurosurgery, Mayo Clinic

200 First Street SW, Rochester, MN 55905

Phone: +1 507-293-9306

Email: brown.desmond@mayo.edu

Key Words: Mesobasal temporal region; awake functional mapping; transcortical approach; inferior fronto-occipital fascículos (IFOF); inferior longitudinal fascículos; optic radiation

Short Title: Resection of mesobasal temporal gliomas

Abstract

Background and Objective

The goal of this paper is to demonstrate using five illustrative cases that the transcortical route for resection of mediobasal temporal region (MBTR) lesions is safe and effective when performed with awake functional mapping and knowledge of the relevant subcortical anatomy. While a number of approaches have been proposed, there is a paucity of reports on transcortico-subcortical approaches to these lesions–particularly in cases with posterior-superior extension. We present a case series of 5 patients with left posterior MBTR gliomas and summarize the relevant subcortical anatomy knowledge of which is a prerequisite for safe resection.

Methods

Five patients with left posterior MBTR gliomas underwent awake resection with functional cortico-subcortical electrical mapping. Details of the approach are presented with a review of relevant anatomy.

Results

Gross total resection was achieved in 4 patients. One patient who had previously undergone radiation therapy had a subtotal resection. There were 4 cases of WHO grade II glioma and one case of WHO grade IV glioma. All patients underwent pre- and postoperative neurological and neuropsychological assessment and there were no new or worsening sensorimotor, visual, language or cognitive deficits.

Conclusions

The transcortico-subcortical approach is a safe and effective approach to lesions of the posterior MBTR. The approach is safe and effective even in cases with superior extension, providing the surgical approach is predicated on knowledge of individual functional anatomy. Awake resection with cortical and axonal mapping with well-selected paradigms is invaluable in maximizing extent of resection while ensuring patient safety.

Introduction

The medial temporal region is part of the limbic system and plays an important role in learning, memory, motivation, emotion and behavior.[1-3] The mediobasal temporal region (MBTR) lies mesial to the collateral sulcus and inferior and mesial to the temporal horn. It includes the parahippocampal gyrus, hippocampal formation, uncus and amygdala.[4,5] Due to its deep location and close proximity to critical neurovascular structures, surgical approaches to the MBTR, especially its posterior and superior parts, are challenging and associated with significant morbidity. Numerous approaches have been described which aim to maximize surgical access while mitigating risk. Transsylvian and anterior temporal lobectomy approaches are usually preferred for anterior MBTR lesions, whereas subtemporal,[6-9] supracerebellar transtentorial,[10-13] occipital/posterior interhemispheric,[14,15] or low posterior transpetrosal approach with petrosectomy,[16] are employed to resect middle or posterior MBTR pathologies. A few authors have also suggested transcortical routes to MBTR lesions but these have not been widely adopted (particularly in the left hemisphere) due to the risk of damage to subcortical language and other networks which are often perceived to have less well-delineated landmarks via transcortical approaches.[17-19]

Herein, we present 5 cases of left posterior MBTR tumors resected via a transcortico-subcortical approach through the middle temporal gyrus. Each surgery was performed awake with cortical and axonal electrical mapping. We review the relevant subcortical anatomy and demonstrate how detailed anatomical knowledge of the underlying tracts can be applied during resection to circumvent otherwise predictable postoperative deficits.

Patients and Methods

Patients selection

Data and imaging were analyzed after anonymization in accordance with the Personal Data Protection Act and the Code of Conduct for Responsible use of Human Tissue and Medical Research. Patients with a glioma involving the left posterior mediobasal temporal region who underwent awake surgery using a transcortico-subcortical approach by a senior surgeon (H.D.) between April 2016 and April 2019 were retrospectively included. All subjects gave informed consent for the retrospective extraction of their clinical data. Approval of the study protocol by the institutional review board was not required as patients were not subjected to procedures outside routine clinical care.

Preoperative clinical and radiological examination

Pre- and postoperative functional outcome was assessed systematically via neurological and neuropsychological assessments by the same team to prevent inter-observer bias, using a previously described protocol.[20] All patients underwent preoperative MRI imaging and postoperative MRI within 24 hours and 3 months post-surgery. Thereafter, patients underwent MRI at 6-month intervals. Volumetric assessment of tumors pre- and post-operatively was performed by H.D. and confirmed by neuroradiology. Gross total resection (GTR) was defined as resection of 100% of the pre-operative FLAIR signal while subtotal resection (STR) was defined as any remaining pre-operative FLAIR signal on post-operative images. Tractography images were generated by the Synaptive Modus Plan™ software (Synaptive Medical Inc., Toronto, Canada) in 2 patients. Pre-operative diffusion MR images (in at least 30 directions) were imported after quality assessment. Tracts were autosegmented and final tractography was compared to accepted anatomical course.

Details of Surgery and Intraoperative Mapping Technique

All patients underwent a left frontotemporal craniotomy and awake resection with cortical and subcortical direct electrical stimulation (DES) as our group previously described.[21-23] Briefly, patients underwent anesthesia induction and placement of a laryngeal mask airway. Local anesthetic was applied, and exposure was performed in standard fashion using anatomic landmarks for placement and size of the craniotomy. Patients were then woken up and the airway was removed to allow full participation in functional mapping. Following durotomy, tumor, sulcal and gyral boundaries were demarcated with intraoperative ultrasonography to confirm localization.

DES was performed using a bipolar stimulator with tips spaced 5-mm apart. A biphasic current with pulse frequency 60 Hz, single pulse phase duration of 1 msec, amplitude 2–4 mA and stimulation duration of 4 seconds was applied. In each case, initial sensorimotor mapping was performed to delineate negative motor, primary sensorimotor and speech (ventral premotor cortex) regions. Awake mapping was performed while patients completed a dual naming and contralateral upper extremity motor task.[24] Objects were presented diagonally on the screen with inclusion of all 4 quadrants for the assessment of visual fields. A trained neuropsychologist documented all language disturbances intraoperatively using a previously reported classification scheme comprised of speech arrest, anomia, paraphasia (phonetic, phonemic, or semantic), initiation disturbance and perseveration.[22] Each thus determined eloquent area was marked and correlated with the anatomical landmarks previously identified on ultrasonography.

Tumor resection then proceeded by first determining a safe corticectomy site in the middle temporal gyrus based on the awake cortical mapping. Resection toward the temporal horn of the lateral ventricle was then undertaken with alternating resection and subcortical DES mapping by following functional pathways progressively from the mapped eloquent cortical sites to the depth of the resection while the patient continued the dual language and motor tasks. Based on anatomic and functional knowledge of the optic radiation (OR), arcuate fasciculus (AF), inferior longitudinal fasciculus (ILF) and inferior fronto-occipital fasciculus (IFOF) pathways (as reviewed below), directed axonal DES during appropriately selected tasks was performed to rapidly identify each structure. Resection was thus continued until eloquent pathways were encountered around the entire surgical cavity and these were then followed according to anatomic and functional boundaries without the aid of intraoperative neuronavigation or MRI. By so doing, no margin was left around cortico-subcortical eloquent networks, to optimize the extent of resection.

Results

Summary of Cases

Specific case details, with neurological, neurocognitive, radiological, surgical and pathological characteristics are presented in **Table 1** and **Figures 1-5**. A narrated video of the resection performed on patient 3 is provided (**Video 1**). All but one patient had a gross total resection on the postoperative FLAIR MRI (**Figures 1, 2, 3, 5**). The lone patient with a subtotal resection had undergone radiotherapy in another institution 3 years prior and the tumor abutted the pulvinar of the thalamus, drastically increasing the risk. An intraoperative decision was made to leave this portion of the tumor due to adherences to the left pulvinar, although the lesion was visible and accessible by the surgical approach (**Figure 4**). No new or worsening sensorimotor, visual, language or cognitive, symptoms were experienced by any patient in our series. All patients returned to work by 3 months post-operatively.

