A porencephalic cyst may be defined as a fluid-filled cavity in the brain resulting from either a prena
tal hemorrhage or an ischemic vascular event, which occurs prior to the capability of the immature brain to mount a gliotic response. A similar focal ischemic or hemorrhagic event that occurs in the late third trimes
ter, postnatally or later in life, results in the formation of gliotic tissue within the atrophic brain lesion, which is known as encephalomalacia.

Porencephalic cyst/encephalomalacia (PC/E) commonly presents with medically intractable epilepsy, congenital hemiparesis, and/or cognitive impairments. Localization of ictal and interictal electroencephalography (EEG) discharges is challenging in patients with PC/E because the fluid-filled cavity and atrophic cortical tissue distort electrical fields and reduce the amplitude of scalp EEG. Therefore, patients with intractable focal epilepsy
secondary to PC/E, which is associated with dense hemiparesis, are frequently subjected to a hemispherectomy due to difficulty in localization with ictal and interictal EEG. For patients with mild hemiparesis, lesionectomy, focal corticectomy, and lobectomy were occasionally performed. When extratemporal PC/E is associated with temporal lobe epilepsy and hippocampal sclerosis, a temporal lobectomy can render these patients seizure free.

Magnetoencephalography (MEG) analysis uses an equivalent current dipole source model overlaid onto MRI to localize sources of interictal epileptiform discharges. Magnetoencephalography is a powerful tool in presurgical evaluation for predicting the epileptogenic zone. Because magnetic fields are comparatively unaffected by the different electrical conductivities of the brain, CSF, skull, and skin, MEG can accurately localize the sources of intraneuronal electric currents that contribute to extracranial magnetic fields. Freedom from conductivity differences becomes particularly relevant in the presence of various pathological brain lesions.

Iida et al. described localized interictal epileptic spikes defined by intraoperative electrocorticography (ECoG) in pathological cortex that extended contiguously beyond the margin of the porencephalic cyst. The precise delineation of the epileptic cortex by ECoG allowed a focal corticectomy to be performed with sparing of acquired motor functions instead of a hemispherectomy. We evaluated the localization of MEG spikes sources (MEGSS) of PC/E in patients with intractable epilepsy. We hypothesized that MEG can localize the extent of the epileptogenic zone at the margin of PC/E and can direct surgical strategy.

**Methods**

We identified 19 children with PC/E who underwent MRI and MEG between 2000 and 2009 at The Hospital for Sick Children in Toronto. Thirteen of 19 children underwent prolonged scalp video-EEG for presurgical evaluation due to intractable epilepsy and had electroclinical seizures during video-EEG at our institution. Five patients were girls and 8 were boys, ranging in age at the time of MEG from 1.8 to 15 years (mean 8.1 years). If a patient had several MEG studies, we analyzed the MEG results closest to the surgery. Clinical data including seizure semiology, developmental status, and neurological examination results were obtained from a retrospective chart review. The study was approved by the research ethics board at The Hospital for Sick Children, and informed consent was not required.

**MRI Procedures**

All 13 patients underwent 1.5-T or 3-T MRI. Our MRI protocol consisted of sagittal T1-weighted, axial and coronal T2-weighted, axial and coronal FLAIR, and axial 3D T1-weighted sequences. One neuroradiologist (E.W.) reviewed the MRI and evaluated the location of PC/E. Lateralization on MRI was determined by the location of the PC/E on MRI.

**Results**

**Clinical Profiles**

Table 1 details the clinical profiles of the 13 patients.

**EEG Studies**

We recorded video-EEG telemetry (Harmony 5.4, Stellate, Natus) using 19 or 25 scalp electrodes (subtemporal electrodes: F9, F10, T9, T10, P9, and P10) placed according to the International 10–20 system. A single reference was placed at Oz, Pz′ (located 1 cm behind Pz), or FCz, whichever was the most inactive electrode. The sampling rate was 200 Hz or 500 Hz.

