Resective surgery for medically refractory epilepsy using intraoperative MRI and functional neuronavigation: the Erlangen experience of 415 patients

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OBJECTIVE Intraoperative overestimation of resection volume in epilepsy surgery is a well-known problem that can lead to an unfavorable seizure outcome. Intraoperative MRI (IMRI) combined with neuronavigation may help surgeons avoid this pitfall and facilitate visualization and targeting of sometimes ill-defined heterogeneous lesions or epileptogenic zones and may increase the number of complete resections and improve seizure outcome.

METHODS To investigate this hypothesis, the authors conducted a retrospective clinical study of consecutive surgical procedures performed during a 10-year period for epilepsy in which they used neuronavigation combined with IMRI and functional imaging (functional MRI for speech and motor areas; diffusion tensor imaging for pyramidal, speech, and visual tracts; and magnetoencephalography and electrocorticography for spike detection). Altogether, there were 415 patients (192 female and 223 male, mean age 37.2 years; 41% left-sided lesions and 84.9% temporal epileptogenic zones). The mean preoperative duration of epilepsy was 17.5 years. The most common epilepsy-associated pathologies included hippocampal sclerosis (n = 146 [35.2%]), long-term epilepsy-associated tumor (LEAT) (n = 67 [16.1%]), cavernoma (n = 45 [10.8%]), focal cortical dysplasia (n = 31 [7.5%]), and epilepsy caused by scar tissue (n = 23 [5.5%]).

RESULTS In 11.8% (n = 49) of the surgeries, an intraoperative second-look surgery (SLS) after incomplete resection verified by IMRI had to be performed. Of those incomplete resections, LEATs were involved most often (40.8% of intraoperative SLSs, 29.9% of patients with LEAT). In addition, 37.5% (6 of 16) of patients in the diffuse glioma group and 12.9% of the patients with focal cortical dysplasia underwent an SLS. Moreover, IMRI provided additional advantages during implantation of grid, strip, and depth electrodes and enabled intraoperative correction of electrode position in 13.0% (3 of 23) of the cases. Altogether, an excellent seizure outcome (Engel Class I) was found in 72.7% of the patients during a mean follow-up of 36 months (range 3 months to 10.8 years). The greatest likelihood of an Engel Class I outcome was found in patients with cavernoma (83.7%), hippocampal sclerosis (78.8%), and LEAT (75.8%). Operative revisions that resulted from infection occurred in 0.3% of the patients, from hematomas in 1.6%, and from hydrocephalus in 0.8%. Severe visual field defects were found in 5.2% of the patients, aphasia in 5.7%, and hemiparesis in 2.7%, and the total mortality rate was 0%.

CONCLUSIONS Neuronavigation combined with IMRI was beneficial during surgical procedures for epilepsy and led to favorable seizure outcome with few specific complications. A significantly higher resection volume associated with a higher chance of favorable seizure outcome was found, especially in lesional epilepsy involving LEAT or diffuse glioma.

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KEY WORDS drug-resistant epilepsy; resective epilepsy surgery; intraoperative MRI; neuronavigation; functional MRI; seizure outcome; surgical complications

ABBREVIATIONS CM = cavernous malformation; DTI = diffusion tensor imaging; ECoG = electrocorticography; EZ = epileptogenic zone; FCD = focal cortical dysplasia; FMR = functional MRI; FOV = field of view; HS = hippocampal sclerosis; IMRI = intraoperative MRI; LEAT = long-term epilepsy-associated tumor; MEG = magnetoencephalography; MPRAGE = magnetization-prepared rapid-acquisition gradient echo.