Discussion

The medial temporal region is a complex anatomical location and is the site of numerous pathologies. Mesial temporal lobe epilepsy secondary to hippocampal sclerosis is observed pathologically in up to 70% of cases.[25] Other lesions include focal cortical dysplasias, neoplasms and vascular malformations. Among neoplastic lesions, low-grade glial or mixed neuronal-glial tumors, such as gangliogliomas and dysembryoplastic neuroepithelial tumors comprise the vast majority. In Yasargil's series, they represented 57% of MBTR tumors, with gangliogliomas, diffuse astrocytomas and anaplastic astrocytomas comprising 21%, 18% and 17%, respectively.[26] In Schramm's series of 235 MBTR tumors, 47% had grade I, 29% grade II, 10% grade III and 11% grade IV tumors.[7] Regardless of the pathological nature, MBTR lesions are often highly epileptogenic likely related to involvement of hippocampal circuitry.

Herein, we report a series of 5 right-handed patients with left posterior MBTR gliomas who underwent awake resection with DES and functional mapping of cortical and subcortical structures. A gross- or near-total resection was achieved in all but one case as the tumor was extremely large and involved critical structures. This was achieved despite postero-superior extension toward the splenium of the corpus callosum and pulvinar. There were no new motor deficits, vascular complications or hemianopia and no patient experienced neurocognitive (including language) worsening. All surgeries were performed by strict reliance on detailed neuroanatomical knowledge of cortical and subcortical structures along with functional mapping for improved safety and efficacy of resections. We postulate these results can be replicated given the prerequisite neuroanatomical knowledge.

Review of relevant white matter tracts to approach MBTR

Given the propensity for development of a wide array of surgical lesions, temporal lobe anatomy and surgical approaches to temporal lobe lesions have been extensively reviewed.[4,5,27-29] The MBTR extends from the medial temporal pole anteriorly to the isthmus of the cingulate gyrus posteriorly (**Figure 6**). It includes the preuncus, uncus, amygdala, hippocampus, and parahippocampal gyrus.[4,5] Medial borders include the edge of the tentorium, midbrain, oculomotor nerve, major circle of Willis arteries, and the basal vein of Rosenthal within the perimesencephalic cistern. Lateral limits are the rhinal and collateral sulci basally and the temporal horn and temporal stem superiorly. The branch of the optic radiation subserving the contralateral visual field, forms the roof of the posterior temporal horn *en route* to the supracalcarine cortex.[30,31] Major arterial supply of the MBTR comes from the anterior choroidal, posterior cerebral and middle cerebral arteries whereas its main venous drainage is via the basal vein of Rosenthal.

The contemporary dual stream model of language theorizes that a dorsal stream comprised by the SLF and AF are responsible for phonological and articulatory integration primarily in the left hemisphere, whereas a ventral semantic stream, including the UF, IFOF and ILF are involved in language comprehension and access to lexical concepts in *both* hemispheres.[32] The perisylvian SLF is comprised of three principal components: an anterior segment connecting the supramarginal gyrus and superior temporal gyrus with the ventral premotor cortex; a posterior segment connecting the middle and inferior temporal gyri with the angular gyrus; and the AF.[33]

The AF is thought to be the primary tract subserving the dorsal phonologic stream.[34] It is a deep, long tract that originates in the middle and inferior temporal gyri.[33] The fibers of the AF then curve superiorly at the level of the inferior limiting sulcus of the insula running anterior to the sagittal striatum (optic radiation, IFOF and tapetal fibers comprising the lateral wall of the atrium). The tract then curves anteriorly and runs horizontally in the white matter of the parietal and frontal operculum lateral to the corticospinal tract before terminating in the inferior portion of the ventral premotor cortex and the inferior frontal gyrus.[33,35,36] Transitory AF dysfunction wrought by DES reproducibly results in phonemic paraphasias.[37,38] whereas structural lesions result in conductive aphasia characterized by both phonemic paraphasias and impaired repetition.[39,40]

The ventral stream is composed of a direct (IFOF) and an indirect (ILF and UF) pathway. The former is the dominant component of the ventral semantic stream. IFOF fibers originate from the middle and inferior occipital gyri, the parietal and temporal cortices. They run anteriorly through the superior and middle temporal gyri forming the lateral border of the temporal horn and inferior two-thirds of the atrium of the lateral ventricle.[41-43] IFOF continues anteriorly narrowing at the level of the limen insula just superior and posterior to UF and then extends through the anterior third of the superior limiting sulcus and superior half of the anterior limiting sulcus[32] before terminating in the dorsolateral prefrontal cortex, pars orbitalis and pars triangularis–all semantic processing areas.[42] IFOF plays a central role in semantic processing of visual stimuli as well as the integration of multimodal sensory input, reading, writing, comprehension and production of meaningful speech.[42,44,45] Indeed, our group previously reported that DES of the left IFOF resulted in semantic language disturbances.[22,46,47] Preservation of IFOF is paramount as its lesions cannot be fully compensated by the indirect ventral stream (UF and ILF).[46,48]

The ILF originates in the dorsolateral occipital cortex and courses anteriorly through the inferior temporal gyrus terminating at the temporal pole.[42,49] It forms the inferolateral border of the temporal horn and atrium of the lateral ventricle and connects the temporal pole, middle and inferior temporal gyri to the hippocampus, parahippocampal gyrus, amygdala, and extrastriate areas.[42,50] DES of the left ILF results in reading disorders[51] and lexical retrieval impairment.[52,53] The UF is anterior to the current trajectory and is not further discussed.

In summary, the MBTR is surrounded by important white matter tracts that are critical for language, cognition, emotion, memory and vision (Figure 7). Surgical approaches to this region thus carry significant risk of damage to these tracts and consequent permanent neurologic compromise. Knowledge of the relevant anatomy is therefore of utmost importance for safe resection of MBTR lesions and surgical approaches to this region must be predicated on a strong hodotopical understanding of the region in order to minimize surgical morbidity.[47,54-56]

Approaches to the posterior MBTR

Various approaches to the posterior MBTR have been proposed. Yaşargil reported successful management of the entire range of MBTR tumors in a series of 177 patients.[26] A transsylvian approach was used in a preponderance of patients except in cases with posterior extension for which an occipital interhemispheric approach was then employed. There was no operative mortality but neurological deficits were reported in 5%. Seizures were cured in 84%. Extent of resection was not reported. The occipital interhemispheric approach is well suited for lesions within the atrium[57] but would likely result in damage to fibers of the SLF, AF, optic radiations, or even IFOF depending on the specific trajectory taken.

Schramm utilized his anatomical classification to describe the preferred use of individual approaches for various tumor types in a series of 235 patients with MBTR lesions.[7,58] Anterior MBTR tumors were deemed less challenging and were removed via a transsylvian approach

(39%) or partial anterior lobectomy (32%). Tumors of the posterior MBTR regions proved challenging and a subtemporal approach was employed in 78% of these lesions. This approach often required additional modifications such as transpetrosal route, unroofing of the external auditory meatus or various transtentorial approaches and superior resection was limited by retraction on the vein of Labbé. The transsylvian route was also employed in 9% but this required transgression of the temporal stem. A transcortical route was preferred for patients with posterior type D lesions (6.6%) resulting in a 29% rate of postoperative visual field cut among those undergoing that approach. Permanent neurologic complications were seen in 7.4% of patients overall. The extent of resection was not reported in this series.

Recently, Morshed et al. proposed a transcortical equatorial approach for MBTR tumors in a series of 50 glioma patients.[17] Posterior MBTR tumors were approached via corticectomy of the middle and/or inferior temporal gyri after selecting the shortest distance from the cortical surface to the lesion. Language mapping was performed in 96.9% of left sided lesions only while motor mapping was performed in 52% of cases overall. EOR was 89.5% and 96.0% for low- and high-grade tumors, respectively, and did not differ by tumor location. However, deficits were present in 24% of patients overall at 3-month follow-up. Selecting the shortest equatorial distance from the target without careful consideration of the underlying subcortical network may result in traversing critical fibers particularly in cases performed under general anesthesia.

