Characterizing magnetic spike sources by using magnetoencephalography-guided neuronavigation in epilepsy surgery in pediatric patients

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Object. The authors sought to validate magnetoencephalography spike sources (MEGSSs) in neuronavigation during epilepsy surgery in pediatric patients.

Methods. The distributions of MEGSSs in 16 children were defined and classified as clusters (Class I), greater than or equal to 20 MEGSSs with 1 cm or less between MEGSSs; small clusters (Class II), 6 to 19 with 1 cm or less between; and scatters (Class III), less than 6 or greater than 1 cm between MEGSSs. Fourteen patients underwent MEGSSs: nine had clusters; two had small clusters, one with and one without clusters; and three had scatters alone. All 13 had clusters. Clusters localized within and extended from areas of cortical dysplasia and at margins of tumors or cystic lesions. All clusters were colocatalized to ECoG-defined epileptic zones. Four of six patients with clusters and/or small clusters underwent complete excisions, and two underwent partial excision with or without multiple subpial transections. In the three patients with scatters alone, ECoG revealed epileptic zones buried within MEGSS areas; these regions of scatters were completely excised and treated with multiple subpial transections. Coexisting scatters were left untreated in nine of 10 patients. Postoperatively, nine of 13 patients were seizure free; the four patients with residual seizures had clusters in unexcised eloquent cortex. Three patients in whom no MEGSSs were demonstrated underwent lesionectomies and were seizure free.

Conclusions. Magnetoencephalography spike source clusters indicate an epileptic zone requiring complete excision. Coexisting scatters remote from clusters are nonepileptogenic and do not require excision. Scatters alone, however, should be examined by ECoG; an epileptic zone may exist within these distributions.

KEY WORDS • magnetoencephalography • magnetic spike source • epilepsy surgery • neuronavigation • pediatric neurosurgery
MS imaging data with intraoperative neuronavigation. We characterized the distributions of MEGSSs with respect to results from ECoG and IVEEG data by using an intraoperative navigation system. We then compared the characterized MEGSSs with patient lesions, surgical results, and seizure outcomes to determine which spike sources required resection for seizure control.

Clinical Material and Methods

Patient Populations

We studied 16 pediatric patients with epilepsy who had undergone cortical excision between October 2000 and January 2003 and whose surgeries were guided by intraoperative neuronavigation combined with MS imaging data and either extraoperative IVEEG or intraoperative ECoG. Table 1 provides a summary of the clinical profiles of the 16 patients. Ten patients were girls. Patients ranged in age from 4 to 18 years (mean 12 years). Their seizure durations ranged from 8 months to 13 years (mean 5 years). Eleven patients had clinical histories and ictal symptoms of partial seizures with secondary generalization, including three patients with focal motor seizures and two with focal sensory seizures; five patients had partial seizures alone. Fourteen patients were experiencing one or more seizures per day at the time of surgery. Four had undergone epilepsy surgery previously. All patients or their parents gave informed consent.

Seizure Profiles and EEG Studies

We performed prolonged IVEEG with the International 10-20 scalp-electrode placement system and a single reference electrode (BMSI System 4000 and 5000; Nicolet, Madison, WI).

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*FM = focal motor; FS = focal sensory; PS = partial seizures; PSG = partial seizures with secondary generalization.

Magnetic Resonance Imaging

Preoperative MR imaging was performed using a 1.5-tesla Signa unit (General Electric Medical Systems, Milwaukee, WI). The epilepsy protocol included the following sequences: sagittal T1-weighted; axial and coronal fluid-echo T1-weighted; coronal fluid-attenuated inversion-recovery, and coronal volumetric 3D Fourier transform gradient echo sequence. If a neoplasm was suspected, Gd-based contrast was injected intravenously.

Magnetoencephalography Studies

We used a whole-head gradiometer-based Omega system (151 channel; CTF Systems, Inc., Port Coquitlam, BC, Canada) at The Hospital for Sick Children in Toronto. We deprived patients of sleep the prior night and tested them while they were supine. We performed intraoperative ECoG recordings and were cross-referenced with the simultaneous MR imaging data with intraoperative neuronavigation. We then compared the characterized MEGSSs with respect to results from ECoG and IVEEG data by using an intraoperative navigation system. We then compared the characterized MEGSSs with patient lesions, surgical results, and seizure outcomes to determine which spike sources required resection for seizure control.