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In lesional epilepsy surgery, the extent of resection is generally the key prognostic factor for seizure outcome. This tendency holds true particularly in cases in which clear borders are missing or the epileptogenic zone (EZ) exceeds the lesion itself, as is often the case in patients with focal cortical dysplasia (FCD). Surgically accessible pathologies associated with medically refractory epilepsy most often include hippocampal sclerosis (HS), long-term epilepsy-associated tumors (LEATs), cavernous malformations (CMs), or FCD, among others. Overall, treatment of these entities results in a favorable seizure outcome when they are completely resected. In addition, intrinsic epilepsy-associated tumors may have diffuse borders and may be located adjacent to motor or temporal speech areas. A CM or FCD may have contact with deep structures such as speech or visual tracts. Thus, the use of intraoperative structural and diffusion tensor imaging (DTI) and neuronavigation can lead to increased resection volume and prevent postoperative neurological deterioration. This is why, in 2002, we began performing surgery on patients with surgically treatable epilepsy in an operating theater equipped with a high-field 1.5-T intraoperative MRI (iMRI) facility. In addition, for lesions near eloquent cortical brain areas or tracts, functional MRI (fMRI) and DTI may help surgeons to localize Broca and Wernicke cortical speech areas and verbal memory areas have been described in detail elsewhere. The local ethics committee of the University Erlangen-Nuremberg approved the use of iMRI, and signed informed consent was obtained from every patient.

iMRI and Neuronavigation

After acquisition of the initial iMRI for planning the neuronavigation and coregistration of functional data, a second iMRI was performed when the surgeon had the impression that complete resection of the lesion or resection of a sufficient extent of the hippocampus (at least 2–2.5 cm) had been completed and planned to close the craniotomy. A third iMRI was performed after resection of the residual lesion or resection of an insufficiently resected hippocampus. Nimsky et al. have already given a detailed description of the intraoperative workflow they used in the iMRI suite (1.5-T iMRI: Magnetom Sonata Maestro Class, Siemens Healthcare).

The first iMRI scans included a T1-weighted MPRAGE sequence (TE 4.38 msec, TR 2020 msec, matrix size 128 × 128, field of view [FOV] 250 mm, slice thickness 1 mm, slab 16 cm), T2-weighted coronal and transversal images (TE 98 msec, TR 6520 msec, matrix size 512 × 307, FOV 250 mm, slice thickness 3 mm), and a DTI sequence (TE 86 msec, TR 9200 msec, matrix size 128 × 128, FOV 240 mm, slice thickness 3 mm). The same scanning protocol was used for both preoperative and intraoperative MRI. While the patient was shifted back into the operating position, preoperative functional data and iMRI data were fused with the inhibitive scans. The lesion or the hippocampus was segmented manually using the neuronavigation software (iPlan 2.6; BrainLAB AG), and trajectories to defined target points were calculated. After registration of functional data and current iMRI data, the data were transferred to an OPMI Pentero operation microscope (Zeiss) and displayed in the FOV intraoperatively. Lesion contours, contours of functional areas (areas at risk), and trajectories to target areas were projected to the patient’s head and painted on the skin. Skin incision was adapted to this painting. During
surgery, real-time 3D reconstructions of lesion contours and risk areas guided the resection and were visible to the surgeon during resection in different colors that corresponded to the depth of field.

**Intraoperative ECoG and Quantification of Resection**

For determination of the EZ in patients in whom the preoperative electroclinical findings revealed a larger EZ than the extent of the lesion (126 patients [30.4%]), additional intraoperative ECoG was performed. Cortical strip, grid, or depth electrodes were placed on the cortex intraoperatively to define the epileptogenic areas in 23 patients. We used a combination of up to four 4- to 6-contact subdural strips, 4-contact depth electrodes for hippocampal and amygdala positioning, or 32-electrode subdural grids (Ad-Tech Medical Instrument Corporation and PMT/Permark Corporation) and an electrode rack that consisted of 16 surface electrodes. The correct anatomical position of the electrodes was confirmed by the first iMRI scans, and the position from the scans was measured by intraoperative neuronavigation. In all patients who underwent ECoG, a distinct resection area was defined from the ECoG measurements and defined as the resection volume for the neuronavigation-controlled resection (tailored resection). The total resection volume was confirmed during IMRI if this volume had been resected completely according to the preoperative and intraoperative MR images (in all cases, the fusion of preoperative and intraoperative MR images was performed), and a complete resection was confirmed if the preoperative lesion contours were within the resected lesion or the ECoG-defined tailored extended lesion volume.

