Subdural interhemispheric grid electrodes for intracranial epilepsy monitoring: feasibility, safety, and utility

Clinical article

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Object. Intracranial monitoring for epilepsy has been proven to enhance diagnostic accuracy and provide localization information for surgical treatment of intractable seizures. The authors investigated their experience with interhemispheric grid electrodes (IHGEs) to assess the hypothesis that they are feasible, safe, and useful.

Methods. Between 1992 and 2010, 50 patients underwent IHGE implantation (curvilinear double-sided 2 × 8 or 3 × 8 grids) as part of arrays for invasive seizure monitoring, and their charts were retrospectively reviewed.

Results. Of the 50 patients who underwent intracranial investigation with IHGEs, 38 eventually underwent resection of the seizure focus. These 38 patients had a mean age of 30.7 years (range 11–58 years), and 63% were males. Complications as a result of IHGE implantation consisted of transient leg weakness in 1 patient. Of all the patients who underwent resective surgery, 21 (55.3%) had medial frontal resections, 9 of whom (43%) had normal MRI results. Localization in all of these cases was possible only because of data from IHGEs, and the extent of resection was tailored based on these data. Of the 17 patients (44.7%) who underwent other cortical resections, IHGEs were helpful in excluding medial seizure onset. Twelve patients did not undergo resection because of nonlocalizable or multifocal disease; in 2 patients localization to the motor cortex precluded resection. Seventy-one percent of patients who underwent resection had Engel Class I outcome at the 2-year follow-up.

Conclusions. The use of IHGEs in intracranial epilepsy monitoring has a favorable risk profile and in the authors’ experience proved to be a valuable component of intracranial investigation, providing the sole evidence for resection of some epileptogenic foci.

Key Words • epilepsy surgery • intracranial electrode • interhemispheric electrode • frontal lobe epilepsy • supplemental motor area • seizure monitoring

FRONTAL lobe epilepsy is one of the most common epilepsy types reported in the literature. It is characterized by frequent and often disabling seizures that tend to be resistant to pharmacotherapy. These characteristics raise the question as to the possibility of surgical therapy and mandate the use of reliable techniques for its presurgical evaluation. Even when frontal lobe seizures are suspected, establishing the exact region of origin can prove extremely difficult, mainly because of sampling error, very rapid seizure spread, and large epileptogenic zones.

The EEG pattern often noted in frontal lobe epilepsy is that of secondary bilateral synchrony, consisting of bilateral bursts of irregular spike and wave activity. However, the nonspecific nature of frontal lobe epilepsy makes intracranial monitoring mandatory. Several electrode arrays including subdural convexity strip or grid electrodes, subdural interhemispheric strip or grid electrodes, and depth electrodes have been used. Neocortical seizures originating from the medial surface of the hemispheres have been poorly localized using surface subdural electrodes involving the convexities. Instead, interhemispheric and depth electrodes have been used especially for this indication. The main disadvantage of depth electrodes is the potential for false-positive localization, when the primary epileptogenic area is unsampled and the site of the secondary involvement is regarded as the epileptogenic focus.

Abbreviations used in this paper: EEG = electroencephalography; IHGE = interhemispheric grid electrode.
Placement of subdural electrodes in the interhemispheric fissure has been our approach to medial neocortical localization. Concerns regarding the safety of interhemispheric electrodes have focused on several technical challenges.15,16 First, a parasagittal craniotomy for access poses additional risk for the patient as opposed to standard bur holes or frontotemporal craniotomy. Second, there is an inherent risk in the separation of the hemispheres, including the risk of retraction injury to the cortex with potential lower limb weakness, and that of disruption to the multiple ascending draining veins and the superior sagittal sinus, with the sequelae of hemorrhage and venous ischemia or infarction. In this paper we describe our institution’s experience with the use of IHGEs, their utility, safety, and contribution as part of an electrode array for invasive EEG monitoring in the localization of patient seizures as well as subsequent potential resective surgery and outcome.

**Methods**

**Patient Sample**

All patients in the Dartmouth Surgical Epilepsy Program who underwent intracranial EEG recording monitoring with electrode arrays, including IHGEs, were identified. Between the years 1992 and 2010, 50 patients underwent invasive epilepsy monitoring that included IHGEs.

