Awake craniotomy for gliomas in a high-field intraoperative magnetic resonance imaging suite: analysis of 42 cases

Clinical article

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Object. The object of this study was to describe the experience of combining awake craniotomy techniques with high-field (1.5 T) intraoperative MRI (iMRI) for tumors adjacent to eloquent cortex.

Methods. From a prospective database the authors obtained and evaluated the records of all patients who had undergone awake craniotomy procedures with cortical and subcortical mapping in the iMRI suite. The integration of these two modalities was assessed with respect to safety, operative times, workflow, extent of resection (EOR), and neurological outcome.

Results. Between February 2010 and December 2011, 42 awake craniotomy procedures using iMRI were performed in 41 patients for the removal of intraaxial tumors. There were 31 left-sided and 11 right-sided tumors. In half of the cases (21 [50%] of 42), the patient was kept awake for both motor and speech mapping. The mean duration of surgery overall was 7.3 hours (range 4.0–13.9 hours). The median EOR overall was 90%, and gross-total resection (EOR ≥ 95%) was achieved in 17 cases (40.5%). After viewing the first MR images after initial resection, further resection was performed in 17 cases (40.5%); the mean EOR in these cases increased from 56% to 67% after further resection. No deficits were observed preoperatively in 33 cases (78.5%), and worsening neurological deficits were noted immediately after surgery in 11 cases (26.2%). At 1 month after surgery, however, worsened neurological function was observed in only 1 case (2.3%).

Conclusions. There was a learning curve with regard to patient positioning and setup times, although it did not adversely affect patient outcomes. Awake craniotomy can be safely performed in a high-field (1.5 T) iMRI suite to maximize tumor resection in eloquent brain areas with an acceptable morbidity profile at 1 month.

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Key Words • awake craniotomy • cortical mapping • glioma surgery • iMRI • EOR • oncology

Abbreviations used in this paper: DTI = diffusion tensor imaging; DWI = diffusion-weighted imaging; EOR = extent of resection; fMRI = functional MRI; GTR = gross-total resection; iMRI = intraoperative MRI; LMA = laryngeal mask airway; OR = operating room; PR = partial resection; STR = subtotal resection.

This article contains some figures that are displayed in color online but in black-and-white in the print edition.
Awake craniotomy in intraoperative MRI

elements, especially as relates to patient positioning and anesthesia techniques. A few studies have described the awake craniotomy procedure in a high-field (1.5 T) iMRI suite.1-3,11,13,24 Our group has previously demonstrated the safety of combining multimodality electrophysiological monitoring with high-field (1.5 T) iMRI for the resection of gliomas in eloquent brain areas.2 Here we report on a consecutive series of 42 cases (41 patients) treated with awake craniotomy in the high-field iMRI suite and discuss our experience in this patient population.

Methods

Patient Selection

Clinical information was obtained from the Department of Neurosurgery Clinical and Imaging Database and The University of Texas MD Anderson Cancer Center Tumor Registry. These data were searched for all awake craniotomy procedures performed for the removal of intraaxial tumors near and/or within eloquent cortices using iMRI between February 2010 and December 2011. Patients had been selected for the procedure since their tumors had a close anatomical relationship to eloquent brain regions according to preoperative MRI. These regions included receptive and expressive speech areas in the dominant hemisphere and motor or sensory cortex in either hemisphere. The institutional review board at the MD Anderson Cancer Center approved and reviewed this study.

The mean preoperative tumor volume was measured in all patients using postcontrast T1-weighted MR images obtained before and after resection. In nonenhancing tumors, T2-weighted images were used for volume determination. Postoperative MRI was performed in all patients within 48 hours of the craniotomy procedure. A computerized volumetric analysis technique, as described by Shi et al.,21 was applied using Vitrea software (Vital Images Inc.). Before each awake craniotomy procedure, patients underwent a complete neurological examination performed by the attending physician. Language function was also assessed in a detailed examination by neuropsychologists, including object naming and recall, counting, language fluency and comprehension, reading, and writing.

