Risk Reduction in Dominant Temporal Lobe Epilepsy Surgery Combining fMRI/DTI Maps, Neuronavigation and Intraoperative 1.5-Tesla MRI

Karl Rössler^a Bjoern Sommer^a Peter Grummich^a Hajo M. Hamer^b Elisabeth Pauli^b
Roland Coras^c Ingmar Blümcke^c Michael Buchfelder^a

^aDepartment of Neurosurgery, ^bDepartment of Neurology, Epilepsy Centre, and ^cDepartment of Neuropathology, University Hospital Erlangen, Erlangen, Germany

Key Words

Dominant temporal lobe epilepsy surgery · Functional imaging · Speech and memory functional magnetic resonance imaging · Visual field diffusion tensor imaging · Neurological and seizure outcome · Complications in epilepsy surgery

Abstract

Background: In dominant temporal lobe epilepsy surgery, speech, memory and visual systems are at risk. **Objective:** Functional magnetic resonance imaging (fMRI) and diffusion tensor imaging combined with intraoperative neuronavigation and MRI were investigated retrospectively regarding risk reductions for favorable neurological and seizure outcome. **Methods:** Functional imaging risk maps were generated for 14 patients suffering from dominant temporal lobe epilepsy [7 with hippocampal sclerosis (HS), 7 with various lesions] and used for neuronavigation-guided tailored resection. Postoperative neurological and seizure outcome and complications were evaluated. **Results:** None of the patients had postoperative speech dysfunction despite 2.3/3.6-cm mean hippocampal/neocortical resec-

tion. Verbal memory decline was found in 2 of the 14 (14.3%) patients, correlating with surgical lesions in fMRI memory-activated functional areas in the dominant posterior parahippocampal gyrus. Verbal memory scores did not statistically differ between the HS and the lesional group, neither pre- nor postoperatively. A contralateral visual field defect occurred in 1 patient (7.1%). An Engel class I seizure outcome was found in 12 patients (85.7%), and 11 were completely seizure free (78.6%) at a mean follow-up of 19.5 months. **Conclusion:** This retrospectively investigated protocol led to an excellent neurological and seizure outcome and a low complication rate in dominant temporal lobe epilepsy surgery.

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Introduction

Dominant temporal lobe epilepsy surgery has its defined postoperative risks of neurological deterioration [1–3]. Neocortical resections may compromise sensory cortical speech areas [4] and removal of mesial structures may endanger memory function, whereas lobar re-

sections can be complicated by hemianopia [1, 5]. Bilateral Wada testing may help to define the dominant temporal lobe and investigate reorganization of speech and memory to ipsilateral distant areas or to the contralateral side, but it is not able to demonstrate the topographical localization of functional areas on the magnetic resonance (MR) scans used for navigated surgery [6, 7]. Employing functional MR imaging (fMRI), localization of eloquent brain areas involved in speech and memory processing can be fused with MR scans and thus guide surgical interventions by using neuronavigation [8].

Furthermore, neuronavigation is able to colocalize fMRI functional areas to the intraoperatively exposed cortex [9]. Additionally, diffusion tensor imaging (DTI) localizes subcortical tracts, which can also be integrated in the intraoperative neuronavigation to avoid damage [10–12]. Moreover, intraoperative MRI may enable the surgeon to compensate for brain shift during neuronavigation and may help to guide maximized resection and to avoid injury to adjacent eloquent cortical or white matter tract systems [13]. Combining fMRI, neuronavigation and intraoperative MRI for surgery of lesional dominant temporal lobe epilepsy is promising and may lead to favorable postoperative results and enhance the percentage of seizure-free patients.

To investigate this hypothesis, we retrospectively analyzed the outcome of patients, in whom we integrated speech, memory and visual tract functional maps for surgery within the dominant temporal lobe employing neuronavigation and intraoperative MRI for resection guidance, correction of brain shift and reduction of surgical complications.