Uribe et al. reported a series of 25 patients with MBTR tumors.[59] Cases with superior extension were specifically excluded. Their approach–aided by neuronavigation–was via a limited inferior temporal gyrus corticectomy. The authors report that in order to minimize visual deficits, an opening into the ventricle was made along the inferior wall and floor of the temporal horn. Such a trajectory from the inferior temporal gyrus is likely to damage fibers of the ILF.

While they reported no neurological complications and found a visual field deficit in the sole patient tested, no detailed pre- or post-operative neurological testing was performed to carefully delineate subtle language or other deficits.

Recently, in a series of 23 patients with high-grade gliomas, Quiñones-Hinojosa et al. showed equipoise when resections were undertaken via a middle temporal gyrus or inferior temporal gyrus approach.[60] However, in their series, although GTR was achieved in 92%, new neurological deficits were noted in 22%. Given the involvement of high-grade pathology only, the variability in specific approaches and the unknown extent of posterior and superior extension, direct comparison with outcomes cannot be made.

In our approach, the middle temporal gyrus was selected as this provided a direct trajectory to the temporal horn with avoidance of visual networks. Moreover, our middle temporal gyrus approach provides a safe corridor to the inferior border of the splenium allowing for safe and complete extirpation of posterior MBTR tumors, including with superior extension. The optic radiations, AF, IFOF and ILF are then delineated based on awake axonal mapping, allowing a total or subtotal resection in all cases, with the absence of postoperative deficit.

Conclusions

We present a series of left, posterior MBTR tumors resected via a transcortico-subcortical approach along with a relevant anatomic review. While this is a small series, the approach is rooted in detailed knowledge of the anatomy and function of the subcortical networks. Pre- and postoperative neurological and neuropsychological assessments performed in each case document the absence of postoperative sequelae while volumetric analysis objectively document EOR. This represents a safe and effective approach to postero-superior MBTR tumors and obviates performance of complex and unfamiliar approaches with less desirable safety profiles.

Disclosures

This work was unfunded. The authors have no conflicts of interest to declare.

References

1. Pergola G, Suchan B. Associative learning beyond the medial temporal lobe: many actors on the memory stage. Front Behav Neurosci. 2013;7:162.
2. Phelps EA. Human emotion and memory: interactions of the amygdala and hippocampal complex. Curr Opin Neurobiol. 2004;14:198–202.
3. Sitoh YY, Tien RD. The limbic system. An overview of the anatomy and its development. Neuroimaging Clin N Am. 1997;7:1–10.
4. Campero A, Tróccoli G, Martins C, Fernandez-Miranda JC, Yasuda A, Rhoton AL. Microsurgical approaches to the medial temporal region: an anatomical study. Neurosurgery. 2006;59:ONS279-307; discussion ONS307-308.
5. Fernández-Miranda JC, de Oliveira E, Rubino PA, Wen HT, Rhoton AL. Microvascular anatomy of the medial temporal region: part 1: its application to arteriovenous malformation surgery. Neurosurgery. 2010;67:ons237-276; discussion ons276.
6. Hori T, Tabuchi S, Kurosaki M, Kondo S, Takenobu A, Watanabe T. Subtemporal amygdalohippocampectomy for treating medically intractable temporal lobe epilepsy. Neurosurgery. 1993;33:50–56; discussion 56-57.
7. Schramm J, Aliashkevich AF. Surgery for temporal mediobasal tumors: experience based on a series of 235 patients. Neurosurgery. 2007;60:285–294; discussion 294-295.
8. von Rhein B, Nelles M, Urbach H, Von Lehe M, Schramm J, Helmstaedter C. Neuropsychological outcome after selective amygdalohippocampectomy: subtemporal versus transsylvian approach. J Neurol Neurosurg Psychiatry. 2012;83:887–893.
9. Yang P-F, Zhang H-J, Pei J-S, Lin Q, Mei Z, Chen Z-Q, et al. Neuropsychological outcomes of subtemporal selective amygdalohippocampectomy via a small craniotomy. J Neurosurg. 2016;125:67–74.
10. Chau AMT, Gagliardi F, Smith A, Pelzer NR, Stewart F, Mortini P, et al. The paramedian supracerebellar transtentorial approach to the posterior fusiform gyrus. Acta Neurochir (Wien). 2016;158:2149–2154.
11. Harput MV, Türe U. The paramedian supracerebellar-transtentorial approach to remove a posterior fusiform gyrus arteriovenous malformation. Neurosurg Focus. 2017;43:V7.
12. Konovalov AN, Pitskhelauri DI, Melikyan AG, Shishkina LV, Serova NK, Pronin IN, et al. [Supracerebellar transtentorial approach to tumors of the posterior portions of the medial temporal region]. Zh Vopr Neirokhir Im N N Burdenko. 2015;79:38–47.
13. Moftakhar R, Izci Y, Başkaya MK. Microsurgical anatomy of the supracerebellar transtentorial approach to the posterior mediobasal temporal region: technical considerations with a case illustration. Neurosurgery. 2008;62:1–7; discussion 7-8.

14. Tseng K-Y, Lin J-H, Lin E-Y, Ma H-I. Occipital interhemispheric approach without excision of tentorium for the tumor in the medial temporal region: technical note. Surg Neurol. 2009;71:448–450.
15. Wang S, Salma A, Ammirati M. Posterior interhemispheric transfalx transprecuneus approach to the atrium of the lateral ventricle: a cadaveric study. J Neurosurg. 2010;113:949–954.
16. Janjua MB, Caruso JP, Greenfield JP, Souweidane MM, Schwartz TH. The combined transpetrosal approach: Anatomic study and literature review. J Clin Neurosci. 2017;41:36–40.
17. Morshed RA, Young JS, Han SJ, Hervey-Jumper SL, Berger MS. The transcortical equatorial approach for gliomas of the mesial temporal lobe: techniques and functional outcomes. J Neurosurg. 2019;130:822–830.
18. Onoda K, Tsuchimoto S, Tanioka D, Kiriyama H, Higashi H. Transcortical transchoroidal fissure approach for ruptured distal posterior cerebral artery (P2-P3 junction) aneurysm associated with packed intraventricular hemorrhage--two case reports. Neurol Med Chir (Tokyo). 2003;43:38–42.
19. Rutledge C, Jonzzon S, Winkler EA, Hetts SW, Abla AA. Transcortical transventricular transchoroidal-fissure approach to distal fusiform hyperplastic anterior choroidal artery aneurysms. Br J Neurosurg. 2019;1–5.
20. Herbet G, Moritz-Gasser S. Beyond language: mapping cognition and emotion. Neurosurg Clin N Am. 2019;30:75-83.
21. Duffau H, Capelle L, Denvil D, Sichez N, Gatignol P, Taillandier L, et al. Usefulness of intraoperative electrical subcortical mapping during surgery for low-grade gliomas located within eloquent brain regions: functional results in a consecutive series of 103 patients. J Neurosurg. 2003;98:764–778.
22. Duffau H, Gatignol P, Mandonnet E, Peruzzi P, Tzourio-Mazoyer N, Capelle L. New insights into the anatomo-functional connectivity of the semantic system: a study using cortico-subcortical electrostimulations. Brain. 2005;128:797–810.
23. Duffau H, Lopes M, Arthuis F, Bitar A, Sichez J-P, Van Effenterre R, et al. Contribution of intraoperative electrical stimulations in surgery of low grade gliomas: a comparative study between two series without (1985-96) and with (1996-2003) functional mapping in the same institution. J Neurol Neurosurg Psychiatry. 2005;76:845–851.
24. Metz-Lutz M. Standardisation d’un test de denomination orale : controle des effects de l’age, du sexe et du niveau de scolarite chez des sujets adultes normaux. Rev Neuropsychol. 1991;1:73–95.
25. Chong S, Phi JH, Lee JY, Kim S-K. Surgical Treatment of Lesional Mesial Temporal Lobe Epilepsy. J Epilepsy Res. 2013;8:6–11.
26. Yaşargil MG, von Ammon K, Cavazos E, Doczi T, Reeves JD, Roth P. Tumours of the limbic and paralimbic systems. Acta Neurochir (Wien). 1992;118:40–52.
27. Kucukyuruk B, Richardson RM, Wen HT, Fernandez-Miranda JC, Rhoton AL. Microsurgical anatomy of the temporal lobe and its implications on temporal lobe epilepsy surgery. Epilepsy Res Treat. 2012;2012:769825.
28. Ribas EC, Yagmurlu K, Wen HT, Rhoton AL. Microsurgical anatomy of the inferior limiting insular sulcus and the temporal stem. J Neurosurg. 2015;122:1263–1273.
29. Roper SN, Rhoton AL. Surgical anatomy of the temporal lobe. Neurosurg Clin N Am. 1993;4:223–231.