Anesthesia Technique

The first step in planning an awake craniotomy in the iMRI suite is preoperative assessment and interview of the patient, which are performed by the surgeon and anesthesiologist. In addition, the surgical plan as well as explicit details of what to expect and what will be required of the patient is explained to him or her. A specific history regarding claustrophobia, anxiety, obstructive sleep apnea, and pain conditions involving the body contralateral to the side of surgery is solicited. The asleep-asleep technique using the laryngeal mask airway (LMA) in combination with a scalp block is primarily used for awake craniotomies in the iMRI suite at our institution.

In our series, the asleep-asleep-anesthetic technique was adopted as described by Huncke et al.8 After MRI-compatible patient monitors (Invivo) are applied, the patients routinely receive 4 mg of ondansetron, 20 mg of famotidine, and 10 mg of metoclopramide, all given intravenously. To induce anesthesia, we intravenously administer 50–100 mg of propofol plus 0.1–0.2 μg/kg/min of remifentanil with or without 50 mg of rocuronium. An LMA is then inserted, and the patient is gently turned to the appropriate position, usually the right or left lateral position. In some instances, especially for frontal tumors, a supine position with the head turned is used. The patient is placed comfortably with adequate padding of any bony prominences against the mattress of the operating table. After this, approximately 40 ml of 0.5% ropivacaine with 1:200,000 epinephrine is used to block sensation in the scalp and forehead. The cutaneous nerves supplying the scalp that are regionally blocked include the greater occipital, lesser occipital, auriculotemporal, zygomaticotemporal, and supraorbital nerves. The head is immobilized using a 3- to 5-point fixation device, and after proper ventilation and positioning, the patient undergoes preoperative scanning.

During the asleep portion of the operation, anesthesia is maintained with sevoflurane or isoflurane plus remifentanil (0.05–0.2 μg/kg/min). Ropivacaine 0.5% with epinephrine is also used along the skin incision. After the craniotomy flap is opened, the dura mater is blocked with a 1:1 mixture of 1% lidocaine and 0.25% bupivacaine. Once the dura is opened, the patient is gradually awakened. At this point, all medications are stopped, usually with a 30-minute lead time requested. If the patient becomes uncomfortable during the resection, remifentanil (0.02 μg/kg/min) is restarted. Once the awake testing portion is complete along with resection of the tumor, the patients requiring reintubation with the LMA are re-seated with dexametomidine (0.5–0.7 μg/kg/hr), propofol (25–50 μg/kg/min), and remifentanil (0.02–0.05 μg/kg/min) until the end of the procedure. For some patients, dexametomidine is given as an alternative after functional testing and during closure, and no LMA is used for these cases.

The anesthetic technique used in the iMRI suite is the same as that used in the regular operating room (OR) with slight modifications. Sevoflurane or isoflurane is used instead of desflurane (desflurane vaporizer is not compatible with MRI), and the Classic or Supreme LMA, instead of the Proseal LMA, is used because of the latter's metal reinforced shaft. Extra medications are used for priming since longer intravenous and infusion lines are required. Patients take longer to awaken since sevoflurane or isoflurane is used, and the duration of a case is longer because of added scan times.

The iMRI unit's design and the need for equipment in the OR to be MRI compatible are unique challenges. Some of these challenges include OR setup rearrangements; a decrease in immediate accessibility to all medications, equipment, and extra personnel; occasionally the less-than-ideal positioning of the patient on the MRI table; and an increase in patient discomfort. The equipment and boom in the iMRI suite are rearranged for awake craniotomy cases. Figure 1 shows the OR setup for a left-sided awake craniotomy procedure with the head of the table outside the 5-gauss line. Power is isolated to certain outlets during the scan mode, which may impair the op-
eration of critical anesthetic equipment. The team must be creative in positioning and draping the patient, since standard OR arm boards and intravenous poles are not MRI compatible. Figure 2 shows a patient being tested with picture cards during the awake procedure. There is ready access to the patient if reintubation is required, and interactions among the surgeon, anesthesiologist, and patient are enhanced by the plastic drapes, which allow additional lighting.