We classified ictal discharges as bilateral independent, unilateral hemispheric, or undetermined; when the ictal discharges were unilateral hemispheric, further localizations were categorized as regional or diffuse hemispheric. Ictal discharges include ictal onset and intra-ictal buildup. We classified interictal discharges as generalized, bilateral independent, or hemispheric; when the interictal discharges were hemispheric, further localizations were categorized as regional or diffuse hemispheric.

**Simultaneous MEG and EEG Recordings**

Magnetoencephalography recordings were performed during the daytime as an outpatient examination. We used a whole-head, gradiometer-based Omega system (151 channels, CTF MEG). The night prior to testing, we deprived patients of sleep because focal interictal epileptiform discharges are accentuated by light sleep. For patients who were unable to remain still during MEG recordings, the study was performed with the patient under general anesthesia using propofol and remifentanil. We collected EEG data simultaneously with MEG recording using 19 electrodes (International 10–20 system). At least 15 2-minute periods of spontaneous data were recorded from each patient. The sampling rate for data acquisition was 625 Hz or 1250 Hz, with a band-pass filter of 3 Hz or 10–70 Hz and a notch filter of 60 Hz. We localized head position at the beginning and end of each set.

We visually identified MEG interictal epileptiform discharges—spikes, polyspikes, and sharp waves (referred to as spikes)—by reviewing the 151-channel raw MEG wave forms and cross-referenced them with the simultaneous EEG recordings. We analyzed individual spikes instead of averaged spikes for dipole source localization to obtain the extent of the epileptogenic zone. 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 selected 1 MEGSS from each individual spike as a single dipole fit from the earliest phase of each spike, with the following criteria: 1) a dipole moment of 50–400 nAm, 2) the dipole staying in 1 location during 10 msec, and 3) the dipole with reasonable magnetic field topography.

An MEGSS cluster was defined as 6 or more MEGSS with 1 cm or less between each spike source. The location and spatial relation of MEG cluster to PC/E was assessed. Localization of MEGSS was compared with ictal zone and interictal zone as determined by scalp video-EEG.
TABLE 1: Clinical profiles of the 13 patients with intractable epilepsy secondary to PC/E*

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Age at Seizure Onset (yrs), Sex</th>
<th>Age at Scalp Video-EEG (yrs)</th>
<th>Age at MEG (yrs)</th>
<th>Seizure Semiology</th>
<th>Development</th>
<th>Neurological Examination</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.3, F</td>
<td>1.4</td>
<td>1.8</td>
<td>epileptic spasms</td>
<td>global developmental delay</td>
<td>rt hemiplegia</td>
</tr>
<tr>
<td>2</td>
<td>1, M</td>
<td>2.4</td>
<td>2.9</td>
<td>epileptic spasms</td>
<td>normal</td>
<td>rt hemiparesis</td>
</tr>
<tr>
<td>3</td>
<td>9, F</td>
<td>15</td>
<td>15</td>
<td>partial Szs</td>
<td>normal</td>
<td>normal</td>
</tr>
<tr>
<td>4</td>
<td>6, M</td>
<td>14</td>
<td>14</td>
<td>partial Szs</td>
<td>cognitive delay, no motor deficit</td>
<td>rt hemiparesis, rt homonymous hemianopsia</td>
</tr>
<tr>
<td>5</td>
<td>0.3, M</td>
<td>2.3</td>
<td>2.3</td>
<td>epileptic spasms, tonic Szs</td>
<td>global developmental delay</td>
<td>lt hemiparesis</td>
</tr>
<tr>
<td>6</td>
<td>0.3, F</td>
<td>14</td>
<td>14</td>
<td>partial Szs</td>
<td>global developmental delay</td>
<td>normal</td>
</tr>
<tr>
<td>7</td>
<td>2, M</td>
<td>2.6</td>
<td>2.8</td>
<td>partial Szs</td>
<td>normal</td>
<td>rt hemiparesis</td>
</tr>
<tr>
<td>8</td>
<td>0.3, M</td>
<td>11</td>
<td>11</td>
<td>partial Szs, 2 secondary generalized tonic-clonic Szs</td>
<td>global developmental delay</td>
<td>rt hemiparesis</td>
</tr>
<tr>
<td>9</td>
<td>1.8, M</td>
<td>2.7</td>
<td>3</td>
<td>epileptic spasms, partial Szs</td>
<td>learning difficulty</td>
<td>slight facial asymmetry (rt weak)</td>
</tr>
<tr>
<td>10</td>
<td>5, F</td>
<td>10</td>
<td>11</td>
<td>partial Szs</td>
<td>mild developmental delay</td>
<td>lt leg shorter, lt homonymous hemianopsia, mild lt paresis</td>
</tr>
<tr>
<td>11</td>
<td>0.4, F</td>
<td>10</td>
<td>10</td>
<td>epileptic spasms, tonic Szs</td>
<td>global developmental delay</td>
<td>rt hemiparesis</td>
</tr>
<tr>
<td>12</td>
<td>4, M</td>
<td>5</td>
<td>5</td>
<td>partial Szs</td>
<td>normal</td>
<td>lt hemiparesis</td>
</tr>
<tr>
<td>13</td>
<td>0.3, M</td>
<td>13</td>
<td>13</td>
<td>partial Szs</td>
<td>cognitive delay</td>
<td>normal</td>
</tr>
</tbody>
</table>