Patients and Methods

Patients

Fourteen right-handed patients (8 male, 6 female, median age 38 years, range 9–70 years), most of them suffering from medically intractable dominant temporal lobe epilepsy, were operated on for left temporal lesions at the Neurosurgical Clinic, University Hospital Erlangen, and retrospectively included in the study. Preoperatively, they were evaluated using a Level IV Epilepsy Center protocol. Eight patients additionally had preoperative Wada tests [14, 15]. In all of the 8 patients, a left-sided speech and verbal memory dominance was found. This was confirmed by the fMRI for speech paradigms, which matched all 8 Wada tests in 100%. Histologically, there were two patient groups: 7 patients had hippocampal sclerosis (HS), and 7 patients had various other lesions (table 1). Clinically, 12 patients had chronic medically refractory temporal lobe epilepsy with a mean duration of 14 years (from 2 to 48

years). Patient 9 (table 1) with a diffuse astrocytoma WHO grade II had a short history of epilepsy beginning 2 months before surgery, and the 9-year-old boy (patient 14) suffering from a ganglioglioma of WHO grade I started to develop overt seizures 3 months before surgery. In 7 patients, a classic history and electroclinical correlate of mesial temporal lobe epilepsy were diagnosed, showing typical HS on multisequential diagnostic 3-tesla MRI scans preoperatively (patients 4–7 and 11–13; table 1) and histologically. The histological subtype of HS was determined by the ILAE classification [16]. Case 12 was combined with focal cortical dysplasia type IIIa according to Blümcke et al. [17]. The other 7 patients also presented with electroclinical temporal lobe epilepsy but exhibited various lesions within the left temporal lobe in the preoperative 3-tesla MRI protocol (1 astrocytoma WHO grade II, 1 ganglioglioma WHO grade I, 1 cavernoma, 1 focal scar tissue, 1 mild malformation of cortical development type II [18] and 2 lesions with microglial activation; table 1). The dominant seizure type was complex-partial in all patients, partly with generalization in 10 patients. Patient demographics and results are displayed in detail in table 1.

Preoperative Functional Imaging Using fMRI and DTI fMRI and DTI Data Acquisition

For fMRI acquisition we used a 1.5-tesla MR scanner with echo-planar imaging (Sonata, Siemens, Erlangen, Germany). Images were taken using 25 slices with 3 mm thickness each and resolution of TR = 2,470 ms, TE = 60 ms. Tests were performed in a block design ('boxcar'). An image-based prospective acquisition correction for head motion was used [19]. Hence, interpolation was done in the k-space. The measurements were interpolated to 75 slices with 1 mm in plane resolution. Activation maps were individually determined by analyzing the correlation for each pixel between signal intensity and a square wave reference function according to the paradigm. Pixels exceeding a threshold of 0.40 were displayed only if at least 6 continuous voxels of the measured slices built a cluster, in order to eliminate isolated voxels. The functional slices were aligned to magnetization-prepared rapid acquisition gradient echo (MPRAGE) images with 160 slices of 1 mm slice thickness and resolution obtained in the same patient position for neuronavigation.

DTI Protocol

DTI uses the directional properties of diffusion of water molecules in the brain tissue. The direction of the greatest diffusion measured with this technique matches the dominant orientation of axons in white matter, thus displaying neuronal fiber tracts. The DTI data were acquired using a single-shot spin-echo diffusion-weighted echo-planar imaging sequence (TE 86 ms, TR 9,200 ms, matrix size 128 × 128, FOV 198 mm, slice thickness 1.9 mm). The DTI technique was used to visualize the course of white matter tracts in the brain in the immediate neighborhood of the surgical field or surgical corridor to the lesions, hence for preservation of the optical radiation in the temporal lobe [20, 21]. It uses the determination of brain tissue water diffusion in three-dimensional space, with the dominant orientation of axons in white matter being given by the direction of the greatest diffusion. The so-called 'fiber tracking', which implies calculation and visualization of nerve fiber bundles, was also described previously from our institution [12, 13, 22]. In this study, tractography was performed using the 'Fiber Tracking' module of