Cortical and Subcortical Stimulation

Immediately before tumor resection, the patient is awakened and, after the LMA is removed, can easily communicate with the neuroanesthesiologist and the surgeon via a microphone that is placed beside him or her. The patient is then asked to perform verbal and visual tasks to facilitate identification of speech areas during stimulation. Any speech hesitation, dysnomia, and speech arrest are noted. An Ojemann stimulator (Radionics Inc.) with 5-mm spacing between the electrodes is used. It is a constant-current generator that produces a train of square-wave biphasic pulses of 1-msec phase duration at a frequency of 60 Hz. For localization of the primary language and motor cortices, stimulus is applied in increments of 1 mA, starting at 0.5 mA; the rolandic cortex is also identified by somatosensory evoked potentials to identify phase reversals and latency shift. The duration of the stimulus on the brain surface is 2 seconds each time. A cortical area is considered eloquent if a motor response or twitch is generated or language errors are made consistently on at least two separate trials. No cortical site is stimulated twice in succession. Multiple sites close to one another were chosen on the cortex exposed by the craniotomy. Usually, 4–6 mA is the maximum stimulus needed to localize the language center, whereas up to 10 mA is needed to localize the motor cortex. Subcortical stimulation is performed with either the Ojemann (bipolar) stimulator or the Prass probe (monopolar) stimulator. The Prass probe, train of 5 at 500 Hz, duration of 0.5 msec, with currents ranging from 2 to 20 mA, is used to elicit a motor response.

In patients in whom language sites are identified, the resection margin is taken within 1–2 cm of cortical areas important for speech function. In patients in whom the primary motor and sensory cortices are mapped, the resection margin is taken closer to the cortical margins (up to 0.5 cm). The resection is stopped if speech function deteriorates but is resumed if full recovery occurs within 5 minutes. During cortical stimulation, simultaneous recording with electrocorticography is not performed because of the tailored craniotomy openings in these patients.

Magnetic Resonance Imaging Studies

The integrated MRI OR (Brainlab AG) includes a 1.5-T MRI scanner (Magnetom Espree, Siemens) that is integrated with the VectorVision Sky neuronavigation system (Brainlab AG) in a specially designed OR with radiofrequency shielding. It is equipped with a rotating table attached to the 1.5-T MRI scanner that allows the patient’s head to be placed outside the 5-gauss line during surgery. Ordinary surgical instruments can be used outside this line. The high-field scanner consists of a superconductive 1.5-T magnet with a length of 160 cm and an inner bore diameter of 70 cm. Both pre- and intraoperative imaging are performed with this magnet. All equipment that is not MRI compatible, such as the operating microscope, intraoperative ultrasonography apparatus, and surgeon’s chair, remain outside the 5-gauss line and are mechanically secured to the wall or ceiling of the OR. An MRI-compatible respirator and anesthesia care monitor are used. Drug infusion continues via infusion pumps while the intraoperative images are obtained.

The different types of imaging sequences obtained preoperatively and intraoperatively include a registration scan, diffusion tensor imaging (DTI), FLAIR, T2-weight-
ed, and diffusion-weighted imaging (DWI). Preoperative spectroscopy and high-resolution DTI (pre- and/or post-operatively) are performed at the surgeon’s discretion. A contrast agent is also used at the discretion of the surgeon and the neuroradiologist. Preoperative scanning is performed after laryngeal mask intubation and positioning of the patient. A 3D data set is obtained using iMRI. Imaging procedures include the following sequences: T1-weighted spin echo: section thickness 1.3 mm, FOV 230 mm², TE 2.5 msec, TR 5 msec, scan time 2 minutes 59 seconds; T2-weighted turbo spin echo: section thickness 1 mm, FOV 230 mm², TE 447 msec, TR 3000 msec, scan time 4 minutes 24 seconds; FLAIR: section thickness 1.5 mm, FOV 230 mm², TE 397 msec, TR 6000 msec, scan time 5 minutes 56 seconds; DTI: section thickness 4 mm, FOV 230 mm², TE 106 msec, TR 3500 msec, scan time 5 minutes 38 seconds; and DWI: section thickness 4 mm, FOV 230 mm², TE 96 msec, TR 4500 msec, scan time 2 minutes 20 seconds. If the tumor demonstrates contrast enhancement in preoperative studies, the T1-weighted spin echo sequence is repeated after intravenous administration of gadopentetate dimeglumine (0.2 ml/kg, Magnevist, Berlex/Schering). Diffusion tensor and diffusion-weighted imaging sequences are obtained to localize nearby white matter fiber tracts and detect early ischemia. Note that in every case the surgeon and the neuroradiologist will confer on the best sequences to guide tumor resection. The desired sequences are automatically registered to the ceiling-mounted navigation system (Cranial 7.8 software, Brainlab). No skin fiducial markers are needed. Data from functional MRI (fMRI) performed 1–2 days before surgery can also be integrated into the 3D data set for intraoperative functional neuronavigation (Figs. 3 and 4).