30. Kawashima M, Li X, Rhoton AL, Ulm AJ, Oka H, Fujii K. Surgical approaches to the atrium of the lateral ventricle: microsurgical anatomy. Surg Neurol. 2006;65:436–445.
31. Rubino PA, Rhoton AL, Tong X, Oliveira E de. Three-dimensional relationships of the optic radiation. Neurosurgery. 2005;57:219–227; discussion 219-227.
32. Middlebrooks EH, Yagmurlu K, Szaflarski JP, Rahman M, Bozkurt B. A contemporary framework of language processing in the human brain in the context of preoperative and intraoperative language mapping. Neuroradiology. 2017;59:69–87.
33. Martino J, De Witt Hamer PC, Berger MS, Lawton MT, Arnold CM, de Lucas EM, et al. Analysis of the subcomponents and cortical terminations of the perisylvian superior longitudinal fasciculus: a fiber dissection and DTI tractography study. Brain Struct Funct. 2013;218:105–121.
34. Hickok G, Poeppel D. Dorsal and ventral streams: a framework for understanding aspects of the functional anatomy of language. Cognition. 2004;92:67–99.
35. Barrick TR, Lawes IN, Mackay CE, Clark CA. White matter pathway asymmetry underlies functional lateralization. Cereb Cortex. 2007;17:591–598.
36. Bernal B, Altman N. The connectivity of the superior longitudinal fasciculus: a tractography DTI study. Magn Reson Imaging. 2010;28:217–225.
37. Duffau H, Capelle L, Sichez N, Denvil D, Lopes M, Sichez J-P, et al. Intraoperative mapping of the subcortical language pathways using direct stimulations. An anatomo-functional study. Brain. 2002;125:199–214.
38. Leclercq D, Duffau H, Delmaire C, Capelle L, Gatignol P, Ducros M, et al. Comparison of diffusion tensor imaging tractography of language tracts and intraoperative subcortical stimulations. J Neurosurg. 2010;112:503–511.
39. Saur D, Kreher BW, Schnell S, Kümmerer D, Kellmeyer P, Vry M-S, et al. Ventral and dorsal pathways for language. Proc Natl Acad Sci USA 105. 2008;18035–18040.
40. Schmahmann JD, Pandya DN, Wang R, Dai G, D'Arceuil HE, de Crespigny AJ, et al. Association fibre pathways of the brain: parallel observations from diffusion spectrum imaging and autoradiography. Brain. 2007;130:630–653.
41. Almairac F, Herbet G, Moritz-Gasser S, de Champfleur NM, Duffau H. The left inferior fronto-occipital fasciculus subserves language semantics: a multilevel lesion study. Brain Struct Funct. 2015;220:1983–1995.
42. Güngör A, Baydin S, Middlebrooks EH, Tanriover N, Isler C, Rhoton AL. The white matter tracts of the cerebrum in ventricular surgery and hydrocephalus. J Neurosurg. 2017;126:945–971.
43. Vassal F, Schneider F, Boutet C, Jean B, Sontheimer A, Lemaire J-J. Combined DTI Tractography and Functional MRI Study of the Language Connectome in Healthy Volunteers: Extensive Mapping of White Matter Fascicles and Cortical Activations. PLoS ONE. 2016;11:e0152614.
44. Klein AP, Sabsevitz DS, Ulmer JL, Mark LP. Imaging of Cortical and White Matter Language Processing. Semin Ultrasound CT MR. 2015;36:249–259.
45. Martino J, Brogna C, Robles SG, Vergani F, Duffau H. Anatomic dissection of the inferior fronto-occipital fasciculus revisited in the lights of brain stimulation data. Cortex. 2010;46:691–699.
46. Duffau H, Herbet G, Moritz-Gasser S. Toward a pluri-component, multimodal, and dynamic organization of the ventral semantic stream in humans: lessons from stimulation mapping in awake patients. Front Syst Neurosci. 2013;7:44.

47. Duffau H, Moritz-Gasser S, Mandonnet E. A re-examination of neural basis of language processing: proposal of a dynamic hodotopical model from data provided by brain stimulation mapping during picture naming. Brain Lang. 2014;131:1–10.
48. Duffau H, Gatignol P, Moritz-Gasser S, Mandonnet E. Is the left uncinate fasciculus essential for language? A cerebral stimulation study. J Neurol. 2009;256:382–389.
49. Mandonnet E, Nouet A, Gatignol P, Capelle L, Duffau H. Does the left inferior longitudinal fasciculus play a role in language? A brain stimulation study. Brain. 2007;130:623–629.
50. Catani M, Jones DK, Donato R, Ffytche DH. Occipito-temporal connections in the human brain. Brain. 2003;126:2093–2107.
51. Zemmoura I, Herbet G, Moritz-Gasser S, Duffau H. New insights into the neural network mediating reading processes provided by cortico-subcortical electrical mapping. Hum Brain Mapp. 2015;36:2215–2230.
52. Herbet G, Maheu M, Costi E, Lafargue G, Duffau H. Mapping neuroplastic potential in brain-damaged patients. Brain. 2016;139:829–844.
53. Herbet G, Moritz-Gasser S, Boiseau M, Duvaux S, Cochereau J, Duffau H. Converging evidence for a cortico-subcortical network mediating lexical retrieval. Brain. 2016;139:3007–3021.
54. De Benedictis A, Duffau H. Brain hodotopy: from esoteric concept to practical surgical applications. Neurosurgery. 2011;68:1709–1723; discussion 1723.
55. Duffau H. Hodotopy, neuroplasticity and diffuse gliomas. Neurochirurgie. 2017;63:259–265.
56. Duffau H. Introduction. Surgery of gliomas in eloquent areas: from brain hodotopy and plasticity to functional neurooncology. Neurosurg Focus. 2010;28:Intro.
57. Geyik M, Erkutlu I, Alptekin M, Gezgin I, Mizrak A, Pusat S, et al. Parieto-Occipital Interhemispheric Precuneal Approach to the Lesions of the Atrium: Experience with 66 patients. Turk Neurosurg. 2017;27:325–332.
58. Schramm J, Aliashkevich AF. Temporal mediobasal tumors: a proposal for classification according to surgical anatomy. Acta Neurochir (Wien). 2008;150:857–864; discussion 864.
59. Uribe JS, Vale FL. Limited access inferior temporal gyrus approach to mesial basal temporal lobe tumors. J Neurosurg. 2009;110:137–146.
60. Quinones-Hinojosa A, Raza SM, Ahmed I, Rincon-Torroella J, Chaichana K, Olivi A. Middle Temporal Gyrus Versus Inferior Temporal Gyrus Transcortical Approaches to High-Grade Astrocytomas in the Mediobasal Temporal Lobe: A Comparison of Outcomes, Functional Restoration, and Surgical Considerations. Acta Neurochir Suppl. 2017;124:159–164.