**Preoperative Evaluation**

Patients underwent preoperative evaluation using noninvasive techniques that included scalp EEG monitoring, 1.5-T MRI, neuropsychological testing, amytal language dominance testing, ictal SPECT, and interictal PET. The results of these evaluations and the clinical presentations of the patients were reviewed in our multidisciplinary epilepsy conference, at which decisions were made regarding surgical candidacy, the possible need for intracranial epilepsy monitoring, and if so, the appropriate electrode array. With the development of more reliable imaging techniques over the years there was a tendency to reduce the use of intracranial monitoring. When a frontal lobe seizure focus was suspected but there was no structural lesion or discordant findings on noninvasive tests (including MRI, interictal and ictal scalp EEG, seizure semiology, neuropsychological testing, and Wada testing), patients were further studied using intracranial electrode arrays that included IHGEs.

**Data Collection**

All charts were retrospectively reviewed. The data collected were the patient’s age at electrode implantation, sex, ictal semiology, scalp EEG localization, preoperative MRI findings, interictal and ictal SPECT findings, interictal PET findings if obtained, electrode arrays implanted, area of resection, pathology findings, postimplantation intervention if resection was not performed, surgical complications, and outcomes using the Engel classification at the 2-year follow-up.

**Surgical Technique**

Frameless stereotactic neuronavigation was employed in all cases. When a preoperative MR image with fiducials was obtained, this image was then imported into our stereotactic treatment planning Unix workstation using Leksell SurgiScope 1.7 (Elekta AB). The patient’s head was then fixed to the operating table using a Mayfield 3-pin fixator. Image guidance was used selectively to position the grid electrodes when there was evidence of specific localization by imaging studies (MRI, SPECT, and others). A craniotomy that extended across the midline was performed, and the operating microscope was used for the interhemispheric dissection (Fig. 1). Retraction was minimized in the interhemispheric fissure, and careful separation of the hemispheres by division of arachnoid adhesions was performed. No bridging veins were sacrificed or injured in any case. The IHGEs (cuvilinear double-sided Ad-tech 2 × 8 or 3 × 8 grids) were subsequently placed (Fig. 2). In those cases in which bridging veins limited access to the interhemispheric fissure, the grids were partially rolled or folded on themselves to enable placement through the available opening; the grids were then unrolled or unfolded in place. Placement of IHGEs was successful in all cases, and subdural strip electrodes never needed to be substituted.

The incision was closed and the electrode secured with a single 2-0 silk suture. Subdural strip and/or grid placement was then performed through the same incision in the ipsilateral side and using bur holes on the contralateral side. The dura was reaproximated but was not closed in a watertight fashion. Occipitotemporal hippocampal depth electrodes were implanted stereotactically through a 4/16-inch bur hole. Prophylactic antibiotics were continued for the duration of the monitoring and for 24 hours following removal of the array. Head dressings were left in place for the duration of the monitoring and the patients were monitored for CSF leakage and fever. A high-resolution head CT scan was performed the evening of surgery and fused with the patient’s preoperative MR image to determine the electrode position.4

Resective surgery of the medial frontal lobe, when performed, was carried out by stereotactic volumetric reference to the contacts on each grid/strip. Resection of

![Fig. 1. Intraoperative photographs obtained in a 44-year-old patient undergoing intracranial electrode implantation. Left: The IHGEs are in place with angiocatheters used for tunneling of the electrodes through the skin. Right: The full IHGE array is in place with the electrodes secured by silk suture.](image-url)
cortical tissue was performed in a subpial fashion. Seizure onset and functional mapping guided the extent of resection (Figs. 3 and 4).

Video-EEG Monitoring

Patients underwent video-EEG monitoring with the goal of capturing at least 3 of their stereotypical seizures. Antiepileptic medications were tapered after the 2nd day of monitoring if seizures did not occur. The patients were monitored for a mean time of 8.8 days (range 3–20 days). Removal of the electrodes and resective surgery were conducted simultaneously at the end of monitoring. Cortical mapping was performed on all the patients.