The surgeon can obtain intraoperative images for re-registration or to verify that the resection is complete. If residual tumor is identified, the navigation system can be updated with new anatomical and functional data, such as those obtained with DTI (Fig. 5). Further tumor resection is performed unless there is a risk of damaging eloquent brain regions.

Control postoperative MRI scans are acquired either at the completion of surgery or within 48 hours after surgery. The system for this postoperative imaging uses a standard 1.5-T General Electric magnet.

**Postoperative Neurological Evaluation**

Postoperative evaluation of neurological outcome was performed after the surgery and at the 1-month follow-up examination. The pre- and postoperative Karnofsky Performance Scale scores were also registered.

**Statistical Analysis**

Comparisons between groups were performed using a t-test, and p = 0.05 was considered to be significant.

**Results**

**Patient and Tumor Characteristics**

In the defined study period, 42 awake craniotomy procedures using iMRI were performed in 41 patients, 25 males and 16 females, with a median age of 41.2 years (range 22–70 years; Table 1). Newly diagnosed tumors were treated in 36 procedures (85.7%) and recurrent tumors in 6 (14.3%). The majority of tumors (73.8%) were on the left side. Nine procedures (21.4%) were performed for glioblastomas multiforme, 19 for anaplastic gliomas (42.9%), and 14 for low-grade gliomas (35.7%). Most tu-
mors were located in the frontal lobe (40.5%) and the frontal lobe with extension to adjacent areas (11.9%), followed by tumors in the temporal lobe (11.9%), temporal lobe with extension to adjacent areas (9.5%), and the parietal lobe (9.5%). A purely insular location was seen in 2 cases, and a combination of insular and its adjacent regions (frontal and/or temporal) was seen in 5 cases. In 21 cases the lesion was related to both the motor and speech cortices, 12 cases to the motor cortex, and 9 cases to the speech cortex. The mean preoperative tumor volume was 49 cm³ (range 3.3–154.2). Among the 41 patients in whom the craniotomy procedure was performed, preoperative neurological deficits were identified in 9 patients (21.9%). Six cases (66.7%) were speech related, 2 (22.2%) were motor deficits, and combined deficits (speech and motor) were found in 1 patient (11.1%).

Surgery Time

Surgery time was calculated from the time of initial skin incision to complete closure of the wound, including direct electrical stimulation mapping, resection, intraoperative imaging, and any subsequent resection of residual tumor if deemed necessary after image review. The mean surgery time was 7.3 hours overall (range 4.0–13.9 hours; Table 2), 7.8 hours for low-grade tumors, and 7.0 hours for high-grade tumors; there was no statistically significant difference between the latter two (p = 0.27). The mean surgery time was 6.5 hours for patients who required only 1 intraoperative scan and 8.0 hours for those with residual tumors requiring reintervention and subsequent postoperative scanning, although there was no statistically significant difference between the two (p = 0.27). Total surgery time exceeded 8 hours in 10 patients, including 5 patients with low-grade tumors and 5 patients with high-grade tumors. In these 10 patients, 7 surgeries were performed for tumors in the insular area. The mean surgery time for the insular versus noninsular (35) tumor cases was 10.9 ± 1.4 hours and 6.3 ± 1.00 hours, respectively.

Other variables included in total surgery time were the time that a patient spent awake and any time required to replace the LMA. The mean awake time during surgery was 2.8 hours overall (range 0.6–7.9 hours), 2.6 hours for patients with low-grade tumors, and 2.9 hours for those with high-grade tumors, with no significant difference between the latter two (p = 0.60).