Figure legends

Figure 1. Patient 1. Pre-operative axial FLAIR (A), coronal T2 (B), coronal T1 (C), sagittal T1 (D) and axial T1 MRI (E) as well as 3D reconstruction (F) showing a left postero-superior MBTR glioma. Tractography in C-F as follows: IFOF (orange); ILF (green); AF (yellow); OR (purple). The lateral edge of the lesion is marked with a red X in D and E which demonstrates the confluence of subcortical tract in the vicinity of the lesion. Postoperative axial FLAIR (G) and coronal T2 (H) MRI 3 months following surgery revealed GTR using a surgical approach via the MTG. AF, arcuate fasciculus; GTR, gross total resection; IFOF, inferior fronto-occipital fasciculus; ILF, inferior longitudinal fasciculus; MBTR, mediobasal temporal region; MTG, middle temporal gyrus; OR, optic radiation

Figure 2. Patient 2. Preoperative axial FLAIR (A) and coronal T2 (B) MRI showing a left MBTR with posterior extension. (C) Intraoperative photograph before resection. Cortical DES identified the vPMC (sites 1, 2) which elicited speech arrest. No eloquent areas have been detected by DES at the level of the temporal cortex (letter tags correspond to the tumor boundaries identified by ultrasonography). (D) Intraoperative photograph after resection demonstrating a surgical approach via the MTG, with functional pathways identified by axonal DES which served as subcortical boundaries. Immediate postoperative axial FLAIR MRI (E) and coronal T2 MRI (F) showing GTR. DES, direct electrical stimulation; GTR, gross total resection; MBTR, mediobasal temporal region; MTG, middle temporal gyrus; vPMC, ventral premotor cortex.

Figure 3. Preoperative axial FLAIR (A) and coronal T2 MRI (B) demonstrating a left posterior MBTR glioma with superior extension. (C) Surgical view 3D reconstruction with tractography shows IFOF (orange); ILF (green); AF (yellow); OR (light blue); CST (dark blue). (D) Intraoperative photograph after resection which shows a positive cortical mapping (1 and 2, ventral premotor cortex; 3, naming site at the level of the posterior STG) and a surgical approach via the MTG, with functional pathways ILF, IFOF and AF identified by axonal DES which served as subcortical boundaries (see Video). Postoperative coronal T2 (E) and axial FLAIR (F)

MRI 3 months after surgery demonstrating GTR. AF, arcuate fasciculus; CST, corticospinal tract; DES, direct electrical stimulation; IFOF, inferior fronto-occipital fasciculus; ILF, inferior longitudinal fasciculus; MBTR, mediobasal temporal region; MTG, middle temporal gyrus; OR, optic radiation; STG, superior temporal gyrus.

Figure 4. Patient 4. Preoperative axial FLAIR (A) and coronal T2 (B) MRI demonstrating a left posterior MBTR glioma with superior extension. (C) Intraoperative photograph before resection. Cortical DES identified the vPMC (sites 1, 2) which elicited speech arrest. No eloquent areas have been detected by DES at the level of the temporal cortex. Intraoperative photograph after MTG corticectomy revealing AF (site 48) and ILF (site 49) identified by axonal DES. (D) Immediate postoperative axial FLAIR (E) and coronal T2 (F) MRI showing residual glioma which was deemed unsafe to remove in this post-radiated patient due to adherences to the pulvinar, although the tumor was clearly visible and accessible thanks to the surgical approach. AF, arcuate fasciculus; DES, direct electrical stimulation; ILF, inferior longitudinal fasciculus; MBTR, mediobasal temporal region; MTG, Middle temporal gyrus; vPMC, ventral premotor cortex

Figure 5. Patient 5. Preoperative axial FLAIR (A), sagittal FLAIR (B) and coronal T2 (C) MRI demonstrating a large left MBTR glioma with postero-superior extension. (D) Intraoperative photograph before resection. Cortical DES identified the vPMC (sites 2, 3) due to articulatory impairment and tongue dysesthesias (sites 1, 4); posterior STG (site 5) which resulted in phonological paraphasias; and posterior MTG (7) which resulted in semantic paraphasias (letter tags correspond to the tumor boundaries identified by ultrasonography). (E) Intraoperative photograph after resection showing a surgical approach via the MTG, with functional pathways which served as subcortical boundaries: axonal DES identified IFOF (45) due to semantic paraphasias; and ILF (50) due to complete anomia. Postoperative axial FLAIR (F), sagittal FLAIR (G) and coronal FLAIR (H) MRI 3 months after surgery, demonstrating GTR. DES, direct electrical stimulation; GTR, gross total resection; IFOF, inferior fronto-occipital fasciculus; ILF, inferior longitudinal fasciculus; MBTR, mediobasal temporal region; MTG, middle temporal gyrus; STG, superior temporal gyrus; vPMC, ventral premotor cortex.

Figure 6. (A) The inferior MBTR is outlined in green. The uncus (asterisks) and tentorium (arrow) are shown. The ventricular system is segmented in blue and the anterior-most portion of the temporal horn is seen just lateral to the MBTR (the area outlined in blue within the MBTR represents an open CSF channel). (B, C, E, F) 3D projections of the cortical surface with the ventricular system segmented in blue for contextual understanding of the anatomical relationships. The OR (B) begin at the lateral geniculate nucleus and then take a lateral course before turning posteriorly to the occipital lobe. This tract forms the roof of the posterior temporal horn. (C) The STG (pink) and MTG/ITG (lavender) are segmented and the SLF/AF (yellow) is shown with branches to both the STG and MTG. (D) Coronal T1 MRI demonstrating the relationship among the atrium of the lateral ventricle (blue outline), OR (green), IFOF (purple) and the SLF/AF. The OR forms the roof of the atrium and sits medial to the SLF/AF whereas the IFOF forms the infero-lateral border and a portion of the floor of the atrium. (E) Relationship between the ventricle (blue), OR (dark green), ILF (light green) and UF (pink). (F) The IFOF (purple) is shown along its course from the occipital to the frontal lobe. The ventricular system is shown segmented in blue. The STG and MTG/ITG are shown in pink and lavender, respectively. AF, arcuate fasciculus; ILF, inferior longitudinal fasciculus; ITG, inferior temporal gyrus; MBTR, mediobasal temporal region; MTG, middle temporal gyrus; OR, optic radiation; SLF, superior longitudinal fasciculus; STG, superior temporal gyrus; UF, uncinate fasciculus

Abbreviation List

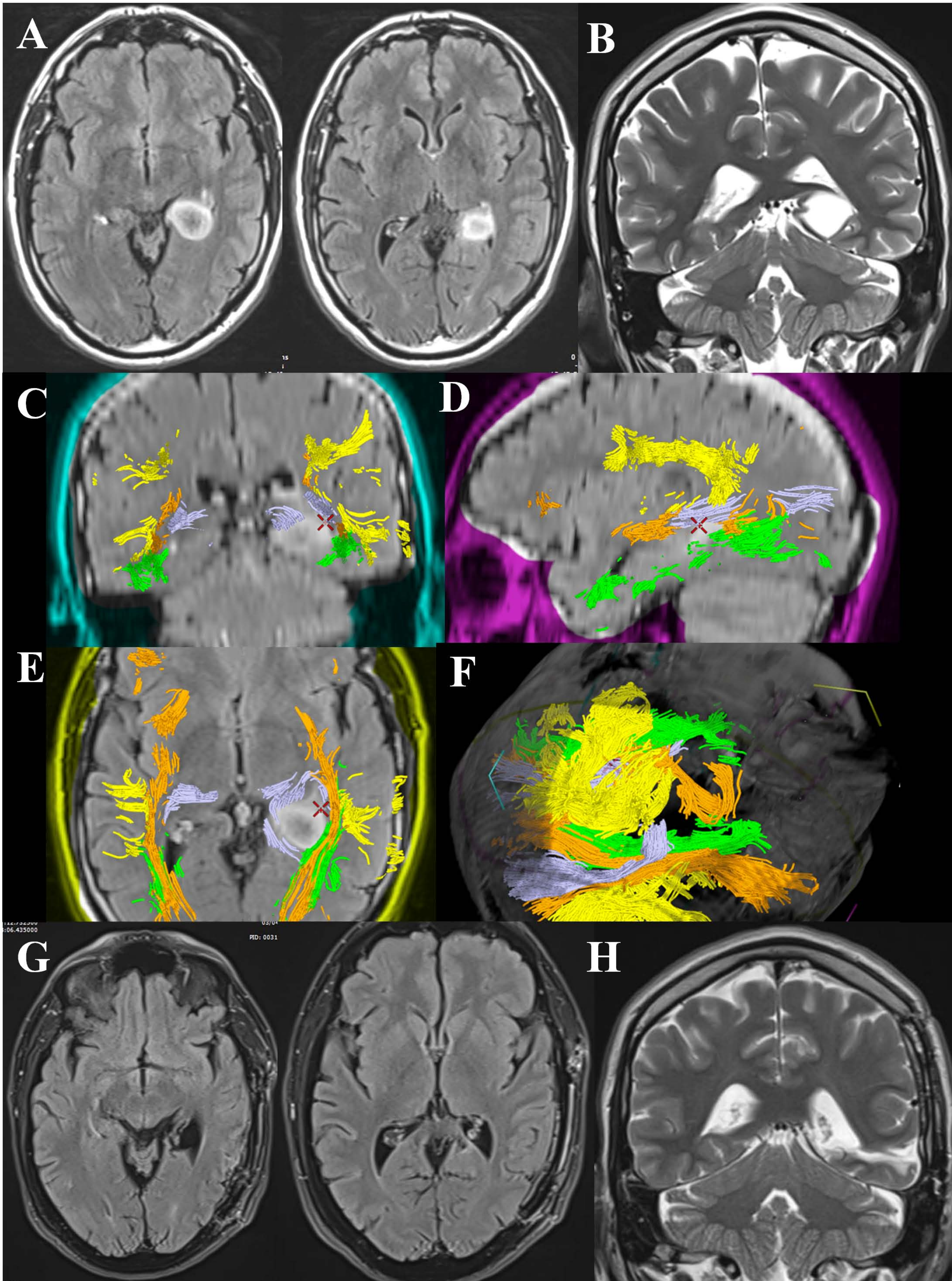
AF, arcuate fasciculus
CST, corticospinal tract
DES, direct electrical stimulation
GTR, gross total resection
IFOF, inferior fronto-occipital fasciculus
ILF, inferior longitudinal fasciculus
ITG, inferior temporal gyrus
MBTR, mediobasal temporal region
MTG, middle temporal gyrus
OR, optic radiation
SLF, superior longitudinal fasciculus
STG, superior temporal gyrus
UF, uncinate fasciculus
vPMC, ventral premotor cortex