**Surgical Technique**

The iMRI suite contains a 1.5-T Magnetom Sonata and a rotating operating table. Patients underwent surgery outside the 5-Gauss line; thus, normal instruments and a microscope were used for surgery. For intraoperative scanning, each patient was draped in a sterile manner and rotated into the scanner. Depending on the localization of the lesion, we performed either a standard craniotomy or a craniotomy modified by neuronavigation. Microsurgical techniques were used for lesionectomies or tailored resections according to intraoperative neuronavigation, with which we kept close to the displayed boundaries of suspected pathological tissue or ECoG-defined extended lesion volumes and spared normal brain. After we had the impression of complete resection, an iMRI scan was performed. If intraoperative MR images displayed remnant pathological tissue or incomplete resection of the designated EZ, we updated the neuronavigation data with iMRI data and continued surgery. A final MRI scan subsequently confirmed the maximum extent of resection before the closing procedure was performed. On average, every intraoperative scan lasted an additional 30 minutes, including time for sterile draping and 3 sequences (MPRAGE, T2-weighted axial, and DTI).

**Histological Diagnoses of the Resected Specimens and Electrode Implantation**

In addition to the main histological diagnoses of HS (n = 146 [35.2%]), LEAT (n = 67 [16.1%]), CM (n = 45 [10.8%]), FCD (n = 31 [7.5%]), and gliotic scar tissue (n = 23 [5.5%]), the pathological diagnoses of the remaining 103 patients included mild gliosis (35 patients), malignant glioma (WHO Grade III or IV; 16 patients), low-grade tumor (i.e., WHO Grade I or II meningioma or astrocytoma; 15 patients), and hypothalamic hamartoma (5 patients). Altogether, 23 patients underwent implantation of grid, strip, and depth electrodes for extraoperative monitoring without histological investigation.

**Definition of Postoperative Neurological Deterioration and Epilepsy Outcome**

Neurological outcome was evaluated and staged soon after surgery when the patient was discharged from the hospital and months after surgery in our outpatient center. In addition, seizure outcome was evaluated at the most recent follow-up visit. The most recent Engel classification was applied to categorize postsurgical seizure outcome. An excellent seizure outcome was defined as Engel Class I or Ia, whereas favorable seizure outcomes included Engel Classes I and II; Engel Classes III and IV were assigned to the poor seizure outcome category. The patients’ most recent neurological and epilepsy outcome data were obtained from the follow-up examinations in the Neurological Epilepsy Centre at the University Hospital Erlangen or via telephone interviews. The neurological follow-up was completed for 88% (365) of the patients. Seizure outcome was available for 90.1% (374 of 415) of the patients. Statistical analysis was performed using parametric and non-parametric statistical tests (GraphPad Prism 5 software), and significance was indicated by a p value of < 0.05.

**Results**

The demographic characteristics of this epilepsy surgery patient cohort are summarized in Table 1. The most common lesions associated with epilepsy were categorized into the following 5 groups: HS (n = 146 [35.2%]), LEAT (n = 67 [16.1%]), CM (n = 45 [10.8%]), FCD (n = 31 [7.5%]), and scar epilepsy (n = 23 [5.5%]) (Fig. 1). Other underlying pathologies such as gliotic epileptogenic lesions, diffuse gliomas, or other lesions were found in 103 patients (24.8%). Temporal surgery was performed for 84.9% of the patients, and the other 15.1% underwent extratemporal surgery. Altogether, in 11.8% of the surgeries, an intraoperative second-look surgery resulting from incomplete resection verified by iMRI was performed. Forty-nine patients had incomplete resections detected during surgery with iMRI (Fig. 2), and 40.8% of these incomplete resections were detected during LEAT surgery. Concerning the specific groups, the highest percentage of second-look surgeries was found within the diffuse glioma group (6 of 16 patients [37.5%]). In the LEAT group, 29.9% (20 of 67) of the patients underwent second-look surgery, and in the FCD group, 12.9% (4 of 31) underwent second-look surgery. The numbers of second-look surgeries in all the groups are provided in Fig. 2.