Some patients were reintubated with the LMA device for the remainder of the procedure following direct electrical stimulation mapping. This decision was based on the anesthesiologist and neurosurgeon preferences. In the 42 procedures, reintubation with LMA device replacement occurred in 33 cases (78.6%).

Scan Times

The mean total scan time for patients, including preoperative, intraoperative, and second intraoperative scans, was 25.3 minutes (range 5.3–58.0 minutes). The mean time for preoperative scanning (42 cases) was 9.0 minutes (range 4.1–32.0 minutes; Table 2). The mean time for intraoperative scanning (39 cases) was 15.6 minutes (range 5.1–27.1 minutes). The mean time for a second intraoperative scan (10 cases) was 7.7 minutes (range 1.1–11.2 minutes).
Awake craniotomy in intraoperative MRI

### TABLE 2: Summary of intraoperative data in patients undergoing awake craniotomy

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean surgery time in hrs (range)</td>
<td>7.3 (4–13.9)</td>
</tr>
<tr>
<td>mean awake time in hrs (range)</td>
<td>2.8 (0.6–7.9)</td>
</tr>
<tr>
<td>mean scanning time in mins (range)</td>
<td></td>
</tr>
<tr>
<td>preop (42 cases)</td>
<td>9.0 (4.1–32.0)</td>
</tr>
<tr>
<td>intraop (39 cases)</td>
<td>15.6 (5.1–27.1)</td>
</tr>
<tr>
<td>2nd intraop (10 cases)</td>
<td>7.7 (1.1–11.2)</td>
</tr>
<tr>
<td>intraop seizures (%)</td>
<td>3 (7)</td>
</tr>
</tbody>
</table>

In 3 cases no intraoperative scan was performed: In 2 of these cases the surgeon believed that an intraoperative scan would not change the course of surgery, and in 1 patient intraoperative seizures prevented resection, and hence a scan was not performed.

The total number of sequences per patient per procedure was 5.8 overall (range 2–11 sequences), with an average of 5.2 sequences for the low-grade tumor group and 6.1 sequences for the high-grade tumor group. There was no statistically significant difference in the number of sequences per patient per procedure between the low- and high-grade tumor groups (p = 0.19).

### Extent of Resection

In the 14 low-grade tumor surgeries, gross-total resection (GTR; defined as ≥ 95% volumetric resection) was accomplished in 5 cases (35.7%; Table 3). One (7.1%) of 14 cases underwent subtotal resection (STR; defined as 85% to < 95% volumetric resection), and 8 (57.1%) of 14 underwent partial resection (PR; defined as < 85% volumetric resection).

In the 28 high-grade tumor surgeries, GTR was accomplished in 12 cases (42.8%). Six cases (21.4%) underwent STR, and 10 cases (35.7%) underwent PR.

There was no statistically significant difference in the average EOR between low-grade and high-grade tumors (p = 0.31). Overall, in the 42 procedures, 17 (40.5%) resulted in GTR, 7 (16.7%) in STR, and 18 (42.8%) in PR. The median EOR overall was 90.0%, with a mean of 76.0%. After the first intraoperative scan, only 10 cases (24%) resulted in GTR, with the rate increasing to 17 cases (40.5%) after re-resection. Hence, in 7 (41%) of 17 cases, iMRI helped to achieve a GTR. In the 17 patients who had a re-resection, the mean EOR increased from 56% to 67%. Of the 17 cases of re-resection, 12 had a resection ≥ 85%; of these 12 cases, 7 had a GTR. Notably, none of these 12 cases developed worsening neurological deficits. Hence, the combination of iMRI and mapping used in a complementary fashion benefited 12 (28.6%) of 42 cases in this study.

We specifically questioned why an STR or a PR was performed in 25 cases. In 4 of the 25 cases, the surgeon and neuroradiologist believed that a GTR had been achieved following the intraoperative scan; however, on postoperative volumetric measurements, it became evident that the resections were actually subtotal. An intraoperative deficit in 4 cases, bifrontal tumors in 5 cases, and intraoperative seizures in 2 cases prevented additional resection. In 10 of the 25 cases unforeseen intraoperative anatomical constraints also prevented additional resection (Table 4).