Intraoperative ECoG and Extraoperative IVEEG

Magnetic Source Imaging: Coregistration of MEG With MR Imaging

Immediately after MEG data collection, we performed axial 3D fast-slow gradient T1-weighted volume acquisition MR imaging (General Electric Medical Systems, Fairfield, CT). T1-weighted MR imaging was performed by using a 1.5-tesla Signa unit (General Electric Medical Systems, Milwaukee, WI). The epilepsy protocol included the following sequences: sagittal T1-weighted; axial and coronal fluid-echo T1-weighted; coronal fluid-attenuated inversion-recovery; and coronal volumetric 3D Fourier transform gradient echo sequence. If a neoplasm was suspected, Gd-based contrast was injected intravenously.

Characterizing magnetic spike sources played on trigonal paper. We created a 3D model of the cortex registering MEG with MR imaging pixels with the aid of the MARK VOXEL program (CTF Systems, Inc.).

Incorporation of MEGSSs Into the Neuronavigation Program

The coregistered data were transferred from the system to Medicine 3.0 (version 3.1) on a Windows 2000 workstation (Microsoft Corp., Redmond, WA). We used a neuronavigation system to correlate spike sources localized by ECoG with MEGSSs. We defined an epileptic zone as the place where epileptic spikes without corresponding EEG spikes.30 We applied a single moving dipole analysis with a single-shell, whole-head, individually created spherical model for a period of 50 msec before and after the peak of each spike. We defined the MEGSSs for each spike as a single dipole fit from the earliest phase of each spike with the criteria of a residual error of less than 30%.

Somatosensory Evoked Fields on MEG

We localized SSEFs on each hemisphere by electrically stimulating the contralateral median nerve. Each data set consisted of 400 trials at a 5-Hz stimulation frequency and 2500-Hz sampling rate. We localized the source of the MEG N20 equivalent peak by using a single moving dipole fit, individually created spherical head models, and a criterion of residual fit error of less than 10%.

Intraoperative ECoG and Extraoperative IVEEG

Surgical Procedures

In 12 patients, we used an extraoperative IVEEG program (Medtronic/Axion) with 16-channel IVEEG electrodes (Multi-Modality Radiographic Markers; IZI Medical Products Corp., Baltimore, MD) placed on the preauricular points and nasion to indicate the exact position of the MEG localization coils for MR imaging coregistration. Slices of 2-mm thickness and spacing were acquired in an axial plane, without angling (TR 11 msec, TE 4 msec). A bandwidth of 15.63 to 32.15 Hz, and a notch filter of 60 Hz. Head localization was performed at the beginning and end of each set.

The MEG epileptic events, spikes and sharp waves (referred to as spikes), were identified by examining the MEG recordings and were cross-referenced with the simultaneous EEG recording. At times, we identified MEG epileptic spikes without corresponding EEG spikes.30 We applied a single moving dipole analysis with a single-shell, whole-head, individually created spherical model for a period of 50 msec before and after the peak of each spike. We defined the MEGSSs for each spike as a single dipole fit from the earliest phase of each spike with the criteria of a residual error of less than 30%.

Intraoperative ECoG, Extraoperative IVEEG, and Magnetic Resonance Imaging

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Characterizing magnetic spike sources

played on trigonal MR images on the MRI Viewer program. We created an appropriate spherical model after co-registering MEG and MR imaging fiducial markers.

The MEGSS and SSEF source were mapped into the MR imaging pixels with the aid of the MARK VOXEL program (CTF Systems, Inc.).

Incorporation of MS Imaging Data Into the Neuronavigation System

The coregistered MR imaging and MEG dipole data were transferred by Digital Imaging and Communications in Medicine 3.0 transmission first to an Advantage Windows 3.1 workstation and then to the Picture Archiving and Communications System. We used a seeded threshold method on ISG Allegro 3D imaging software (Cedara Software Corp., Mississauga, ON, Canada) to create 3D shaded surface displays of the skin surface; brain surface; lesion, if any; spike sources; and SSEF sources. The 2D and 3D data sets were then loaded from the Allegro system into a Zeiss/SNN Neurosurgical Navigational System (Carl Zeiss Canada Ltd., Toronto, ON, Canada). This frameless stereotaxy system was used in the operating room to correlate the MEG data with the surgical field. Surface registration correlated the images with the surgical system. When children suffered from cortical dysplasia and nonenhancing tumors, image fusion correlated the MEG data with $T_2$-weighted or fluid-attenuated inversion-recovery images.