Moreover, iMRI provided additional advantages for 23 patients during the implantation of grid, strip, and depth electrodes (Table 2), the positions of which were corrected.
intraoperatively in 13.0% (3 of 23) of the patients. In patients with an LEAT, the often ill-defined tumor borders were identified clearly during iMRI scanning, especially when T2-weighted images were used. Similarly, remnant hemosiderotic rims after surgery for CMs or residuals in cases of diffuse glioma or gliotic tissue were identified successfully using iMRI. During surgery for HS, the exact amount of hippocampal tissue resected was defined by intraoperative scanning (mean 2.6 cm [146 patients]) and corrected in 16.3% of the surgeries. During resection of FCDs, the planned resection volume defined by MRI and invasive grid monitoring often exceeded the extent of the morphological lesion. In such cases, the resection plan included electrode positions, which were defined as part of the EZ by extraoperative monitoring.

In summary, an excellent postoperative seizure outcome (Engel Class I) was found in 72.7% (272 of 374 with completed follow-up) of the patients during a mean follow-up of 36 months (range 3 months to 10.8 years). In 59.4% (222) of the patients, no seizures during the postoperative course were documented (Engel Class Ia) (Table 1). The greatest likelihood of an Engel Class I outcome was found after surgery for CM (83.7%), HS (78.8%), or LEAT (75.8%) (Fig. 3). Operative revisions that resulted from empyema occurred in 0.3% and from postoperative hematoma in 1.6% of the patients. Postoperative hydrocephalus occurred in 0.8% of the patients. Severe visual field deficits (more than one-quarter loss in vision) were found in 5.2% of the patients, and loss of less than one-quarter occurred in 27.2%. A 5.7% rate of postoperative aphasia was found. More severe complications such as hemiparesis occurred in 2.7% of the patients. No deaths occurred in this series (Table 3). In general, age, sex, hemisphere undergoing surgery, and duration of epilepsy of the patients did not have any significant effect on seizure outcomes in this cohort.

**Discussion**

**Summary of Findings**

We performed a retrospective study of 415 patients treated surgically for medically intractable epilepsy in which an iMRI suite (Fig. 4) and neuronavigation were used. In 11.8% of the surgeries, an intraoperative second-look surgery was performed because of incomplete resection verified by iMRI. Within a broad spectrum of involved pathologies (HS, LEAT, CM, FCD, scar epilepsy, and diffuse glioma), the patients who underwent resection of an LEAT or diffuse glioma had significantly higher intraoperative second-look surgery rates (29 of 67 [43.3%] and 6 of 16 [37.5%, respectively]) than patients with other pathologies. The considerably high percentage of excellent Engel Class I seizure outcomes in 72.7% (272 of 374) of the patients during a mean follow-up of 36 months might be associated with the use of iMRI in this patient cohort. The highest numbers of Engel Class I outcomes were found in patients treated surgically for CM (83.7%), HS (78.8%), or LEAT (75.8%). Typical specific complications of epilepsy surgery, such as hemianopia (5.2%), dysphasia (5.7%), or hemiparesis (2.7%), were rare, although 84.9% of the patients underwent temporal resection. The inclusion of functional imaging (motor and speech fMRI and DTI for pyramidal, speech, and visual tracts) in the surgical navigation plan may be the reason for such a low neurological complication rate.
MRI Resection Control and Intraoperative Functional Neuronavigation

First a low-field and then a high-field iMRI facility was established by the Erlangen iMRI study group nearly 2 decades ago.12-14,27,28,56,57,79 This facility was mainly used for glioma surgery and pituitary surgery, and also for epilepsy surgery.14,27,56 Early results of epilepsy surgeries here demonstrated that low-field iMRI in lesional epilepsy led to an increase in complete resections of epileptogenic lesions from 73% to 87%.12 Because of these encouraging early findings, all surgical procedures for epilepsy performed at the Erlangen Clinic from that time on were carried out using the newly installed high-field iMRI system, and this system was combined with neuronavigation in 2002. Thus, the reported results represent comprehensive experience gained during epilepsy surgeries using this high-field system between 2002 and 2013 with 415 patients.