Table 1. Patient demographics and results

Case	Age, years	Age at onset, years	Epi duration, years	Seizure type	Sex	Wada test	fMRI	fMRI results	Diagnosis	Histology	Engel outcome	Resection type	Extent of TLR, cm	Extent of HR, cm	FU time, months	Visual field deterioration	Speech dysfunction	Memory preop.	Memory postop.
4	29	7	22	c.p./g.	M	0	s, v, m	left-dom.	TLE left, HS	HS NOS	Ia	ATR	3.5	1.8	30	0	0	-1	-1
5	25	10	15	c.p./g.	F	0	s, v, m	left-dom.	TLE left, HS	HS NOS	Ia	ATR	3.8	2.7	19	0	0	-2	-2
6	57	41	16	c.p.	M	0	s, v, m	left-dom.	TLE left, HS	HS MTS 1	Ib	TLR	4.1	2.9	23	0	0	-2	-2
7	24	9	15	c.p./g.	M	left-dom.	s, v, m	left-dom.	TLE left, HS	HS MTS 1	Ia	SAHE	0.0	2.7	33	0	0	0	-2
11	58	23	35	c.p.	F	left-dom.	s, v, m	left-dom.	TLE left, HS	HS MTS 1	Ia	ATR	4.0	2.8	17	0	0	-1	-1
12	28	15	13	c.p./g.	M	left-dom.	s, v, m	left-dom.	TLE left, HS	HS FCD IIIa	Ia	ATR	4.1	3.2	15	y	0	0	0
13	52	4	48	c.p./g.	F	left-dom.	s, v, m	left-dom.	TLE left, HS	HS NOS	Ia	ATE	2.6	2.7	7	0	0	0	0
8	50	46	4	c.p./g.	F	left-dom.	s, v, m	left-dom.	TLE left, lesion	microglial activation	IIIa	ATR	4.0	2.4	19	0	0	-2	-3
9	70	70	0	c.p./g.	M	0	s, v, m	left-dom.	TLE left, lesion	Astro II	Ib	ATR	5.5	3.2	25	0	0	-2	-2
10	47	45	2	c.p./g.	M	0	s, v, m	left-dom.	TLE left, lesion	microglial activation	Ia	ATR	3.7	2.5	24	0	0	-2	0
1	21	19	2	c.p./g.	F	left-dom.	s, v, m	left-dom.	TLE left, lesion	mMCD II	Ia	L-ectomy	2.0	1	22	0	0	0	0
2	29	15	14	c.p./g.	M	left-dom.	s, v, m	left-dom.	TLE reop. left, FCD	scar tissue	Ia	ATR	3.8	1.7	13	0	0	0	0
3	31	29	2	c.p.	F	left-dom.	s, v, m	left-dom.	TLE left, lesion	cavernoma	Ia	L-ectomy	2.5	1.5	17	0	0	0	0
14	9	9	0	c.p.	M	0	s, v, m	left-dom.	TLE left, lesion	GG I	Ia	L-ectomy	3.8	1	10	0	0	0	0

Epi duration = Epilepsy duration; ATR = anterotemporal resection; SAHE = selective amygdalohippocampectomy; HR = hippocampal resection; FU = follow-up; c.p. = complex partial; g. = with generalization; F = female; M = male; fMRI: s = speech, v = visual, m = memory; reop. = reoperation; FCD = focal cortical dysplasia; mMCD = mild form of malformation

of cortical development; Astro = astrocytoma; GG = ganglioglioma; L-ectomy = lesionectomy; TLR = temporal lobe resection; y = yes; 0 = no; NOS = not otherwise specified; MTS 1b = mesial temporal sclerosis type 1b, according to Blümcke et al. [16]; left-dom. = left-dominant; TLE = temporal lobe epilepsy.

the navigation planning software iPlan 2.6 (Brainlab, Feldkirchen, Germany). The diffusion tensor's main axis of direction had a minimum fiber length of 50 mm. The diffusion probability density function was used to determine diffusion tensors and their preferred direction within a specific three-dimensional brain position (voxel). The proportion of molecules in a voxel was calculated by vector from six different diffusion-weighted acquisitions, each obtained with a different orientation of the diffusion sensitizing gradients. We set the starting point (region of interest) for pyramidal tract reconstruction in the primary motor cortex (hand, arm, leg, foot area). Broca's and Wernicke's cortical speech areas as well as the primary visual cortex were

chosen as a starting region of interest for the language and visual tracts.