* Sz = seizure.
in the study, including age at seizure onset and scalp video-EEG, seizure semiology, and cognitive/neurological findings. Age at seizure onset ranged from 3 months to 9 years (mean 2.4 years). Age at scalp video-EEG ranged from 1.4 years to 15 years (mean 8.0 years). Nine patients had partial seizures with or without secondarily generalized seizures. Five patients presented with epileptic spasms, and 1 of these 5 patients had both partial seizures and epileptic spasms. Seven patients had hemiparesis and 1 patient had hemiplegia.

Three patients had normal neurological examination results. Developmental delay and cognitive impairments were observed in 9 patients, whereas 4 patients had no cognitive impairment. Four patients had a history of prematurity (< 37 weeks gestational age), 8 patients were born at term, and in the remaining 1 patient the birth history was not obtained.

MRI Findings

Table 2 details the MRI findings, ictal and interictal EEG findings, MEG findings, and surgical results. Twelve patients had unilateral PC/E: 7 in the left hemisphere and 5 in the right hemisphere. Case 4 showed bilateral encephalomalacia with left hemispheric predominance. Porencephalic cyst/encephalomalacia affected the temporal lobe in 10 patients, extending from the temporal lobe to the extratemporal lobe in 8 patients and involving only the temporal lobe in 2 patients. The remaining 3 patients had extratemporal PC/E. Five patients had an MRI diagnosis of MCA infarcts, 6 had encephalomalacia from prior ischemia or hemorrhage, and 2 were diagnosed with a porencephalic cyst.

Scalp Video-EEG Findings

Ictal EEG discharges were lateralized in 9 patients (69%), involving the left hemisphere in 4 patients and the right hemisphere in 5 patients. In these 9 patients, ictal discharges affected 2 lobes in 4 patients, were diffuse hemispheric in 3 patients, and were localized to 1 lobe in 2 patients. Four patients (31%) had undetermined ictal discharges, neither lateralized nor localized discharges.

Nine patients (69%) showed lateralized interictal discharges. In 4 of the 9 patients, interictal EEG became generalized during non-REM sleep. Seven of the 9 patients had extensive multifocal or diffuse hemispheric interictal discharges. Only 2 patients showed focal interictal discharges in 1 lobe around a PC/E lesion. Bilateral independent interictal discharges were noted in the remaining 4 patients (31%). In 2 of the 4 patients, interictal EEG became generalized during non-REM sleep.

MEG Findings

Figure 1 shows the schema including the location of the PC/E, the cluster of MEGSS, and the resection area in each patient. In 13 patients, the number of MEGSS ranged from 22 to 176, with a mean of 88. All 13 patients had MEGSS clusters on the margin of a PC/E. The cluster of MEGSS was asymmetrically located at the margin of a PC/E. Eleven patients had 1 cluster. The percentage of clustered MEGSS/total MEGSS number ranged from 45% to 99%, with a mean of 83%. Nine patients (69%) had more than 80% clustered MEGSS/total MEGSS number.