Results

Demographics

Between 1992 and 2010, 50 patients underwent placement of intracranial IHGEs for epilepsy monitoring at our institution, with a mean postsurgical follow-up of 2.9 years. Of this group, 38 underwent resection of the seizure focus; the mean age of the patients in this group was 30.7 years old (range 11–58 years old), and 63% were males. Twelve patients did not undergo resection, and these patients were a mean age of 28.5 years old (range 20–54 years old), and 66% were males. In the first group, MRI was normal in 17 patients (44.7%), and abnormal (including areas of encephalomalacia, agenesis of the corpus callosum, heterotopias, and gliosis) in 21 patients (55.3%). In the latter group, MRI was normal in 7 patients (58%) and abnormal in 5 (42%; Table 1)

Complications

Two patients returned after the initial IHGE placement with surgical site infections that resulted in a craniectomy and eventual cranioplasty. After IHGE implantation, 1 patient developed transient lower-extremity weakness that resolved a few days postoperatively. After resective surgery 1 patient developed transient lower-extremity weakness, and 2 patients developed supplemental motor area syndrome, characterized by hemiparesis with preserved tone and mutism in the 1 patient with dominant hemisphere surgery; these conditions had resolved at the time of the 6-week follow-up. No permanent morbidity or death was identified in our series.

Resection Group

The arrays used in the patients who eventually underwent resection included 24 strip and grid electrodes, 2 depth and grid electrodes, 2 grid electrodes only, and 10 depth, strip, and grid electrodes (Table 1). Of the patients with normal MRI scans (17 patients), 9 with onset and prolonged localization of seizure activity in the medial frontal lobe underwent medial frontal resections (Fig. 3), whereas 8 underwent frontal resections without involvement of the medial structures because of seizure onset localized to the lateral convexity cortex. Despite the varied and sometimes inaccurate preoperative presumed localization, an appropriate resection was made possible in all of the patients with medial frontal resections because of the information provided by the IHGEs (Table 2).

In a similar way, among 21 patients with abnormal MRI, medial frontal resection was enabled with the information provided by the IHGEs in 12 patients. Conversely, the medial structures were spared in 3 patients because of

Fig. 2. Image of a curvilinear double-sided 3 x 8 IHGE.

Fig. 3. Preoperative (A) and postoperative (B and C) MR images obtained in a 44-year-old patient with medial frontal localization of epilepsy. A: Coronal T2-weighted image. B: Sagittal T1-weighted image coregistered with an immediate postoperative high-resolution head CT scan demonstrating the location of the IHGEs. C: Coronal T2-weighted image of the same patient demonstrating medial frontal resection.
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evidence from IHGEs of noninvolvement in seizure activity (Table 3).

**Nonresection Group**

The electrode arrays used in the patients who ultimately did not undergo surgical resections included 9 grid and strip electrodes, 1 grid electrode only, and 2 depth, strip, and grid electrodes (Table 1). Twelve patients did not undergo resection because they were determined to have multifocal seizure onset (10 patients), or a single seizure focus localizing to the leg area of the motor cortex preventing resection. These patients continued with medical management (8 patients), or underwent vagus nerve stimulator placement (2 patients) or callosotomies (2 patients).

**Utility of IHGEs**

The use of IHGE enabled the appropriate resective epilepsy surgery in 21 (55%) of the 38 patients who eventually underwent resection. The medial frontal structures were spared in 11 (34%) of the 32 patients who underwent frontal resections because of the data provided by the IHGEs. Cortical mapping with the use of IHGEs prevented potentially harmful resections in 2 (9%) of 23 patients with medial frontal localization.