Speech and Memory Paradigms

In this study, we used specific cognitive tasks for memory and speech localization. A block design experiment was chosen, which is known to have the benefit of a better signal-to-noise ratio, greater sensitivity in the detection of subtle activation patterns in individuals, and better recognition of artifacts than an event-related design [23, 24]. The paradigms used are described in detail elsewhere [8].

Fig. 1. Case example: patient 3, a 31-year-old female suffering from epilepsy due to a left temporomesial cavernoma, presented with a history of medically refractory left temporal lobe epilepsy with daily complex partial seizures. MRI investigation demonstrated a left temporomesial cavernoma with a hemosiderosis around the le-

sion. The MPRAGE planning MRI is demonstrated, with functional areas fused. The lesion is outlined in pink (A), the adjacent memory-relevant fMRI area (B) and Wernicke's area are drawn in green (C) and the visual tract DTI is drawn in purple (D; colors refer to the online version only).

For speech and memory paradigms, visual stimulation was performed. We projected words onto a chalkboard which the patient could clearly see through a mirror inside the MR scanner in supine position. To identify language regions and lateralization, we performed either a 'build sentence from a given noun' or 'conjugate a

given verb' task to avoid the activation of factual knowledge, which is defined as information gained by the individual's semantic ability such as remembering vocabulary. All paradigms were based on verbal material.

To localize regions of factual knowledge, we used either (a) the recall of names of well-known countries' capital cities or (b) multiplication tasks using single digits. During the capital city paradigm, names of 40 well-known countries were displayed for recall. The interstimulus interval was adjusted to the abilities of the subject, and the tasks were completed in covert mode where the patient had just to think of the answer.

For examining encoding and recall in short-term memory, patients were asked to memorize three consecutively displayed numbers and recall them after the third number. This task also hindered the use of factual knowledge.

We tested the ability of recall in consolidated memory only by letting the patient recall words related to numbers shown during measurements or remembering owners of telephone numbers. The words or names that were related to the numbers were learned before measurements, followed by a period of distraction of the patient's attention.

A test battery of paradigms was performed in every patient, demonstrating individual differences in the effectiveness of single paradigms for the generation of speech- and memory-activated areas. Thus, the localization of Wernicke's, Broca's and memory-activated areas was displayed on the images, and clear hemispheric dominance could be determined.

An evaluation of the fMRI protocol in respect to accuracy and correlation to the clinical outcome was successfully performed in a previous study [8].

Intraoperative Functional Neuronavigation and MRI

Functional MR images for memory and speech networks as well as DTI reconstruction of the visual pathway of the left hemisphere were integrated in the MPRAGE T1 neuronavigation images. Risk areas as well as the lesion volumes were segmented and displayed in different colors on the scans and projected through the microscope onto the intraoperative operating field. Thus, the operation microscope (Pentero, Zeiss, Oberkochen, Germany) was used to integrate the functional risk maps for targeting and guiding the resection of the lesions intraoperatively using standard microsurgical techniques as described earlier [25]. During lesion resection, the ocular displayed risk areas were respected and lesioning of risk brain areas avoided, especially concerning speech- and memory-relevant cortical areas and the visual tract. At the end of resection, the extent of neocortical resection and of hippocampal resection was measured in centimeters and documented in the patient's surgical report. One patient had a selective transcortical amygdalohippocampectomy, where the neocortical resection was rated 0. Values of the amount of resected tissue in centimeters are displayed in table 1.

Intraoperative MRI Protocol and Resegmentation of Residual Lesions

Surgical Workflow

Details of the intraoperative workflow and setup have been published before [26]. In summary, imaging in the MR operating room started before surgery after rotating the patient with the head fixed in a ceramic head holder (NORAS MRI products GmbH, Höchberg, Germany) into the intraoperative MRI scanner under general anesthesia before draping (1.5-tesla MRI, Magnetom Sonata Maestro Class, Siemens Healthcare, Erlangen, Germany). MRI scans included a T1-weighted MPRAGE sequence [TE 4.38 ms, TR 2,020 ms, matrix size of 128×128 (interpolated