Relationship of MEG to EEG Findings

Ictal EEG discharges were lateralized and concordant with MEGSS hemisphere in 8 patients (62%). One patient (Case 1) showed discordant lateralization between ictal EEG discharges and MEG cluster. In 4 patients with undetermined ictal EEG discharges (Cases 2, 6, 8, and 11), MEG showed clustered MEGSS in 1 or 2 lobes. Interictal EEG discharges were lateralized and concordant with MEGSS hemisphere in 9 patients (69%). Three of 4 patients with bilateral independent interictal EEG discharges showed less than 80% clustered MEGSS/total MEGSS number.

Epilepsy Surgery

Resective surgery was offered when the cluster of MEGSS, anatomical localization of the PC/E, seizure semiology, and video-EEG localization data were all concordant. Nine patients underwent resective surgery (Table 2; Fig. 1). The patient in Case 3 underwent left temporal lobectomy and amygdalohippocampectomy, including resection of a MEGSS cluster, after intracranial video-EEG monitoring. Patient 9 underwent resection of a porencephalic cyst in the left temporoparietal region as well as MEGSS clusterectomy in the left inferior Rolandic region. This patient developed recurrent seizures, consisting of eye deviation followed by tonic seizures and periodic spasms, after resection of the porencephalic cyst and MEGSS cluster, and underwent a second MEG that showed clustered MEGSS. Subsequently, he underwent intracranial video-EEG using subdural grid electrodes 7 years after the first surgery and had further cortical excision over the left parietal, temporal, and occipital regions. Five patients underwent MEGSS clusterectomy with (Cases 4, 5, 10, and 13) or without (Case 12) lesionectomy using the neuronavigation system and intraoperative motor mapping. One patient (Case 6) underwent a temporal lobectomy and amygdalohippocampectomy. Patient 11 underwent left functional hemispherectomy because the seizure semiology of epileptic spasms and tonic seizures and the cluster of MEGSS involved hand motor cortex and the patient had right hemiparesis. Eight of 9 patients achieved seizure freedom following surgery (follow-up range 24–47 months, mean 35 months). The 1 remaining patient suffered residual seizures (Case 9).

The other 4 patients did not undergo resective surgery (Cases 1, 2, 7, and 8). Case 1 had clustered MEGSS in the bilateral hemispheres with predominant clustered MEGSS in the left hemisphere, which was discordant to the side of ictal EEG discharges over the right hemisphere. Cases 2 and 7 became seizure free after the presurgical evaluation. Case 8 was lost to follow-up.