### Anesthesia and Awake Craniotomy

The LMA device was reinserted in 33 (78.6%) of 42 procedures after the surgeon believed that the goals of surgery had been met. In all of these cases, careful positioning of the neck preoperatively prevented any reintubation problems. In 10 (25.6%) of 39 procedures, patients were awake during intraoperative scanning and remained cooperative. In 17 of 42 cases further resection was necessary, and in 6 of these cases the patients were reawakened after the scanning.

### Seizures

Three patients (7%) had intraoperative seizures, and only 1 of them had a GTR after the seizures were controlled. In the other 2 patients, who had tumors in the motor gyrus, repeated seizures resulted in only PR of the tumors.

### Neurological Outcomes

New or worsening neurological deficits were observed in 11 (26%) of 42 cases immediately after surgery. At the 1-month follow-up, however, only 1 patient (2.4%) had a new or worsened neurological deficit.

### Discussion

The use of iMRI for the safe maximal resection of intrinsic brain tumors is well established; however, studies showing the utility of both low-field and high-field (1.5 T) iMRI for awake craniotomy procedures and the associated challenges are limited. In some earlier cases, awake craniotomy in the neurosurgical setting has been shown to result in higher rates of GTR and lower rates of postoperative neurological deficits compared to standard unawake craniotomy in the neurosurgical setting has been shown to result in higher rates of GTR and lower rates of postoperative neurological deficits compared to standard awake craniotomy.

### TABLE 4: Reasons for resection ≤ 85% in 25 cases

<table>
<thead>
<tr>
<th>Reason</th>
<th>No. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>surgeon believed that GTR achieved</td>
<td>4 (16)</td>
</tr>
<tr>
<td>intraop deficit</td>
<td>4 (16)</td>
</tr>
<tr>
<td>bifrontal tumor</td>
<td>5 (20)</td>
</tr>
<tr>
<td>seizures</td>
<td>2 (8)</td>
</tr>
<tr>
<td>anatomical limiting factors*</td>
<td>10 (40)</td>
</tr>
</tbody>
</table>

* For example, undue retraction on blood vessels and eloquent brain, difficulty splitting the sylvian fissure, tumor infiltrating eloquent cortical and subcortical structures, and so forth.
work we showed that intraoperative multimodality electrophysiological mapping can be seamlessly incorporated into high-field iMRI for tumor resections. Initially when we started the procedure of combining awake craniotomy with high-field iMRI, there were a number of challenges to overcome, including patient comfort and position as well as new draping and anesthetic techniques unique to the iMRI environment.

Of the 6 awake craniotomy studies on high-field iMRI published in the literature thus far, ours represents the largest patient experience (Table 5). In the series described by Leuthardt et al. and the case report by Parney et al., an overhead moveable magnet was used for scanning. However, in the other series, including ours, the position of the magnet was fixed on the floor, and the patient was moved toward the scanner for intraoperative scans. The overall operative time in our patient population was 7.3 hours, which is longer than the times reported in the other published studies. In our study, however, 7 (17%) of 42 cases had tumors primarily in the insular region and a combination of insular and adjacent frontal and temporal lobes, requiring longer operative times (10.9 ± 1.4 hours). For tumors outside the insular region (35 cases), the mean operative time was 6.3 ± 1.00 hours, which is more acceptable given the technology of the high-field iMRI. Moreover, the mean awake time during surgery was 2.8 hours overall (range 0.6–7.9 hours), with patients harboring insular tumors being awake the longest. In 42 awake procedures, there were no adverse events that occurred to either the patient or personnel.

The mean total scan time for patients, including preoperative, intraoperative, and (if needed) second intraoperative scanning, was 25.3 minutes (range 5.3–58.0 minutes) and did not seem to significantly compromise total operative times. During rescanning, the upper coil must be replaced, requiring excellent compliance and cooperation from the patient since they have limited visibility in the scanner. We have been successful in keeping almost one-third (25.6%) of the patients awake during intraoperative scanning without any reported problems. Of the 17 patients who required a re-resection, 6 of them were reawakened after the intraoperative scan, with no difficulties. In 10 of these 17 patients, however, the surgeon felt that the remainder of the resection could be safely performed while the patient was asleep, as the residual tumor was in a safe area for re-resection. Hence, in almost one-third of the cases (29%), the iMRI and mapping techniques were complementary in achieving a safe maximal resection of the tumor without causing any additional neurological decline. Because of the limited access to a patient’s airway in the iMRI suite as compared with the regular OR, the occurrence of seizures is a concern. In this study 3 patients (7%) had seizures, which is comparable to the rate (9%) in our large series of 309 patients previously described. In all 3 cases the anesthesiologist had good and ready access to the patient airway and controlled the seizures without any additional complications. In 1 of these cases, a GTR was achieved; however, in the other 2 cases with intraoperative seizures, the tumors were in the motor gyrus and were only partially resected.