Residual Lesions and Second-Look Surgeries

The focus of this retrospective study with patients surgically treated for medically intractable epilepsy within a well-established epilepsy surgery program at the Erlangen University Hospital was centered on the frequency of second-look surgeries according to the different enti-
ties treated. Concerning the histological diagnoses of the resected lesions, the surgically treated patients most frequently suffered from HS (n = 146 [35.2%]), LEAT (n = 67 [16.1%]), CM (n = 45 [10.8%]), FCD (n = 31 [7.5%]), or scar epilepsy (n = 23 [5.5%]), similarly to other reported large cohorts of surgically treated patients with epilepsy.19,23,40,64 During this period, the number of temporal lobe surgeries declined and the number of extratemporal resections increased, but not significantly. Similar findings have been reported in the literature.47 Nevertheless, temporal lobe surgeries were performed most often in this series (84.9% of all patients), as expected. The mean duration of epilepsy in these patients was 17.5 years (range 1 month to 55 years), which is not surprising and has been reported frequently in large series.23

The overall probability of an intraoperative second-look surgical intervention throughout all the interventions for these patients was found to be 11.8%. It is interesting to note that there were distinct pathologies that resulted in a significantly higher proportion of second-look interventions; most significantly, 40.8% of those in the second-look surgery group were undergoing surgery for an LEAT (mainly involving gangliogliomas or dysembryoplastic tumors). Altogether, 29.9% of the patients with an LEAT had an intraoperative need for additional resection, although the surgeon had the impression that the lesion had been resected totally before intraoperative scanning. According to iMRI, residual tumor was visualized and resected totally in most of these cases within the same surgery. For this reason, patients in this cohort with an LEAT were found to have an excellent long-term seizure outcome (76.9% had an Engel Class I result). In comparison with those found in the literature, our results match with the best reported results (Engel Class I seizure outcomes between 46.3% and 85.7% in those who underwent surgery for an LEAT).3,18,32,33,41,45,46,53,63,64,82

As expected, in the few patients with diffuse gliomas treated for refractory epilepsy (16 of 415 patients), a high percentage (37.5% [6 of 16]) underwent second-look surgery because of the diffuse borders of such lesions. All other entities for which intraoperative second-look interventions were performed as a result of iMRI detecting an

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**TABLE 2. Advantages of iMRI and neuronavigation for lesional and nonlesional epilepsy surgery**

<table>
<thead>
<tr>
<th>Lesional Epilepsy</th>
<th>Nonlesional Epilepsy</th>
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<tr>
<td>Planning of location &amp; extent of skin incision, craniotomy, &amp; dural opening</td>
<td>Implementation of preop PET/MEG data into resection planning via image fusion</td>
</tr>
<tr>
<td>Segmentation of lesion &amp; surrounding epileptogenic tissue (e.g., hemosiderotic rim in a CM)</td>
<td>Verification of resected PET/MEG foci with iMRI during op (e.g., ganglioglioma, FCD)</td>
</tr>
<tr>
<td>Planning of the trajectories for atraumatic targeting of deep-seated lesions</td>
<td>Verification of preplanned electrode position during electrode implantation &amp; intraop correction of electrode malposition</td>
</tr>
<tr>
<td>Outlining of lesion borders (e.g., in ganglioglioma resection); implementation of functional imaging (iMRI/DTI) data for sparing of eloquent tissue</td>
<td>Implementation of EEG data from invasive monitoring into the resection approach; implementation of functional imaging (iMRI/DTI) data for sparing of eloquent tissue</td>
</tr>
<tr>
<td>Intraop outlining of residual lesions &amp; resection during the same op (intraop second-look surgery)</td>
<td>Intraop comparison of preplanned resection target (EZ) with resection extension during op; intraop second-look surgery with further resection</td>
</tr>
</tbody>
</table>

**EEG = electroencephalography.**

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**FIG. 3.** Seizure outcomes within each different pathology group after surgery using iMRI and neuronavigation (the percentages are similar to those in seizure-free patients).
overlooked residual lesion or insufficient resection length of the hippocampus (defined as less than 2.0 cm) comprised only a small fraction (between 16.3% [hippocampus re-resection] and 4.1% [scar epilepsy]) of the second-look surgery group. In 6.1% of this cohort, in patients who had electrode implantations, a correction of electrode position was performed intraoperatively as a consequence of the intraoperative MR images.