to 256×256), FOV 250 mm, slice thickness 1 mm, slab 16 cm], T2-weighted coronal and transversal images (TE 98 ms, TR 6,520 ms, matrix size 512×307 , FOV 250 mm, slice thickness 3 mm) and DTI sequences (TE 86 ms, TR 9,200 ms, matrix size 128×128 , FOV 240 mm, slice thickness 3 mm). Images then were transferred into the navigation system (Vector Vision Sky, Brainlab) and fused with the functional images obtained the day before surgery using neuronavigation software (iPlan 2.6, Brainlab). We used the MPRAGE and T2 images for segmentation of the lesion and coregistration of functional data. After planning the ideal trajectory, we transferred the navigation plan to the operation microscope (OPMI Pentero, Zeiss). Coregistration of preoperative and initial intraoperative MRI sequences with anatomical structures was performed with a median error of 2 ± 0.7 mm of the navigation system.

Surgical Technique and Intraoperative MRI

With the aid of navigational trajectory and superimposing the boundaries of the segmented lesion, the skin flap and craniotomy were planned before skin incision. Consequently, the lesionectomy was then performed after skin incision and craniotomy using microsurgical techniques. If the neurosurgeon had the impression that the intended resection extent was reached and/or he was too close to the displayed boundaries of eloquent brain areas or white matter fiber tracts, an intraoperative MRI scan was acquired, using the above protocol. In cases of a resectable residual lesion, the residuals were resegmented in the navigation system, and the new contour of the residual lesion was projected onto the surgical field. Surgery was continued, the residual lesion was resected if not eloquently located, and completeness of lesionectomy was documented with a new intraoperative 'final' intraoperative MRI scan before the closing procedure started. In cases where the residual lesion was considered impossible for resection due to eloquent location, we performed the standard dural closure and reinsertion of the skull bone right away. Altogether, in cases of primary complete resection, one intraoperative MRI scan was obtained. In cases of residual lesions, two intraoperative MRI scans were obtained. According to the intraoperative images, brain shift could be automatically corrected for the resection of the residual lesions. Seven patients had MRI lesions, where the resection volume was segmented in the navigation system with the iPlan software. In 7 patients with HS, a target volume of 2.5 cm of hippocampus and a 3-cm resection of the temporal pole were attempted.

Neuropsychological Testing

Verbal memory was assessed using the Berlin Amnesia Test [27], a standardized German memory test battery for quantitative assessment of amnesic deficits. Here we used the total verbal memory score (learning of structured and unstructured word lists, testing by free recall and recognition). Results were transformed into z-scores using normal values from healthy subjects. The Berlin Amnesia Test is a German memory inventory composed of eight material- and recall-specific subtests aiming at the diagnosis of memory impairment as a result of brain pathology [27]. The test is adapted to detect empirically established amnesic symptoms [28], with special consideration given to differentiation between individuals in the lower performance range. In addition to the normal population, normative data are also available on specific subpopulations of amnesic patients; z-score values were statistically compared using Student's t test.

Fig. 2. The intraoperative MPRAGE T1 image is fused with the preoperative scans. The lesion is resected completely, the functional areas are preserved.

Results

Speech- and memory-activated brain areas as well as visual tracts were successfully localized by preoperative fMRI using standard paradigms and DTI imaging in every patient, respectively (fig. 1). Speech-relevant fMRI signals were detected predominantly on the left inferior frontal

gyrus and the left posterior superior temporal gyrus. Memory fMRI signals were predominantly localized on the posterior parahippocampal gyrus on the left side in all patients, close to the collateral sulcus, with only weak signals on the corresponding right side, leading to the conclusion that all patients were left dominant. This was confirmed by the Wada test in 8 patients, of whom all were