Classification of MEGSS Distributions

We classified the MEGSS distributions into four groups by number and density: Class I (clusters), consisting of 20 or more spike sources with 1 cm or less between adjacent sources; Class II (small clusters), consisting of six to 19 spike sources with 1 cm or less between adjacent sources; Class III (scatters), consisting of less than six spike sources regardless of the distance between sources, or spike sources with greater than 1 cm between sources regardless of the number of sources in a group; and Class IV (no MEGSS).

Intraoperative ECoG, Extraoperative IVEEG, and Surgical Procedures

In 12 patients we performed intraoperative ECoG by using a 4 × 5 surface electrode array (Ad-Tech, Racine, WI). Along with preoperative scalp EEGs, MR imaging, and clinical symptoms, we used the MEGSS distributions to determine the areas for craniotomy, the trajectories for intraoperative ECoG, and the exposures for extraoperative IVEEG. During surgery, we used the frameless stereotaxy system to correlate spike sources localized by ECoG with MEGSS. We defined an epileptic zone as the place where synchronized spike discharges were seen at three or more intracranial electrodes. We retrospectively analyzed the part of the MEGSS distribution that had been surgically treated, using the 3D surface renderings of MR-MEG images, the intraoperative digital pictures of brain surface imaging with ECoG, and the digital pictures of IVEEG monitoring. Treatments were classified as cortical excision, MST, and untreated.

In cases in which the lesion or epileptic zone was not within the central sulcus, we identified the central sulcus by using intraoperative SSEFs and/or cortical stimulation. We compared the localization of the central sulcus with that of the sulcus closest to the SSEF source on the 3D MR-MEG images.

Pathological Examination

Resected tissues were processed for conventional histological and immunohistochemical analysis with the avidin–biotin complex or peroxidase–antiperoxidase technique.

Seizure Outcome

Postoperative seizure outcome was graded according to Engel’s classifications: Grade I, free of disabling seizures; Grade II, rare disabling seizures; Grade III, worthwhile improvement; or Grade IV, no worthwhile improvement.

Results

Magnetencephalography Findings

We obtained MEGSS data in 13 of 16 patients. Three patients had no MEGSS (Class IV). The number of spike
synchronous sources obtained for individual patients ranged from four to 198.

Table 2 provides descriptions of MEGSS areas and their distribution in relation to MR imaging findings. Nine patients had Class I MEGSS distributions; two had Class II, one with coexisting Class I and one without Class I; three had Class III MEGSS alone. All 13 patients had Class III MEGSS in epileptogenic hemispheres. Figure 1 shows examples of these distribution patterns. Eight patients had MEGSS in the contralateral nonepileptogenic hemisphere.

As revealed on MR imaging, 11 patients had lesions in the left hemisphere, four had lesions in the right, and one had no lesions. Of the 15 lesions, five were tumors, two were residual tumors at the margins of previous excisions, four were cortical dysplasias, two were postexcision cavities after epilepsy surgery, one was a porencephalic cyst, and one was encephalomalacia with cyst.

Three of four patients with cortical dysplasia demonstrated on MR imaging had Class I MEGSSs within the areas of the lesions that also extended contiguously out from the lesions; they also had coexisting Class III MEGSSs that were remote from the lesions. Figure 2 shows the Class I MEGSSs in the patient in Case 2 who had cortical dysplasia. The remaining patient had Class III MEGSSs alone that diffused and contiguously spread from the frontal lesion to the central, parietal, and temporal regions.

One patient in whom MR imaging revealed no lesions had Class I MEGSSs that were localized in the left inferior frontal, central, and superior temporal regions and a single Class III MEGSS in the parietal region distant from the Class I MEGSS areas.

In the six patients in whom MR imaging demonstrated cysts in two patients, a postexcision cavity in one patient, a tumor in one patient, or residual tumors in two patients, asymmetrical Class I or II MEGSSs occurred at the margins of the lesions. The patient in Case 8 also had Class I MEGSSs contiguously extending from the margin of the cyst. In the two patients in whom MR imaging demonstrated tumor and postexcision cavities had Class III alone. Three patients with tumors had no MEGSSs (Class IV).