Discussion

MEG as a Presurgical Diagnostic Modality in PC/E

Magnetoencephalography spike sources can delineate the extent of the epileptogenic zone adjacent to and
<table>
<thead>
<tr>
<th>Case No.</th>
<th>Hem Region</th>
<th>Diagnosis</th>
<th>Scalp Video-EEG Findings</th>
<th>MEG Findings</th>
<th>Surgery</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>MRI Lesions</td>
<td>Ictal Discharges</td>
<td>Interictal Discharges</td>
<td>No. of MEGSS</td>
</tr>
<tr>
<td>----------</td>
<td>------------</td>
<td>-------------</td>
<td>---------------------</td>
<td>-----------------</td>
<td>-------------</td>
</tr>
<tr>
<td>1</td>
<td>lt</td>
<td>F-P-T</td>
<td>MCA infarct, PVL</td>
<td>rt F bilat independent multiple</td>
<td>146</td>
</tr>
<tr>
<td>2</td>
<td>lt</td>
<td>F-P</td>
<td>MCA infarct</td>
<td>unk it generalized hemispheric</td>
<td>119</td>
</tr>
<tr>
<td>3</td>
<td>lt</td>
<td>T</td>
<td>encephalomalacia</td>
<td>lt T-O it T</td>
<td>22</td>
</tr>
<tr>
<td>4</td>
<td>lt</td>
<td>T-P</td>
<td>T-P</td>
<td>Lt T-O-P-F it T-P-F</td>
<td>137</td>
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<tr>
<td>5</td>
<td>rt</td>
<td>P-T</td>
<td>encephalomalacia</td>
<td>rt P-O bilat independent multiple</td>
<td>22</td>
</tr>
<tr>
<td>6</td>
<td>rt</td>
<td>T</td>
<td>porencephalic cyst</td>
<td>unk rt/generalized hemispheric</td>
<td>51</td>
</tr>
<tr>
<td>7</td>
<td>lt</td>
<td>F-P-T</td>
<td>MCA infarct</td>
<td>lt hemispheric it hemispheric</td>
<td>71</td>
</tr>
<tr>
<td>8</td>
<td>lt</td>
<td>T-O-P-F</td>
<td>encephalomalacia</td>
<td>unk bilat independent/g general</td>
<td>38</td>
</tr>
<tr>
<td>9</td>
<td>lt</td>
<td>T-O</td>
<td>porencephalic cyst</td>
<td>lt hemispheric it hemispheric</td>
<td>80</td>
</tr>
<tr>
<td>10</td>
<td>rt</td>
<td>F-P-O</td>
<td>encephalomalacia</td>
<td>rt C C-T-P</td>
<td>176</td>
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<tr>
<td>11</td>
<td>lt</td>
<td>F-T-P</td>
<td>MCA infarct</td>
<td>unk it/generalized F</td>
<td>114</td>
</tr>
<tr>
<td>12</td>
<td>rt</td>
<td>F-P</td>
<td>encephalomalacia</td>
<td>rt hemispheric it &amp; rt hemispheric</td>
<td>73</td>
</tr>
<tr>
<td>13</td>
<td>rt</td>
<td>T-P</td>
<td>MCA infarct</td>
<td>rt generalized F-C-T</td>
<td>103</td>
</tr>
</tbody>
</table>

* C = central; F = frontal; Hem = hemisphere; MCA = middle cerebral artery; O = occipital; P = parietal; Pt = patient; PVL = periventricular leukomalacia; T = temporal; unk = unknown.
The locations of PC/E and the cluster of MEGSS are depicted by schema in each patient. In each patient, the left schema shows the lateral view and the right shows the anterior-posterior view ("Frontal") or posterior-anterior view ("Occipital"). When the ventricle is dilated asymmetrically, the ventricles are depicted. The blue area shows encephalomalacia, yellow shows a cystic lesion, dotted area is the cluster of MEGSS, and red line shows the resected area.
Magnetoencephalography in porencephalic cyst/encephalomalacia

asymmetrical to the PC/E in patients with intractable epilepsy secondary to PC/E. Electroencephalography source localization is challenging in this situation because of electrical conductivity differences between the cyst, atrophic cortex, CSF, bone, and skin. In fact, ictal and/or interictal epileptiform discharges on EEG in PC/E could be localized contralateral to the side of the lesion. However, magnetic field is not affected by these different conductivities. Therefore, localization of MEGSS in patients with cystic lesions, atrophic brains, and postoperative scar tissue can be relatively accurate for delineating the epileptogenic zone for epilepsy surgery.

Scalp EEG findings in patients with PC/E often show generalized/bilateral/diffuse hemispheric distributions of ictal and interictal discharges. The EEG findings of PC/E may not be sufficient to localize the epileptic foci or even to make a diagnosis of focal epilepsy. However, the vast majority of our patients showed only a single MEGSS cluster, which included more than 80% of the MEGSS localized at the margin of PC/E.