High-field iMRI provides excellent-quality images that can assist the surgeon with both preoperative and intraoperative planning. Incorporating overlaid presurgical mapping images, including fMRI, DTI, and, more recently, the deformable anatomical template and navigated transcranial magnetic stimulation data, into the workflow can also aid surgical planning. The system software allows for automatic registration during rescanning, which expedites the workflow.

The use of iMRI was beneficial in achieving a more complete resection given the proximity of these tumors to eloquent cortex. After the first intraoperative scan, only 10 cases (24%) had GTR, which increased to 17 cases (35.7%) after re-resection. Hence in 7 (41%) of 17 cases, the iMRI helped to achieve GTR. In 25 cases a GTR could not be achieved. In a majority of these cases (10 [40%] of 25) unforeseen intraoperative anatomical constraints (for example, undue retraction on blood vessels and eloquent brain, difficulty splitting the Sylvian fissure, tumor infiltrating eloquent cortical and subcortical structures, and so forth) prevented additional resection from being performed. This highlights the challenge when operating in eloquent regions of the brain despite the use of iMRI. Nonetheless, excellent neurological outcomes were achieved in this study, with only 1 patient (2.4%) having a new or worsened neurological deficit at the 1-month follow-up.

Conclusions

We have demonstrated that awake craniotomy in the high-field (1.5 T) iMRI setting is a safe and useful means of maximizing EOR with a lower incidence of postopera-

<table>
<thead>
<tr>
<th>Authors &amp; Year</th>
<th>No. of Procedures</th>
<th>Mean Op Time in Hrs (range)</th>
<th>Mean No. of Intraop Scans (range)</th>
<th>Mean Scanning Time in Mins (range)</th>
<th>Anesthesia Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weingarten et al., 2009</td>
<td>10</td>
<td>6.8 (3.8–8.7)</td>
<td>2 (1–3)</td>
<td>(30–40)†</td>
<td>IV</td>
</tr>
<tr>
<td>Nabavi et al., 2009</td>
<td>38</td>
<td>NR</td>
<td>NR</td>
<td>(20–60)†</td>
<td>IV</td>
</tr>
<tr>
<td>Goebel et al., 2010</td>
<td>25</td>
<td>(4–5.5)†</td>
<td>1.4 (0–2)</td>
<td>NR</td>
<td>IV</td>
</tr>
<tr>
<td>Leuthardt et al., 2011</td>
<td>12</td>
<td>4.76 (2.7–6.02)</td>
<td>NR</td>
<td>44.4 (28.8–69)</td>
<td>LMA + IV</td>
</tr>
<tr>
<td>Parney et al., 2010</td>
<td>1</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>IV</td>
</tr>
<tr>
<td>Present case</td>
<td>42</td>
<td>7.3 (4.0–13.9)</td>
<td>1.2 (0–2)</td>
<td>25.3 (5.3–58.0)</td>
<td>LMA + IV</td>
</tr>
</tbody>
</table>

* Field strength of iMRI was 1.5 T in all studies. IV = intravenous; NR = not reported. † Mean not specified.
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tive neurological deficits. Intraoperative navigation and electrophysiological monitoring can be seamlessly incorporated into the OR with no adverse events to patients.

Disclosure

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 to the study and manuscript preparation include the following. Conception and design: Prabhu, Maldaun, Khawja. Acquisition of data: Prabhu, Maldaun, Khawja. Analysis and interpretation of data: Prabhu, Maldaun, Khawja. Drafting the article: all authors. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the article: all authors. Critically revising the article: all authors.

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