Somatosensory evoked fields were obtained bilaterally in 15 of the 16 patients. In one patient (Case 8), whose lesion was a large porencephalic cyst in the left temporoparietal region, no SSEFs in the left hemisphere were seen after right median nerve stimulation but a right hemisphere SSEF was demonstrated with left median nerve stimulation.

**Intracranial Video Electroencephalography/ECoG Findings**

Table 3 correlates the MEGSS with IVEEG/ECoG findings, surgical procedures, diseases, and seizure outcomes. Four patients (Cases 1, 2, 4, and 5), who had epileptic zones adjacent to functional cortex, underwent IVEEG monitoring for 5 days (Fig. 2B). All of these patients had ictal onset zones in the left hemisphere.

Twelve patients underwent intraoperative ECoG. In two patients (Cases 7 and 10), the intraoperative ECoG was recorded following the recording of left hemisphere SSEF in patients (Cases 1 and 11), who had cortical dysplasia (Fig. 2B). After the SSEF had been recorded, the electrodes were moved to another scalp location adjacent to the epileptic zone. The patient in Case 11 had no ECoG recorded following the recording of the SSEF that was seen on intraoperative ECoG.

Data for correlation with MEGSSs were available in 12 patients in whom MR imaging revealed nonepileptogenic zones, whereas the remainder had a combination of III MEGSS sites and epileptogenic zones. Among the 12 patients with III MEGSS sites that did not overlap MEGSSs in other patients, 11 patients had epileptogenic zones, whereas the other did not have epileptogenic zones. Among the eight patients with epileptogenic zones, all Class I MEGSSs were located in the central sulcus and sensorimotor cortex in six patients.

Seven patients underwent at least one intraoperative depth electrode recordings. The electrodes were placed in the central sulcus for the SSEF recording and/or by cortical stimulation.

**Variation in SSEF Recording Sites**

Surgical Procedures

The surgical procedures consisted of lesionectomy with cortical excision in seven patients, cortical excision in five patients, and lesionectomy without MEGSS. The surgical procedures consisted of lesionectomy with cortical excision in seven patients, cortical excision in five patients, and lesionectomy without MEGSS in one patient. Three patients had residual tumors at the margins of previous excisions. In one patient (Case 4), the supratemporal cortex adjacent to the tumor was not spared. In two patients, the residual tumor was located in the right hemisphere and did not overlap MEGSS in the left hemisphere.

The surgical procedures were performed in 12 patients who had both MEGSSs and clinical epilepsy. In three patients with Class III MEGSSs, the epileptogenic zones did not overlap MEGSSs in two patients (Cases 3 and 6), whereas the remaining seven had coexisting Class III MEGSSs that did not colocalize. Electrocorticography was available in 12 patients who had both MEGSSs and clinical epilepsy. In three patients with Class III MEGSSs, the epileptogenic zones did not overlap MEGSSs in two patients (Cases 3 and 6), whereas the remaining seven had coexisting Class III MEGSSs that did not colocalize. Electrocorticography was available in 12 patients who had both MEGSSs and clinical epilepsy.

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Characterizing magnetic spike sources

Data for correlation of MEG with IVEEG/ECoG were available in 12 patients who had both MEGSSs and epileptic zones demonstrated on IVEEG/ECoG. In nine of these patients, all Class I MEGSSs colocalized with the epileptic zones. Among these nine, two had coexisting Class III MEGSSs that also colocalized with the epileptic zones, whereas the remaining seven had coexisting Class III MEGSSs that did not colocalize. Electrocoagulography did not overlap MEGSSs in two patients (Cases 3 and 6). In the patient in Case 3, who had mesial occipital cortical dysplasia, MEGSS distributions were revealed over the lateral-to-mesial occipital surface but no data from depth electrode recordings were available of the deep mesial occipital region with intact visual field. The patient in Case 6 underwent prior surgery for inferior frontal gliosis and had interictal spikes recorded following the excision of residual lesions. In three patients (Cases 11, 15, and 16) no interictal zones were seen on intraoperative ECoG.