In summary, in concordance with a former investigation of our iMRI study group using low-field MRI, in which the rate of re-interventions resulting from insufficient resection was 14%, a very similar result was found in the current study as a result of an unsatisfactory result from iMRI may also have contributed to the improvement in seizure outcomes (Fig. 2). Either way, with 79.3% of patients with an Engel Class I outcome, the result is also among the best results ever reported in the literature (Engel Class I outcomes in the literature are between 66% and 89%).

In general, patients suffering from seizures as a result of FCD or scar tissue after trauma or surgery have had lower rates of seizure outcome success after resection. It is unfortunate that the use of iMRI and neuronavigation did not seem to influence the seizure outcome in this patient group positively, as determined by retrospective analysis; an Engel Class I outcome in only 50% of these patients in the current study requires significant improvement, although for 12.9% of the patients with FCD and 8.9% of the patients with scar epilepsy, second-look surgery enlarged the resection volume (Fig. 2). This goal of enhanced seizure outcome after resection may be reached only by the application of new diagnostic methods and advanced surgical techniques in addition to iMRI and neuronavigation, as stated in a recent review paper.

<table>
<thead>
<tr>
<th>Complication</th>
<th>Erlangen Series</th>
<th>Literature</th>
</tr>
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<tbody>
<tr>
<td>Neurological</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Visual fields deficit</td>
<td>27.1</td>
<td>46–64</td>
</tr>
<tr>
<td>More than one-quarter</td>
<td>5.2</td>
<td>7–11.1</td>
</tr>
<tr>
<td>Memory deficit</td>
<td>15.9</td>
<td>16–55</td>
</tr>
<tr>
<td>Psychiatric abnormality</td>
<td>6.6</td>
<td>7.8–39</td>
</tr>
<tr>
<td>Dysphasia</td>
<td>5.7</td>
<td>1.7–7.7</td>
</tr>
<tr>
<td>Cranial nerve deficit</td>
<td>4.1</td>
<td>2.5–3.2</td>
</tr>
<tr>
<td>Hemiparesis</td>
<td>2.7</td>
<td>0.9–5.1</td>
</tr>
<tr>
<td>Death</td>
<td>0</td>
<td>0.4–1.4</td>
</tr>
<tr>
<td>General</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydrocephalus</td>
<td>0.8</td>
<td>0.7</td>
</tr>
<tr>
<td>Hematoma</td>
<td>1.6</td>
<td>1.4</td>
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<tr>
<td>Empyema</td>
<td>0.3</td>
<td>1.4</td>
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The seizure outcomes in our group of patients with CM were found to be extraordinary, with 83.3% Engel Class I and 76.2% Engel Class Ia (totally seizure free) outcomes. However, in lesional epilepsy and especially after CM resection in patients with epilepsy, outcomes are generally reported to be favorable, with rates of Engel Class I outcomes of 65%–86% in the literature. Nevertheless, the CM seizure outcome results in the current study are among the top results reported in the literature. The rationale of these optimal results could be that we also performed resection of the hemosiderotic rim in nearly all patients with CM within the underlying study, as reported earlier. Although this strategy is controversial according to the current literature, our experience indicates that total resection of the CM and the hemosiderotic rim seems to optimize the seizure outcome.

The seizure outcomes of patients who underwent resection for HS were found also to be optimal, with a rate of 79.3% of patients reaching Engel Class I during a mean follow-up of 36 months (range 3 months to 10.8 years). Following the discussion about the extent of hippocampal removal in patients with HS, there seems to be no difference in outcomes when resections are between 2.5 and 3.5 cm. However, resection of less than 2 cm seems to diminish the result considerably. In this respect, the intraoperative enlargement of resection volume in patients with HS in 5.5% (8 of 146) of the patients in this series as a result of unsatisfactory result from iMRI may also have contributed to the improvement in seizure outcomes (Fig. 2).