diagnosed as left dominant with left-sided verbal memory dominance (table 1). Integration of functional images into intraoperative risk maps used for neuronavigation led to a 100% gross total resection rate of the preplanned resection volume in every patient, as confirmed by intra- and postoperative MRI (fig. 1, 2). None of the patients were found to have postoperative speech disturbances (table 1). Although all patients were left dominant and had temporomesial resections with 2.3/3.6-cm mean hippocampal/neocortical resection, verbal memory decline was found in only 2 of the 14 patients (14.3%; table 1). The extent of hippocampal resection in the HS group (7 patients) compared to the lesional group (7 patients) was statistically different ($p < 0.04$; 1.9 cm in the lesional vs. 2.7 cm in the HS group), but the verbal memory z-scores of the 7 HS group patients were not statistically different from those of the 7 patients suffering from other lesions, neither preoperatively nor postoperatively. The analysis of the 2 cases demonstrating verbal memory decline (case 7, from 0 to -2 z-score, and case 8, from -2 to -3 z-score; table 1) revealed surgical lesioning or even resection of preoperatively mapped fMRI essential memory cortical areas within the posterior parahippocampal gyrus, as demonstrated by comparing preoperative memory fMRI and late postoperative scans. In contrast, in 12/14 patients with unchanged postoperative or even improved verbal memory tests, as in 1 patient (case 10, 2 z-scores), essential memory fMRI cortical areas within the posterior parahippocampal gyrus were preserved. There was no correlation between the length of hippocampal resection and seizure outcome (2.2 cm in 8 Engel Ia patients vs. 2.6 cm in 4 Engel II patients, not significant). Superior visual field defects occurred in a single patient (7.1%). An Engel class I seizure outcome was found in 12 patients (85.7%); 11 of them were completely seizure free (78.7%; mean follow-up 19.5 months).

Discussion

Summary of Findings

In dominant temporal lobe surgery with resection of temporomesial structures in order to obtain favorable seizure outcome in patients with HS and various other lesional temporal lobe epilepsies, we retrospectively evaluated the integration of a pre- and an intraoperative protocol of fMRI and DTI combined with neuronavigation, image fusion and MRI to preserve speech, verbal memory and visual fields. In every patient, we successfully localized investigated functional areas preopera-

tively by fMRI and were able to resect preplanned lesion volumes gross totally while preserving speech in 100%, visual tracts in 92.9% and memory in 85.7% using fMRI risk maps, neuronavigation and intraoperative MRI. Notably, verbal memory decline occurred in those 14.3% of the patients in whom we were not able to preserve an fMRI-mapped essential memory-relevant area in the dorsal parahippocampal gyrus close to the collateral sulcus. Thus, the preservation of not only the posterior hippocampus but also the posterior parahippocampal gyrus close to the collateral sulcus seems to be important for avoiding verbal memory decline after temporomesial resection for dominant HS or other temporomesial lesions.

Success-to-Risk Ratio in Dominant Mesial Temporal Lobe Surgery

The risk profile of epilepsy surgery in the dominant temporal lobe is generally serious [2]. Various eloquent structures are at risk: (1) sensory speech function within the dorsal superior temporal gyrus, (2) memory-related functions within the hippocampus and parahippocampal gyrus, and (3) Meyer's loop, part of the visual tract within the superior-lateral border of the temporal ventricular horn [1, 4, 5]. In patients with HS, resection of a significant amount of hippocampus, parahippocampal gyrus as well as amygdala and uncus is necessary to achieve at least a 60–70% success rate in Engel class I outcome [29].

In contrast, significant resection of mesial structures in the dominant hemisphere leads to memory decline in up to 44% of patients [3]. Therefore, medically intractable patients with normal or only slightly reduced memory function are not even selected for surgery within the dominant temporal lobe in some centers [29]. According to recent fMRI studies, the dorsal part of the hippocampus and/or the dorsal parahippocampal gyrus seem to be essential for memory function in dominant HS patients [24]. Thus, we applied memory fMRI paradigms to localize memory-specific key areas for preservation during surgery. Furthermore, we used image fusion, neuronavigation and intraoperative MRI to generate preoperative risk maps, in order to project segmented risk areas onto the operating field during resection via the surgical microscope [9, 30]. Additionally, intraoperative MRI was applied for the evaluation and intraoperative correction of the resection amount as well as for the compensation of brain shift inaccuracy during neuronavigation [31, 32].

Sensory aphasia is another possible complication following dominant temporal lobe surgery. There is some

evidence that temporal lobectomy leads to higher percentages of seizure-free patients in temporal lobe epilepsy and HS than does selective amygdalohippocampectomy [33, 34]. Thus, even including only frontal parts of the superior temporal gyrus in the resection may result in severe word finding difficulties in 12–16% of the patients [35]. Reliable fMRI study techniques for visualization of speech-relevant cortical networks within the temporal neocortex are inevitable for individualized preoperative mapping and intraoperative conservation of speech-relevant cortical areas during surgery [8]. Thus, we prospectively studied the integration of fMRI speech areas into our resection maps in dominant temporal lobe epilepsy for evaluation of possible risk reduction.