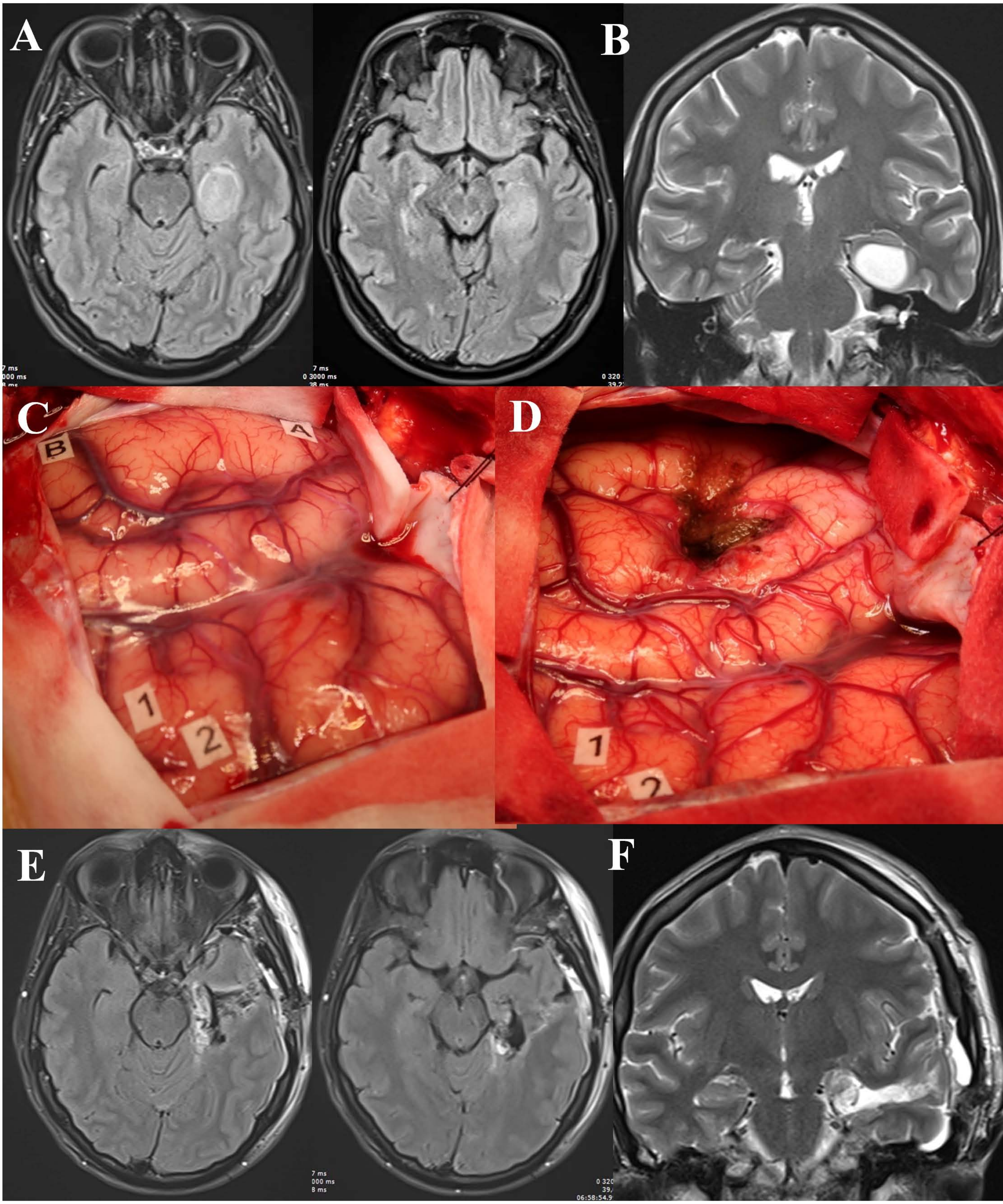
Highlights

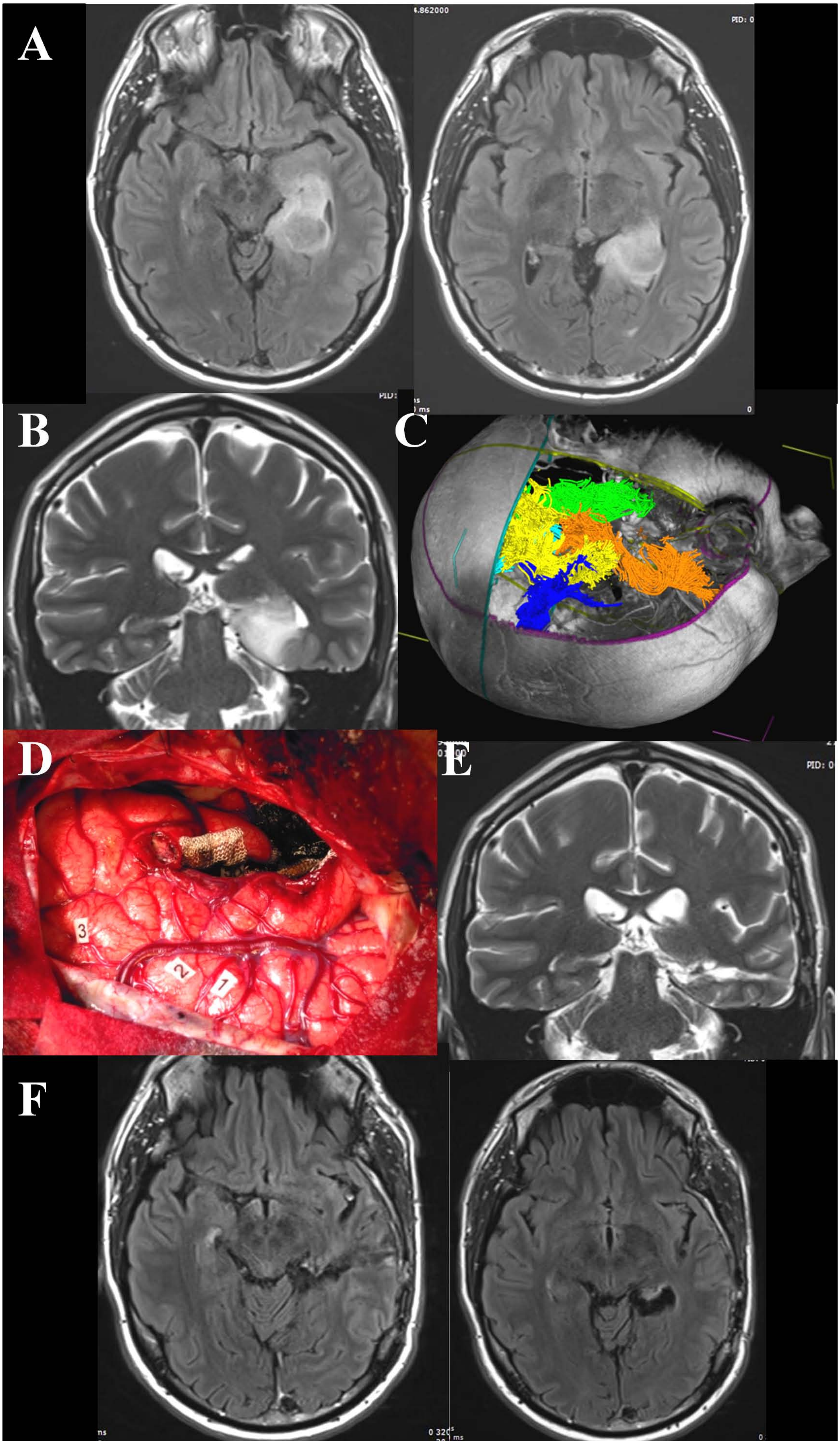
- Posterior mediobasal temporal region tumors are challenging to resect
- Resection of tumors in this region is associated with high morbidity
- Awake intraoperative mapping improves the margin of safety
- Successful mapping requires knowledge of the relevant white matter anatomy including the arcuate fasciculus, the inferior longitudinal fasciculus, the inferior fronto-occipital fasciculus and optic radiations

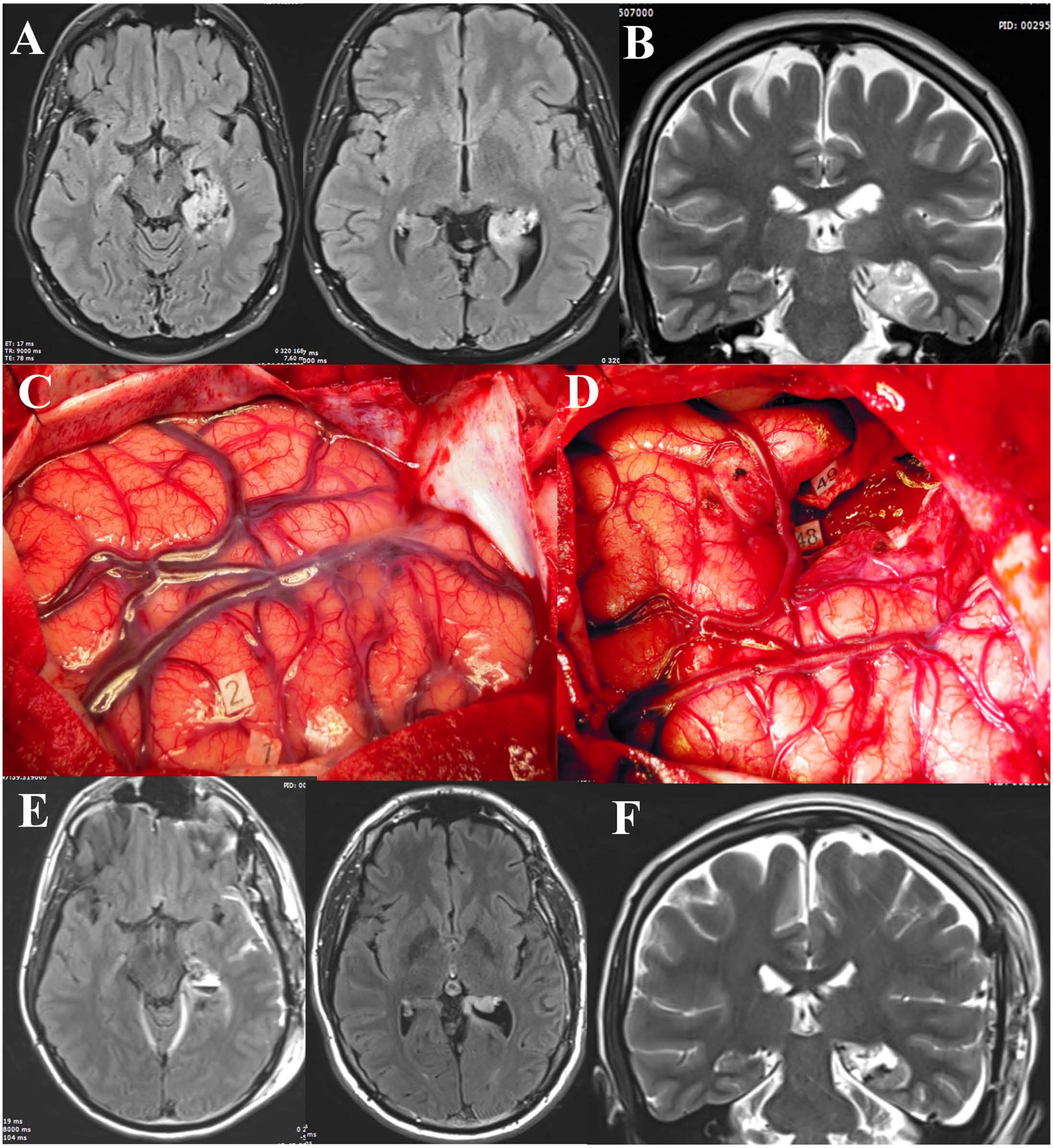
Table 1. Clinical, radiological and pathological characteristics of included patients

	Age/Sex	Presentation Details	Pathology	EOR	Post-op Assessment
Patient 1	54/M	Sudden hearing loss prompted MRI resulting in incidental lesion discovery. Followed locally for prior to referral and remained asymptomatic, with no cognitive deficit. Ultimately referred due to lesion growth.	WHO Grade II Glioma	GTR	Transient slowed reading task No visual field cut Returned to work at 3 months
Patient 2	34/F	Right temple pressure prompting MRI which showed incidental lesion. Asymptomatic. Normal cognitive assessment.	WHO Grade II Glioma	GTR	No neurocognitive deficits No visual field cut Returned to work at 3 months
Patient 3	32/M	Generalized seizure. Followed locally for 2 years prior to referral with continued seizures. Ultimately referred due to continued growth and new punctate contrast enhancement. Pre-op assessment showed deficits in verbal memory and semantic fluency.	WHO Grade IV Glioma	GTR	Stable neurocognitive deficits No visual field cut Complete seizure control Returned to work at 3 months
Patient 4	24/M	New-onset seizures prompting MRI. Underwent stereotactic needle biopsy revealing diffuse astrocytoma. Received 30 sessions of radiotherapy in another department. Referred 3 years later due to intractable partial epilepsy and increasing tumor volume. Baseline neuropsychological assessment revealed deficits in working memory, attention and executive functions.	WHO Grade II Glioma	STR	Stable neurocognitive deficits No visual field cut Complete seizure control Returned to work at 3 months
Patient 5	52/M	Progressive memory impairment and emotional disturbance prompted MRI. Referred 3 years later due to refractory symptoms and lesion growth. Preoperative neuropsychological assessment revealed deficits in language.	WHO Grade II Glioma	GTR	Stable neurocognitive deficits No visual field cut Returned to work at 3 months