**Outcomes and Pathological Findings**

Of the 38 patients who underwent eventual resective surgery:

**TABLE 1: Demographics and IHGE array characteristics of the study population**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Resection</th>
<th>No Resection</th>
</tr>
</thead>
<tbody>
<tr>
<td>no. of patients</td>
<td>38</td>
<td>12</td>
</tr>
<tr>
<td>mean age in yrs (range)</td>
<td>30.7 (11–58)</td>
<td>28.5 (20–54)</td>
</tr>
<tr>
<td>no. of males (%)</td>
<td>24 (63)</td>
<td>8 (66)</td>
</tr>
<tr>
<td>no. w/ normal MRI (%)</td>
<td>17 (44.7)</td>
<td>7 (58)</td>
</tr>
<tr>
<td>no. w/ abnormal MRI (%)</td>
<td>21 (55.3)</td>
<td>5 (42)</td>
</tr>
<tr>
<td>grid &amp; depth electrodes</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>grid &amp; strip electrodes</td>
<td>24</td>
<td>9</td>
</tr>
<tr>
<td>strip, grid, &amp; depth electrodes</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>grid electrodes</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

**TABLE 2: Preimplantation and postimplantation localization, as well as operative intervention, performed in patients with normal MRI**

<table>
<thead>
<tr>
<th>Resection</th>
<th>Postop Localization</th>
<th>Preop Localization</th>
<th>No. of Patients</th>
</tr>
</thead>
<tbody>
<tr>
<td>medial frontal cortex</td>
<td>interhemispheric grid (medial frontal cortex)</td>
<td>nonspecific (7); frontal (2)</td>
<td>9</td>
</tr>
<tr>
<td>frontal cortex</td>
<td>subdural frontal orbitofrontal grid (orbitofrontal cortex)</td>
<td>nonspecific (4); frontal (3); temporal (1)</td>
<td>8</td>
</tr>
</tbody>
</table>
TABLE 3: Preimplantation and postimplantation localization, as well as operative intervention, performed in patients with abnormal MRI

<table>
<thead>
<tr>
<th>Resection</th>
<th>No. of Patients</th>
<th>Preop Localization (no. of patients)</th>
<th>Postop Localization</th>
</tr>
</thead>
<tbody>
<tr>
<td>interhemispheric frontal cortex</td>
<td>12</td>
<td>nonspecific (6); frontal (5); temporal (1)</td>
<td>interhemispheric grid (medial frontal cortex)</td>
</tr>
<tr>
<td>frontal cortex</td>
<td>3</td>
<td>frontal (3)</td>
<td>subdural frontal orbital frontal grid (orbital frontal cortex)</td>
</tr>
<tr>
<td>amygdala &amp; hippocampus (1 included occipital)</td>
<td>2</td>
<td>temporal (2)</td>
<td>hippocampal depth electrode (hippocampus)</td>
</tr>
<tr>
<td>occipital cortex</td>
<td>4</td>
<td>nonspecific (4)</td>
<td>occipital subdural grid (occipital cortex)</td>
</tr>
</tbody>
</table>

epilepsy surgery, 27 (71%) had an Engel Class I outcome and 4 (11%) had an Engel Class II outcome at the 2-year follow-up. Six patients (16%) had an Engel Class III outcome and 1 (3%) had an Engel Class IV outcome at the 2-year follow-up.

The 32 patients who underwent frontal lobe resective surgery had a variety of pathological diagnoses including gliosis, cortical dysplasia, pyramidal cell loss, and ectopic oligodendrogial cells.

**Discussion**

Seizure control with resective epilepsy surgery has been less favorable for frontal lobe epilepsy in comparison with the more common temporal lobe epilepsy.1-16,22,27,32,33,36,37 The percentage of seizure-free patients has ranged from 13% in the first pre-MRI series14 to 70% for patients with lesional frontal lobe epilepsy in the current MRI era,23 comparable to the rate for patients undergoing surgery for temporal lobe epilepsy. In addition, in the last 2 decades we have made major advances in our understanding of the semiology and anatomical topography of frontal lobe epilepsies and especially seizures involving the supplementary motor area.7-10,19,24,39 A recent study23 demonstrated that dual-sided IHGEs do not reliably isolate signals from only 1 hemisphere. Recordings from the visual cortex in the human brain demonstrated that these electrodes, as expected, record only faintly from the cortical surface they face through the falx. However, it was demonstrated that electrodes facing the falx pick up strong signals from the cortex behind them. Therefore, the data provided by IHGEs should be interpreted in conjunction with other monitoring information to definitively determine seizure onset laterality.