Resective surgery for intractable epilepsy may be successful for select children and adolescents with a congenital or early-acquired brain lesion, despite abundant generalized or bilateral epileptiform discharges on EEG. The mechanisms for generalized and contralateral epileptiform discharges on scalp EEG are unknown, but may be a manifestation of potentially reversible secondary epileptogenesis resulting from an interaction between the early lesion and the developing brain. The widespread epileptiform discharges on scalp EEG were not necessarily a sign of widespread/hemispheric epileptogenic zone. When MEGSS analysis of the earliest component of generalized/diffuse spikes consistently localized to a single region, the primary epileptogenic focus can be identified by the clustered MEGSS.

Epilepsy Surgery for PC/E

In our study, MEGSS was localized to the margin of PC/E asymmetrically. An MEGSS cluster can be localized on 2 or 3 adjacent margins of PC/E or on a single margin of PC/E. None of our patients had an MEGSS cluster remote from the lesion. In patients with PC/E, MEG is an important tool to localize the epileptogenic zone, which is asymmetrical at the margin of the cystic lesion.

Magnetoencephalography has been applied to localize somatosensory evoked fields for presurgical evaluations. Magnetoencephalography can accurately localize the primary motor function and somatosensory area in children with intractable epilepsy. Magnetoencephalography source analyses provide the spatial relationship between functional cortex and epileptic areas and can direct the surgical strategy, such as lesionectomy in addition to MEGSS clusterectomy in patients with PC/E, who have the epileptic focus distal to the motor cortex. When the PC/E and MEGSS cluster are close to the hand motor cortex, intraoperative cortical motor mapping during lesionectomy in addition to MEGSS clusterectomy can potentially assist in the preservation of motor function.

Patients with congenital hemihypertrophy have been considered good candidates for hemispherectomy. However, a subset of patients with PC/E may be good candidates for hemispherectomy with potentially altered function of the affected limb. In these patients with mild hemiparesis and no hemianopia, it would be optimal to retain motor function; therefore, hemispherectomy is not an ideal surgical option for seizure control. Rather, the surgical approach in such cases can be excision of the PC/E as well as focal cortical resection guided by intraoperative ECoG so as to preserve motor function and visual fields in patients with porencephaly-related intractable focal epilepsy. Burneo et al. reported on patients with extratemporal porencephaly and intractable seizures and suggested that such patients should be evaluated early and be considered for temporal lobectomy with clinical, MRI, and EEG findings support the diagnosis of temporal lobe onset seizures. Carreño et al. reported that some patients may benefit from focal extratemporal resection, using invasive studies to confirm focal seizure onset and to perform functional mapping to spare the visual field.

The use of MEG in patients with PC/E may facilitate tailored resection in conjunction with intraoperative cortical motor mapping when MEGSS identify a distinct epileptic area adjacent to the PC/E but distant from the motor cortex, and precisely delineate the location and extent of the MEGSS cluster along the margins of the PC/E. In this way, the epilepsy surgery can be planned based on the relationship between the epileptic focus determined by ictal and interictal EEG, interictal MEGSS, and the localization of functional sensory motor area also determined by preoperative MEG study. In our cases, 7 of 9 patients achieved seizure freedom from the resection of PC/E and clustered MEGSS at the margin of PC/E without extraoperative video-EEG recording. If the cluster of MEGSS is located at the margin of PC/E and is related to seizure onset zone, clusterectomy of MEGSS could be performed without the need for intracranial video-EEG recording.

Intraoperative ECoG is helpful for confirming the extent of clustered MEGSS in 1-stage surgery. When a patient has mesial temporal sclerosis remote from extratemporal PC/E, careful assessment of seizure semiology and the scalp video-EEG is necessary to determine whether the epileptogenic zone is the mesial temporal sclerosis, extratemporal PC/E, or both.

Conclusions

Magnetoencephalography can provide a more precise location of the epileptogenic zone in PC/E, which was asymmetrical at the margin of PC/E in patients with intractable epilepsy and bilateral/diffuse/hemispheric EEG findings. The value of MEG in this regard is related to the lack of MEG signal interference by the anatomical distortion of brain from PC/E. Resection of the clustered MEGSS along with the PC/E could achieve favorable seizure outcomes in patients in whom MEG localized the epileptogenic zone.

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