Moreover, visual field defects are reported in up to 100% of patients undergoing surgical temporal lobectomies [36]. Therefore, we also decided to prospectively integrate DTI reconstruction of the optical radiation into surgical treatment plans for neuronavigation a few years ago, also due to the fact that Meyer's loop seems to be located even more anterior on the left side, with significant individual differences [5, 22]. According to the goal of the study – to evaluate postoperative risk reduction of visual field defects after dominant temporal lobe surgery – we integrated the visualization of Meyer's loop by DTI in preoperative neuronavigation resection maps for this study.

Functional Imaging, Neuronavigation and Intraoperative MRI in Dominant Temporal Lobe Surgery

Integration of neuronavigation and intraoperative MRI into surgery of lesional temporal lobe epilepsy in our hands resulted in significantly higher complete resection rates in temporal topectomies than reported previously. Thus, lesions can be targeted more safely, and resection rates of 96% are achievable, with a significant reduction of postoperative complications [26]. Including functional information into neuronavigation allowed specifically sparing eloquent cortical areas or deep and eloquent fiber tracts during surgery (fig. 1, 2). Applying the reported protocol to a small retrospective series of dominant temporal lobe surgeries, we achieved a 100% resection rate of segmented lesions with verbal memory deterioration in only 14.3% and superior visual field narrowing in only 7.1% of patients, resulting in an Engel class I outcome of 85.7%, with 78.6% of the patients rendered completely seizure free. These numbers are obviously superior to previously reported surgical results in those specific high-risk lesional dominant temporal lobe epilepsy patients.

Memory Preservation in Dominant Temporal Lobe Surgery

There is an ongoing debate about the ability of postoperative compensation for verbal memory decline after surgery of the posterior parts of the ipsilateral hippocampus versus contralateral temporomesial structures [37]. We found a relevant fMRI memory-related cortical area within the posterior parahippocampal gyrus, which influenced the postoperative memory outcome more positively when preserved than small hippocampal resection (fig. 1, 2). In patients with preservation of this area, no verbal memory deterioration occurred, contrasting with 2 patients with surgical lesioning or even total removal of this area who had a significant deterioration in postoperative memory scores. This finding was independent of the amount of resection of the hippocampus, which was relatively small (mean 2.3 cm) but nevertheless resulted in high percentages of seizure-free patients (Engel class Ia in 78.6% of the patients in this series). These findings provide evidence that the preservation of the posterior parts of the parahippocampal gyrus may be important for memory preservation in surgery of dominant HS patients.

Strength and Weaknesses of the Study

Unfortunately, this study was performed retrospectively, and a protocol without randomizing patients into surgery with and without functional imaging and intraoperative MRI was chosen. On the one hand, we were convinced of an outcome benefit from our protocol in epilepsy patients because of a significant risk reduction in a previous investigation using an fMRI/DTI/intraoperative MRI protocol in tumor patients. On the other hand, it was evident that the number of patients needed for a prospective multiarmed study in this specific patient group of lesional dominant temporal lobe surgery would not have been reached in a foreseeable period of time.

One of the main strengths of the study is that we were able to investigate a homogeneous, epileptologically well-characterized patient population. Nevertheless, we are convinced that a larger number of patients and a longer follow-up period are necessary to prove the benefits from our protocol for operative risk reduction in lesional dominant temporal lobe epilepsy patients.

Conclusion

The reported protocol using functional imaging (speech and memory fMRI as well as visual tract DTI) in surgery of the dominant mesial temporal lobe combined

with neuronavigation and intraoperative MRI led to a favorable neurological and seizure outcome in a small patient series. Further investigations using this strategy are necessary to see if the labor- and cost-intensive pre- and intraoperative protocol may lead to a significantly better outcome in a larger patient cohort undergoing dominant

temporal lobe epilepsy surgery, especially in patients with HS. Moreover, to prove the cost-effectiveness of this protocol compared to a prospective series of patients without using such expansive and sophisticated technology, a prospective comparison of larger patient numbers is needed.

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