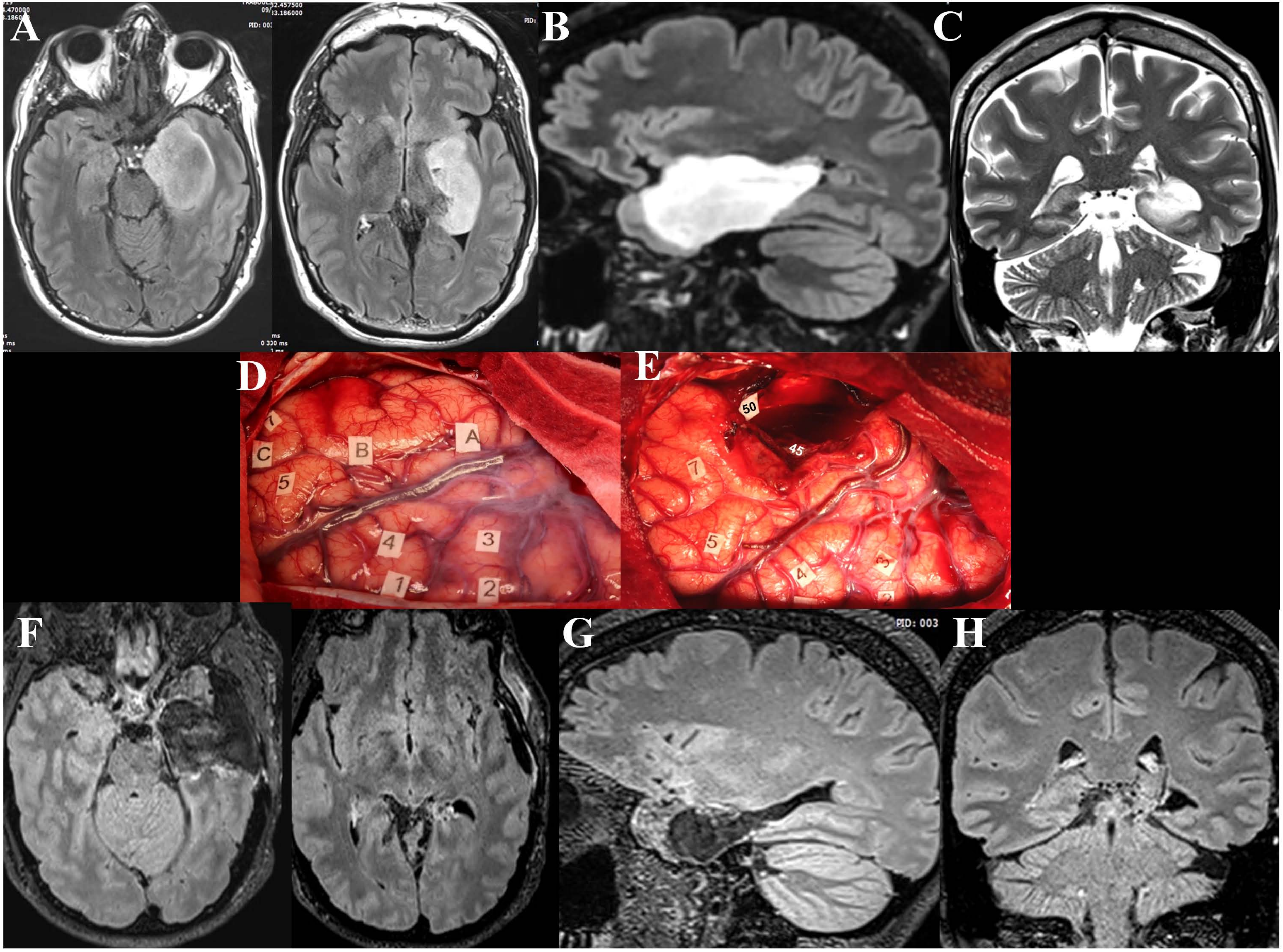

A
B
C
D
E
F
G
H

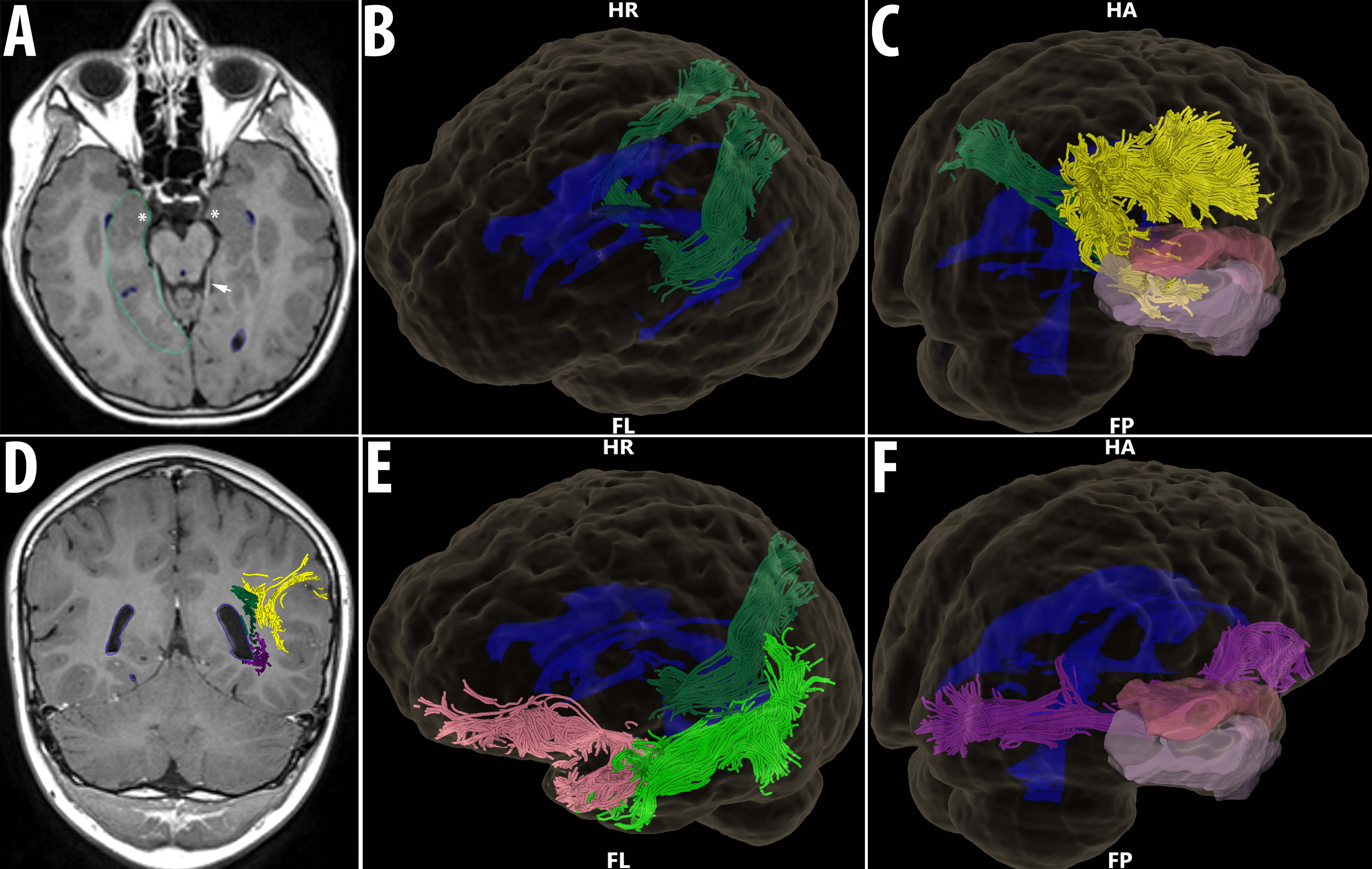

A
B
C
B
A
1
2
D
1
2
E
F


A
4.862000
B
C
D
3
2
1
E
F



A
B
C
D
E
F


A
B
C
D
E
F
G
H
A
B
C
1
2
3
4
5
7
50
45
PID: 003


A
B
HR
FL
C
HA
FP
D
E
HR
FL
F
HA
FP