In the current analysis, the use of IHGEs enabled the appropriate resective epilepsy surgery in 55% of the patients who eventually underwent resection. Forty-three percent of those patients had normal preoperative MR images. In the patients with medial frontal localization, IHGEs provided the sole definitive evidence for localization. On the other hand, data provided by IHGEs prevented resection of medial structures in 34% of patients with eventual frontal localization. Concurrent mapping from the IHGEs prevented medial resections in 2 patients with localization to the leg area of their motor cortex. The above advantages are unique to IHGEs and underscore their crucial role in the intracranial investigation of frontal lobe epilepsy. Seventy-one percent of our patients undergoing resective epilepsy surgery had Engel Class I outcomes at the 2-year follow-up, in accordance with rates reported in the current literature.

Concerns have been raised on the use of IHGEs.6,47 The parasagittal craniotomy performed for access poses additional risk for the patient compared with the standard

though depth electrodes have a reasonable safety record in experienced hands, they are nevertheless invasive, and their complication rates multiply with the denser arrays sometime necessary for the accurate detection of medial origin foci.

With the development of MRI, more emphasis has been placed on resection of a visible lesion. When this is not possible, functional imaging techniques such as PET and SPECT have been used with good results in temporal lobe epilepsy.12 However, unlike temporal lobe epilepsy in which ictal perfusion changes are relatively slow, rapid perfusion changes occur in extratemporal epileptic foci and especially in the medial frontal lobe, making the application of this technique in seizure localization limited.14

In an attempt at more accurate localization of frontal lobe epilepsy, the placement of subdural electrodes in the interhemispheric fissure has been performed by several groups.2,5,10,11,28,30,35 Interhemispheric electrodes are superior to surface or lateral cortical electrodes because they are in direct contact with the recorded area, providing more accurate information. One of their initial applications was by Lüders et al. in 1987. Although there are several series13,15,21,22,32,33,40 of patients undergoing surgery for frontal lobe epilepsy, some of which underwent IHGE placement, the literature lacks an analysis on the safety profile, usefulness, and outcomes of IHGE in patients with intracranial seizure monitoring. In addition, most of the literature on IHGEs demonstrates their use on cortical stimulation studies in humans, and their application to the mapping of the medial frontal lobe.1,16,22,32,33,40,44 A recent study23 demonstrated that dual-sided IHGEs do not reliably isolate signals from only 1 hemisphere. Recordings from the visual cortex in the human brain demonstrated that these electrodes, as expected, record only faintly from the cortical surface they face through the falx. However, it was demonstrated that electrodes facing the falx pick up strong signals from the cortex behind them. Therefore, the data provided by IHGEs should be interpreted in conjunction with other monitoring information to definitively determine seizure onset laterality.
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mur holes or frontotemporal craniotomy. In addition, there is an inherent risk in the separation of the hemispheres, including the risk of retraction injury to the cortex with potential lower-limb weakness, and that of disruption to the multiple ascending draining veins and the superior sagittal sinus. However, in the current analysis we demonstrate a favorable safety profile for IHGEs. There was no permanent morbidity or any deaths from electrode implantation, and no cases of hemorrhage or venous infarction were observed.

Conclusions

Interhemispheric grid electrodes are an integral part of the preoperative investigation of frontal lobe epilepsy. By providing effective medial frontal localization, IHGEs can enable selective resection of medial frontal structures or preservation of medial structures in cases in which the medial frontal lobe remains uninvolved. In the cases in which a parasagittal seizure focus was identified, IHGEs led to and determined the limits of resective surgery. Furthermore, mapping with IHGEs can prevent resective surgery that could result in permanent deficits in patients whose seizures would originate in the leg area of the motor strip. Investigation with IHGEs is well tolerated and has a favorable risk-benefit profile.

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: Roberts, Bekelis. Acquisition of data: Bekelis, Radwan, Moses, Thadani, Jobst, Bujarski, Darcey. Analysis and interpretation of data: Roberts, Bekelis, Radwan, Moses, Thadani, Jobst, Bujarski, Darcey. Drafting the article: Bekelis. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the article: Bekelis. Critically revising the article: all authors.

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