Surgical Procedures

The surgical procedures consisted of lesionectomy with cortical excision in seven patients, cortical excision in five patients, and lesionectomy alone in three patients (those without MEGSSs). The patient in Case 3 with mesial occipital cortical dysplasia underwent a partial lesionectomy to spare the visual field. We performed MSTs over the eloquent cortex in six patients.

One patient (Case 11), in whom no interictal zones were seen on ECoG, underwent lesionectomy with additional cortical excision based on the location of the Class II MEGSS distributions.

Three patients underwent lesionectomies alone because they were in Class IV (no MEGSS). In one patient with a mesial temporal tumor, we performed a lesionectomy through an anterior temporal lobectomy from which sporadic ECoG spikes had been recorded. In two patients, whose interictal zones were undefined because their tumors showed limited spikes over only two ECoG electrodes and no MEGSS distributions, we performed only lesionectomies.

Correlation of Surgical Management of MEGSS to Seizure Outcome

Follow-up periods ranged from 8 to 38 months (mean 23 months). Twelve patients experienced no seizures after surgery, with a mean follow up 21 months; three of the 12 had no MEGSS distributions (Class IV).

In the nine seizure-free patients in whom MEGSS distributions were seen, five had Class I. The Class I MEGSS distributions were completely excised in three of the five patients. In the remaining two patients (Cases 8 and 10), we treated part of the Class I MEGSS areas with MSTs or left the area untreated. Four patients with residual seizures had Class I MEGSS areas that were not completely excised. The patients in Cases 1, 2, and 5 underwent MSTs over parts of Class I MEGSS areas in their eloquent cortices. In Cases 3 and 5, Class I MEGSS areas were not treated to spare the visual cortex and language cortex, respectively. Of these four patients, three had cortical dysplasia and one had gliosis. One patient with cortical dysplasia, who underwent MSTs over the inferior centroparietal and posterior temporal regions where part of a spike source cluster was localized, has suffered severe seizures after surgery and has been poorly controlled.

Three patients with Class III MEGSS areas alone were seizure free after surgery. We performed cortical excisions and MSTs over the entire scattered MEGSS areas that colocalized with the epileptic zones. Class II MEGSS distributions were found in two patients;
one (Case 6) had coexisting Class I and III MEGSS areas; the other (Case 11) had coexisting Class III MEGSSs. The patient in Case 6 was seizure free after complete excision of the Class I MEGSSs, although the Class II and III MEGSS areas were untreated. The patient in Case 11 underwent cortical excision of only the Class II MEGSS without treatment of the Class III MEGSSs and had a seizure-free outcome. Coexisting Class III MEGSSs were untreated in nine of 10 patients with Class I and/or Class II MEGSS areas.

Pathological Examination

Histological examination confirmed cortical dysplasia in four patients, including cortical dysplasia with balloon cells in the patient in Case 1 who had had no positive diagnostic criteria for tuberous sclerosis complex. Seven patients had low-grade tumors consisting of dysembryonic neuroepithelial tumor and cortical dysplasia (three patients), ganglioglioma (two patients), and low-grade glioma (two patients). Of the remaining five patients, two had gliosis, one had Sturge–Weber syndrome, one had a porencephalic cyst, and one had encephalomalacia and a cyst.

Discussion

Classification of MEGSS Areas

In this study we define four classes of MEGSS areas in 16 pediatric patients with and without lesions. Class I consists of 20 or more spike sources within a 1-cm distance and these occurred in nine patients. Class II has between six and 19 spike sources, and two patients exhibited Class II MEGSSs. Class III contains fewer than six spikes or has a spike source distance of greater than 1 cm; 13 patients had Class III distributions. Three patients with tumors had no spike sources and were classified as Class IV. All 10 patients with Class I and/or II spike sources had coexisting Class III spike sources.