In general, patients suffering from seizures as a result of FCD or scar tissue after trauma or surgery have had lower rates of seizure outcome success after resection. It is unfortunate that the use of iMRI and neuronavigation did not seem to influence the seizure outcome in this patient group positively, as determined by retrospective analysis; an Engel Class I outcome in only 50% of these patients in the current study requires significant improvement, although for 12.9% of the patients with FCD and 8.9% of the patients with scar epilepsy, second-look surgery enlarged the resection volume (Fig. 2). This goal of enhanced seizure outcome after resection may be reached only by the application of new diagnostic methods and advanced surgical techniques in addition to iMRI and neuronavigation, as stated in a recent review paper.
General and Neurological Complications

Compared with the reported complications during surgical procedures for epilepsy, the observed general and neurological complications in this study were considerably low (Table 3). It is remarkable that severe visual field deterioration (loss of more than one-quarter) was found in only 5.2% of the patients, which is much lower than rates in the literature. This outcome might have its origin in the inclusion of functional images of the visual tracts in many patients.

Limitations of the Study

Important limitations of our study are the lack of prospective, randomized controlled data that compare surgeries of epileptogenic lesions with and without using iMRI combined with neuronavigation and the lack of a control group for comparison. As an alternative to iMRI and neuronavigation, especially when combined with functional data, awake craniotomy may serve as an alternative as a state-of-the-art procedure with that has been used extensively for the identification of eloquent brain areas and the avoidance of post-surgical deficits. In addition, intraoperative electrophysiological and neurological monitoring using cortical and tract stimulation are available as state-of-the-art methods for avoiding postoperative deficits, even in the setting of iMRI. Such techniques were not used for the patients reported here. Nevertheless, our study group has validated this multimodal neuronavigation approach and integration of fMRI and DTI within conventional surgery in many studies performed during the last decade. Another problem concerning the use of neuronavigation and preoperative functional data during surgery is volumetric brain deformation and intraoperative loss of cerebrospinal fluid (brain shift), which diminishes the accuracy of the depicted eloquent brain areas and fiber tracts. In our study, we took into account brain structural translocation and performed iMRI updates with new navigation data and reassignment of residual pathological tissue using navigation-planning software. In all of our patients in whom resection was performed, we were able to remove remnant tissue completely when it was not located within functional areas. Intraoperative ultrasound combined with neuronavigation may also have been used to correct for brain shift during surgery, but the structural resolution was not comparable with that with the use of MRI. Because of the lack of availability of a high-end intraoperative ultrasound system combined with neuronavigation in our center, we were not able to compare the advantages of such a system over iMRI in epilepsy surgery.

Conclusions

Using 1.5-T iMRI seems to confer considerable advantages in epilepsy surgery. Particularly in cases in which the borders of the lesion are not clearly visible during surgery, an intraoperative MR image enables the exact definition of residual lesional tissue for second-look resection during the same procedure. Especially in lesional cases, this protocol may lead to a better seizure outcome, as already demonstrated in the literature for complete resections. This advantage was found to be especially prominent during surgery for LEATs (40.8% of the patients who underwent second-look surgery in this study; Fig. 2), during which 29.9% (20 of 67) of the patients required second-look surgery to resect the tumor completely. However, intraoperative imaging also offered patients suffering from HFS the chance to optimize the extent of resection, and immediate correction of malposition was possible for patients who were selected for implantation of electrodes. In FCD or scar epilepsy cases, a convincing advantage was not found. In addition, the combination with neuronavigation and functional images in the investigated patient cohort seemed to have contributed to a low rate of severe complications (Table 3). We did not observe any adverse effects with the use of iMRI in epilepsy surgery, and it is notable that there were no increased infection rates.

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Disclosures
The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author Contributions
Conception and design: Roessler. Acquisition of data: all authors. Analysis and interpretation of data: Roessler, Hofmann, Sommer. Drafting the article: Roessler. Critically revising the article: Roessler, Sommer, Coras, Kasper, Hamer, Blumcke, Stefan, Nimsky, Buchfelder. Approved the final version of the manuscript on behalf of all authors: Roessler. Statistical analysis: Hofmann, Sommer. Study supervision: Roessler.

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