Fig. 2. Case 2. A: Sagittal T1-weighted MR image revealing Class I and III MEGSS (white dots). The cross-point of the orthogonal yellow lines indicates the middle of the Class I MEGSS distribution at the inferior part of the motor cortex. Remote Class III MEGSS were localized in the anterior portion of inferior temporal gyrus. B: Operative view of the exposed left hemisphere superimposed with the numbers of intracranial EEG electrodes. The yellow circle represents the ictal onset zone. The green circle represents active interictal zone. Functional mapping identified tongue and hand motor representations (white dots) and language representations (black squares). C: Schematic drawing showing MEGSS (red area), cortical excision (black circle), MST (blue circle), and SSEF (green dot). Class I MEGSS (red area) are located over the inferior frontocentral and superior temporal regions. We performed partial cortical excision of the ictal onset zone, because the language and motor cortices coexisted with the epileptogenic cortical dysplasia, and MSTs over the inferior frontal and superior temporal regions of remaining ictal onset zone and the active interictal zone of the parietal region. Because the inferior temporal region with Class III MEGSS (red dots) was not in the active interictal zone on intracranial EEG recording, no surgery was performed. The patient has had rare facial twitching without generalized seizures 28 months after the surgery. D: Intraoperative MEG neuronavigation system showing 3D reconstructed brain surface and the pointer (blue bar), which targeted the cross-point of yellow lines in Fig. 2A. The green area represents sensory cortex based on SSEFs. The location of the central sulcus was confirmed by the following functional mapping using subdural electrodes.
Characterizing magnetic spike sources

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</tr>
<tr>
<td>7</td>
<td>lt</td>
<td>mes-mid-post T</td>
<td>III (11)‡</td>
</tr>
<tr>
<td>8</td>
<td>lt</td>
<td>C-T</td>
<td>I</td>
</tr>
<tr>
<td>9</td>
<td>lt</td>
<td>P</td>
<td>I</td>
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<tr>
<td>10</td>
<td>lt</td>
<td>inf Fr-post-sup T</td>
<td>I</td>
</tr>
<tr>
<td>11</td>
<td>lt</td>
<td>inf Fr-post-sup T</td>
<td>no spike on ECoG</td>
</tr>
<tr>
<td>12</td>
<td>lt</td>
<td>mid-sup Fr</td>
<td>no spike on ECoG</td>
</tr>
<tr>
<td>13</td>
<td>lt</td>
<td>ant-mes T</td>
<td>no spike source</td>
</tr>
<tr>
<td>14</td>
<td>rt</td>
<td>ant T</td>
<td>no spike source</td>
</tr>
<tr>
<td>15</td>
<td>rt</td>
<td>P, 2 electrodes</td>
<td>no spike source</td>
</tr>
<tr>
<td>16</td>
<td>rt</td>
<td>Fr, 2 electrodes</td>
<td>no spike source</td>
</tr>
</tbody>
</table>

* BC = balloon cells; CD = cortical dysplasia; DNT = dysembryonic neuroepithelial tumor; FU = follow up; GG = ganglioglioma; LGG = low-grade glioma.
† ECoG did not cover entire MEGSS area.
‡ Indicates the number of MEGSSs in a part of Class III.

Mamelak, et al. proposed a classification of MEGSSs in adult patients with neocortical epilepsy. They divided spike sources into four classes based on the number of spikes and the distance between spikes. They concluded that the MEG data should be used to guide placement of intracranial electrodes when many spike sources are tightly clustered; however, they did not use neuronavigation with MEGSS data to direct cortical excision. In addition, their report lacked information about scattered MEGSSs. Here, we expand on their work by characterizing MEGSS data as Class I (clusters), Class II (small clusters), and Class III (scatters) for use in directing focal resection or extraoperative intracranial recording in pediatric epilepsy surgery. In pediatric patients with epilepsy, spike discharge patterns for specific epileptic syndromes and prolonged IVEEG studies are highly variable.28,32 A report on 12 pediatric cases with lesional extrahippocampal epilepsy defined a cluster of MEGSSs as more than 20 spike sources. All of the clustered spike sources were localized within and/or adjacent to the lesions and corresponded to epileptogenic zones that were corroborated by ECoG and positive surgical outcomes.23 In the study of lesional extrahippocampal epilepsy, MEGSS areas were asymmetrical and occurred at the margins or in the extra-marginal region of tumors, and in cases of cortical dysplas-

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Management of MEGSS Zones
Classification and characterization of MEGSS areas allow for unique surgical management of pediatric patients undergoing epilepsy surgery. Class I MEGSSs indicate that the entire area encompassed by the clustered MEGSSs should be excised when feasible. If any part of the clustered MEGSS area is left unexcised, the seizure outcome becomes less favorable. In particular, cortical dysplasia, visible dysplastic lesions, and epileptogenic zones outside of essential cortical areas beyond the visible abnormalities should be resected completely for seizure control.

In patients with only Class III MEGSS areas, the epileptic zone may be buried among the scattered MEGSSs. Careful evaluation of MR imaging, other neuroimaging studies, seizure semiology, and intracranial electrode placement is necessary for successful identification and removal of the epileptic zone in these cases. Conversely, in patients with Class I and III MEGSS distributions, the area of Class III MEGSS is less likely to be in the epileptic network but is possibly a part of anatomical and/or functional networks connected to the epilepsy network. Removal of this area may not be necessary for seizure control.

Classification of MEGSS areas may reflect a pathophysiological hierarchy. Our classification of MEGSSs differs from the previous classification because we further divide the clustered spike sources into two groups: Class I (clusters), greater than or equal to 20 MEGSS with less than 1 cm distance between MEGSS, and Class II (small clusters), between six and 19 MEGSS with less than 1 cm distance. In two patients (Cases 6 and 11), Class II MEGSSs coexisted with Class I and III MEGSSsoverlapping the eloquent cortex indicating functionally abnormal central cortex. Patients with tumors and in Class IV (no spike source) may require only lesionectomy. For the two patients in was unable to localize the zone of seizure origin in the remaining 12 patients who had diffusely clustered or few MEGSS distributions.

Intraoperative MEG Neuroanavigaton System for Epilepsy Surgery
In this study, 3D reconstructed MR-MEG data incorporated into the intraoperative navigational system precisely localized epileptic regions on the exposed brain surface. Little is known about the combined MEG imaging–frameless stereotactic neurosurgical technique in the surgical treatment of intractable epilepsy. Duffner, et al.65 presented a technical case report on the use of MEG imaging-based neuronavigational guidance for the treatment of recurrent gliomas in the precentral region. They were able to resect the tumor safely and the epileptiform spike focus.

We successfully transferred the SSEF localization to the 3D images on the navigation system in 15 of 16 pediatric patients, including three children younger than 10 years of age. The SSEF was intraoperatively correlated to the central sulcus in six of seven patients in whom there was an epileptic area around the central sulcus. Somatosensory evoked potential and cortical stimulation in children and young children is difficult because they require an anesthetic for the procedure and are not cooperative.56 Moreover, children with cortical dysplasia who are younger than 14 years have a higher stimulation threshold to activate a functionally abnormal central cortex.6 Sensory and motor cortices extended across the central sulcus more often in patients with cortical dysplasia than in patients with noncortical dysplasia.

Therefore, 3D MEG neuronavigation offers advantageous preoperative and intraoperative information for precise localization of the central sulci in children whose SSEFs and motor function are unpredictable in difficult intraoperative situations.

This technique applied to MEGSSs distributions allows neurosurgeons to plan the optimal preoperative trajectory for preventing functional deficits and to perform intraoperative determination of epileptogenic lesions and epileptic zones.

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Characterizing magnetic spike sources

Conclusions

We investigated whether characterization of MEGSS distributions would be useful for surgical management and concluded that Class I MEGSSs indicated a primary epileptic zone requiring complete excision but that coexisting scattered spike sources of Class III did not. When MEGSS clusters (Class I) overlap unresectable eloquent areas, our results predict that seizure control will be limited. Class III MEGSS areas alone may reveal underlying epileptogenic areas and should be examined by ECoG. Complete excision of a region delineated by Class I and II MEGSS data produced satisfactory surgical outcomes.

Acknowledgment

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References

EDULLOBLASTOMA is a brain malignancy in children, astrocytoma being the first, accounting for approximately 12.9% of pediatric brain tumors in Japan.

Malignant medulloblastoma of the cerebellum and causes cerebellar ataxia and headache secondary to obstruction of the CSF pathway. It has an inherent tendency to recur and metastasize through the CSF space, thereby hindering radical cure of the disease. In this regard, medulloblastoma is classified as a Grade IV tumor by the WHO system.

Abbreviations used in this paper:

- D2R = dopamine D2 receptor
- GAPDH = glyceraldehyde-3-phosphate dehydrogenase
- MBEN = medulloblastoma with extensive nodularity
- mRNA = messenger RNA
- PCR = polymerase chain reaction
- SD = standard deviation
- SDS = sodium dodecyl sulfate
- SSCP = single-strand conformation polymorphism
- WHO = World Health Organization

References: