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Resective Surgery for Intractable Epilepsy in Children: Radiologic Evaluation

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Epilepsy surgery is gaining popularity for the treatment of children with intractable seizures in whom either a focal or extensive unilateral structural brain lesion is demonstrated. We evaluated the pre- and postoperative imaging findings in 29 patients (aged 22 days to 19 years) who underwent hemispherectomies, 12 total and 17 subtotal. Pathologic correlation was obtained in all cases. Preoperatively, positron emission tomography and electroencephalography demonstrated abnormalities in all of the 28 children studied, but frequently could not characterize the lesion. CT or MR or both demonstrated focal or unilateral lesions in only 19 of these but gave additional information regarding the nature of the lesion. Preoperative angiographic findings were abnormal in five of 17 patients studied and were particularly useful in the evaluation of the extent of abnormality in patients with Sturge-Weber syndrome. Postoperatively, CT and MR demonstrated early complications such as the development of epidural blood and fluid collections, parenchymal hemorrhage, infection, and early hydrocephalus. Postoperatively, MR demonstrated the early development of septations, the presence of subarachnoid hemorrhage, and/or the deposition of hemosiderin in four patients, findings that historically have been associated with the development of devastating clinical complications.

From these data, a recommended protocol of radiologic evaluation for patients undergoing hemispherectomy has been established.

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Surgery for intractable epilepsy is being performed with increasing frequency in both adults and children [1, 2] with focal epileptogenesis. In the pediatric age group, epilepsy surgery may be performed not only in patients with localized temporal lobe lesions but also in children who have extensive unilateral hemispheric lesions. When performed early in life, surgical intervention has been shown to result not only in the cessation of seizures but also in a remarkable recovery of function due to the plasticity of the remaining infant brain once the "noxious tissue" has been removed [3, 4].

Cerebral hemispherectomy was first performed by Dandy [5] in 1928 in a patient with a right hemispheric glioma, and was later performed in patients with intractable seizures associated with either infantile hemiplegia [3, 6] or Sturge-Weber syndrome [7]. Although early results were promising with respect to seizure control [3, 5, 6], the procedure fell into disfavor following later reports of high mortality from delayed hemorrhagic complications in approximately 15% of cases [4, 8–15]. The decline in popularity occurred despite a high percentage of good results, reports of successful second surgeries, and modifications made to the original surgical technique to prevent the development of late complications [4, 9, 11, 12, 16].

Not only have refinements in surgical techniques occurred since the earlier reports of hemispherectomy but several new imaging techniques have become increasingly available that provide more appropriate selection of patients prior to
surgery and accurate postoperative evaluation. Thus, hemispherectomy is once again being performed to control intractable seizures in children with infantile hemiplegia.

This article reviews the pre- and postoperative findings of various neuroimaging techniques in children undergoing focal cortical resection or hemispherectomy for the treatment of a unilateral seizure focus.

Materials and Methods

The neuroimaging studies of 29 patients who had undergone surgery for the treatment of medically intractable seizures were reviewed. Of these 29 patients, 28 had surgery performed between February 1986 and February 1989 following referral to our pediatric epilepsy program. The remaining patient, in whom surgery had been performed 14 years previously, is now also being followed up by the program. The patients, 15 boys and 14 girls, were 22 days to 19 years old at the time of surgery (mean age, 6.6 years). Twelve patients had total hemispherectomy (hemidecortication) and 17 had subtotal hemispherectomy or focal cortical resection. The follow-up period from the date of surgery ranged from 6 months to 14 years (mean, 23.3 months). Pathologic correlation was available in all cases.

TABLE 1: Pathologic Findings in 29 Patients with Medically Intractable Seizures

<table>
<thead>
<tr>
<th>Pathologic Group/Specific Diagnosis</th>
<th>No. of Cases</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CNS tumors</strong></td>
<td></td>
</tr>
<tr>
<td>Astrocytoma</td>
<td>5</td>
</tr>
<tr>
<td>Oligodendroglioma</td>
<td>1</td>
</tr>
<tr>
<td>Mixed oligodendroglioma-astrocytoma</td>
<td>1</td>
</tr>
<tr>
<td>Ganglieneuroma</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>4</td>
</tr>
<tr>
<td><strong>Neurophakomatoses</strong></td>
<td></td>
</tr>
<tr>
<td>Sturge-Weber syndrome</td>
<td>3</td>
</tr>
<tr>
<td>Neurofibromatosis</td>
<td>1</td>
</tr>
<tr>
<td>Tuberous sclerosis</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>5</td>
</tr>
<tr>
<td><strong>Hamartomatous/migrational disorders</strong></td>
<td></td>
</tr>
<tr>
<td>Megalencephaly</td>
<td>1</td>
</tr>
<tr>
<td>Cerebral cortical dysgenesis</td>
<td>5</td>
</tr>
<tr>
<td>Total</td>
<td>6</td>
</tr>
<tr>
<td><strong>Asphyxia/infection</strong></td>
<td>14</td>
</tr>
</tbody>
</table>

During the preoperative evaluation, 28 of the 29 patients had prolonged EEG monitoring and positron emission tomography (PET) with $^{18}F$-2-deoxy-2-fluoro-o-glucose (FDG), which measured local cerebral metabolism of glucose. Continuous EEG video monitoring was used to determine the locations of seizure onset, the consistency of localization across multiple seizures, and any interictal EEG abnormalities. Monitoring was done by using the International 10–20 electrode placements with additional electrodes as necessary to clarify electrical fields [17]. In those patients who underwent subtotal hemispherectomy or focal cortical resection, intraoperative electrocorticography was used to determine the extent of resection [18]. All FDG-PET scans were obtained with either a NeuroECAT positron tomograph (CTI, Knoxville, TN), operated in the high-resolution mode, which provides a spatial resolution of 8.4 mm in the plane of section and a 12.4-mm slice thickness [19], or the CTI 831 positron tomograph, which provides a spatial resolution of 4.2 mm in the plane of section and a 6.3-mm slice thickness [20]. The FDG-PET technique, as applied to children, and the dosimetry have been described previously [21, 22]. Preoperative CT and MR studies were available for review in 27 and 24 patients, respectively. At least one of these studies was performed in 28 of the 29 patients. The patient who had neither study underwent surgery in 1975.

CT scans at our institution were obtained on a GE 9800 scanner (General Electric, Milwaukee, WI). The slice thickness was 10 mm, and images were obtained both before and after contrast administration, except in those patients with strong allergic histories, in whom only unenhanced images were obtained.

MR scans at our institution were obtained on a 0.3-T whole-body system (Fonar, Melville, NY) by using spin-echo sequences, 600–800/28–30 (TR/TE) and 2000–3000/84–85, and a 10-mm slice thickness. Plane selection depended on the patient's clinical history and suspected abnormality. However, both T1- and T2-weighted pulse

**TABLE 2: Findings on Preoperative Evaluation of Seizure Patients**

<table>
<thead>
<tr>
<th>Imaging Study</th>
<th>Normal</th>
<th>Abnormal</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positron emission tomography</td>
<td>0</td>
<td>28</td>
<td>28</td>
</tr>
<tr>
<td>Electroencephalography</td>
<td>0</td>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td>CT</td>
<td>9</td>
<td>16</td>
<td>25</td>
</tr>
<tr>
<td>MR</td>
<td>8</td>
<td>16</td>
<td>24</td>
</tr>
<tr>
<td>Angiography</td>
<td>12</td>
<td>5</td>
<td>17</td>
</tr>
</tbody>
</table>

Fig. 1.—Cerebral cortical dysgenesis.
A, Gross pathologic specimens of normal brain (left) and cerebral cortical dysgenesis (right). In abnormal specimen, cortex is thickened (arrows), and there is poor gray-white matter differentiation.
B, Microscopically in cerebral cortical dysgenesis, total disarray of neurons is seen, with loss of normal cortical layering. Neurons (arrows). (Courtesy of H. Vinters, UCLA Medical Center, Los Angeles, CA.)
In 4-year-old girl with perinatal birth injury and abnormal CT, MR, and FDG-PET studies.

A, Ictal FDG-PET at age 11 months shows areas of hypermetabolism in right parietal and frontal cortices, basal ganglia, and thalamus (arrowheads).

B, Interictal FDG-PET at age 4 years shows hypometabolism of right cerebral hemisphere with some preservation of metabolic activity in parietal lobe, occipital cortex, and basal ganglia (arrowheads).

C, CT shows a porencephalic right lateral ventricle.

D, MR, in addition to showing porencephalic right lateral ventricle, shows high-signal-intensity gliosis in adjacent white matter.

sequences were always obtained in the axial plane in order to better correlate them with FDG-PET studies, which were also obtained in this plane. In postoperative patients and those with suspected temporal lobe lesions, images were obtained in the coronal plane also. Because our institution is a referral center for epilepsy surgery, some patients had had preoperative CT and/or MR studies performed at outside institutions prior to referral to our center. Because of the potential problems involved in sedating children with frequent seizures, these studies were not repeated if considered of good quality when reviewed.

Preoperative angiography was performed in 17 of the 29 patients. Postoperatively, CT and MR scans were available for review in 17 and 16 patients, respectively. Although all patients except one had follow-up studies, in six patients these were performed at outside institutions and were not available for review. The only patient who was not followed up was the 22-day-old child, who died during surgery from anesthesia complications.

Results

Pathologic Correlation

Pathologic correlation was obtained in all cases. Findings were divided into four groups: (1) CNS tumors, (2) neurophakomatoses, (3) hamartomatous lesions and migrational disorders (including cerebral cortical dysgenesis), and (4) abnormalities related to cerebral asphyxia or infection. The number of children within each of these groups and their specific diagnoses are summarized in Table 1. In the five children in whom a diagnosis of cerebral cortical dysgenesis was made, gross visual examination demonstrated that the brains of these children frequently appeared grossly normal with no abnormality of the sulci and gyri. On microscopic examination, however, the cytoarchitecture was markedly abnormal [23] (Fig. 1).

Preoperative Evaluation

Results of the various preoperative tests performed in this series are provided in Table 2. Preoperative EEG and FDG-PET scans demonstrated abnormalities in 29 and 28 children (100%), respectively. Although these tests were very sensitive in the detection of abnormal areas, they often could not characterize the nature of the lesion, nor could EEG accurately define its borders. CT and/or MR demonstrated focal or unilateral lesions in only 19 (68%) of the 28 children studied.
In these 19 patients, CT and MR gave additional information regarding the nature of the lesions (Fig. 2).

In the nine children whose EEG and FDG-PET studies indicated the epileptogenic region but demonstrated no focal CT and/or MR findings (Fig. 3), pathologic examination revealed that five children had findings consistent with cerebral cortical dysgenesis. Of the remaining four, one with neurofibromatosis had areas of heterotopic gray matter and gliosis, one had a low-grade astrocytoma, one had nonspecific cytoarchitectural abnormalities, and one had only minimal gliotic changes seen in the specimen even with extensive histologic analysis; in this latter case, no pathologic diagnosis was given. The age and sex of each of these children together with their pathology and FDG-PET findings are given in Table 3.

In 23 patients, both CT and MR examinations were performed preoperatively. Focal abnormalities were seen by both techniques in 15 patients (65%), and no abnormality was demonstrated by either in eight patients (35%). In the 15 cases in which both CT and MR were abnormal, MR was superior to CT in demonstrating areas of gliosis and the presence of associated delayed myelination in four patients (Figs. 2 and 3). CT was superior in demonstrating areas of calcification in two patients. In no case was there an abnormal MR study in combination with a normal CT study.

Angiograms were abnormal in five (29%) of the 17 patients studied. In three patients, the capillary blush and abnormal venous drainage characteristic of Sturge-Weber syndrome were seen (Fig. 4). In one patient with a porencephalic cyst,
displacement of the cerebral vessels by the cyst was evident. In the fifth patient, who developed seizures following a stroke at 26 months of age, diffuse narrowing of the left internal carotid artery just distal to the left ophthalmic artery and complete occlusion of the left anterior and middle cerebral arteries were identified.

Postoperative Evaluation

Figure 5 shows the normal postoperative MR appearance. Postoperatively, the development of epidural hematomas and other fluid collections was demonstrated in 14 patients. Twelve of these collections resolved without complication. In two cases, however, examination of the fluid following tapping showed it to be infected. The infected fluid collections could not be distinguished from sterile collections on the basis of their appearance on CT or MR images. In one patient, an area of high signal intensity was identified in the left thalamus on both T1- and T2-weighted images, characteristic of subacute hemorrhage (Fig. 6). This was identified on scans obtained 11 days after surgery.

On MR scans obtained after initial surgical recovery, the development of a subdural membrane and septations was seen in four patients (33% of total hemispherectomy cases) 11, 17, and 19 months and 14 years following surgery (Fig. 7). Evidence of prior subarachnoid hemorrhage with hemosid-
Fig. 6.—Early complications. A and B, Coronal SE 800/28 (A) and axial SE 2000/84 (B) MR images show epidural fluid collection on both sequences (arrowheads). Fluid collection (solid arrows) has high signal intensity on both T1- and T2-weighted images due to presence of hemorrhage or high protein fluid within it. Also present is localized area of subacute hemorrhage in region of left basal ganglia (arrowheads) and loculated postsurgical air collection (open arrows).

Fig. 7.—Early subdural membrane formation. A and B, Coronal SE 800/30 (A) and axial SE 2000/85 (B) images. Subdural membrane is beginning to form around hemispherectomy cavity (arrows). It demonstrates medium signal intensity on T1-weighted image and high signal intensity on T2-weighted image. Adjacent CSF has normal signal intensity.

Fig. 8.—Septation formation with early hemosiderin deposition. A and B, Axial SE 800/28 (A) and SE 2000/84 (B) images. Septations have developed, and there is evidence of a small amount of hemosiderin deposition along posterior border of septations on T2-weighted image (arrows). CSF demonstrates normal signal intensity.
Fig. 9.—Septation development and subarachnoid hemorrhage 14 years after hemispherectomy. A and B, Axial SE 800/28 (A) and SE 2000/84 (B) images. Multiple septations transect areas of loculated hemorrhagic CSF. Hemosiderin deposition is seen along septations and along edge of remaining hemisphere.

Hemosiderin deposition was seen in three (25%) of these (Fig. 8). In two patients, the loculated fluid seen between septations was of varying signal intensity, indicating repeated bleeding episodes rather than a single event (Fig. 9). All of the children with this set of complications had undergone total hemispherectomy. In one child, hydrocephalus developed after a shunt malfunction.

Discussion

Surgical resection of epileptogenic tissue is being used increasingly for the treatment of intractable epilepsy of widely varying etiologies provided that a focal or unilateral seizure focus is confirmed. In patients undergoing hemispherectomy, contralateral hemiplegia must be present prior to surgery. The resurgence of hemispherectomy in the current era of multi-technique neuroimaging raises the issue as to which of the available neuroimaging methods should be used to both aid in the selection of appropriate surgical candidates and to subsequently follow their postoperative course.

Surgical Technique

In all cases requiring hemispherectomy, one entire hemisphere is removed with sparing of the thalamus and striatum and their blood supply (Fig. 10). Initially, the middle, anterior, and posterior cerebral arteries are ligated and then the draining veins are coagulated and divided. The corpus callosum is divided and the choroid plexus carefully preserved. The tissue is then dissected and the hemisphere removed as one or two specimens. The large remaining space communicates with the ventricular system through the foramen of Monro. A drainage tube connected to a sterile closed-drainage system is left in the subdural space to allow drainage of CSF and blood products. After 7 days, the drain is removed, and a subdural to peritoneal shunt is placed. Figure 5 shows the normal postoperative MR appearance.

Selection of Surgical Candidates

As surgical resection is rarely indicated in children with bilateral seizure foci, both EEG and FDG-PET scanning play
vital roles preoperatively, not only in the demonstration of the seizure focus but also in confirming that no seizure focus exists in the contralateral hemisphere. The studies are complementary. FDG-PET scanning will accurately localize and define the extent of abnormality present, but EEG is still needed to prove that the abnormality shown by the FDG-PET study is indeed an epileptic focus. In centers that do not have access to FDG-PET scanning, preoperative evaluation with chronic grid or depth-electrode recording may be necessary when ictal scalp EEG data are ambiguous or contradictory [21]. Although FDG-PET scanning has been shown to be extremely sensitive and accurate in demonstrating the epileptogenic zone [21], it is nonspecific at characterizing the underlying structural abnormality. Therefore, CT and/or MR play important roles that are complementary to PET and EEG in the preoperative evaluation of such patients. It is the combination of information obtained from all these methods, together with the clinical assessment, that enables a decision to be made regarding the appropriateness of surgical treatment in these patients.

Even though MR has been proved to be superior to CT in the demonstration of temporal lobe lesions [24, 25] (Hadley DM et al., presented at the annual meeting of the Society of Magnetic Resonance in Medicine, August 1989), and is the preferred technique for the evaluation of migrational disorders and neurophakomatoses [26–31], in this series CT and MR were equal at diagnosing abnormalities preoperatively. This is in contrast to results obtained in adult epilepsy surgery groups, in which MR has been shown to be superior to CT in the detection of lesions preoperatively. We speculate, however, that in a larger study group in which there are more isolated temporal lobe lesions or in situations in which scans are tailored to optimize the detection of cerebral cortical dysgenesis, MR should also be more sensitive than CT in the pediatric population.

Angiography proved to have a limited use in children undergoing hemispherectomy, being most useful in patients with Sturge-Weber syndrome by helping to define, preoperatively, the extent of the leptomeningeal angiomata. In children undergoing focal resection, intraoperative electrocorticography is now routinely performed because it accurately defines the borders of the abnormality at the time of surgery [32], making the preoperative angiogram less essential in this role.

Our epilepsy program currently routinely employs a combination of EEG, PET-FDG, and MR in the preoperative assessment of potential surgical candidates. A protocol for the pre- and postoperative assessment of surgical patients is outlined in Table 4.

Cerebral Cortical Dysgenesis

In this study, nine children with focal abnormalities on FDG-PET scans and EEG had no corresponding abnormalities on CT and/or MR scans. Review of the pathologic specimens of these patients showed that cerebrocortical dysgenesis was demonstrated in five of them.

Cerebral cortical dysgenesis is thought to be a form of migrational disorder. In patients with this abnormality, there is localized disruption of the normal cortical lamination by an excess of large aberrant neurons scattered randomly through all but the first layer. The aberrant nerve cells, which are frequently pyramidal, are in total disarray, lacking columnar organization. In a smaller number of these patients, although the cerebral surface is normal, on cut section there may be localized thickening of the cortical ribbon and its junction with the white matter may be blurred [23]. Areas of heterotopic gray matter also are frequently present in association with the cortical dysgenesis.

As MR images can clearly map out the zones of gray and white matter and also clearly depict the surface anatomy of the brain, it would seem feasible that some of the abnormalities present in patients with cerebral cortical dysgenesis could be demonstrated by MR. Why then did we not detect these abnormalities? In infants, the inherently higher water content of the brain changes the relative signal intensities of the gray and white matter [33], and thus can make differentiation of the gray and white matter difficult at certain ages. This is particularly true between approximately 8 and 12 months of age in developmentally normal children and at later ages in those with developmental delay, as may be seen in children with chronic seizure disorders. During these periods, MR detection of areas of thickened cortex and areas of heterotopic gray matter may be extremely difficult or impossible. Obviously, if such subtle abnormalities are to be identified with MR imaging, it is imperative that the radiologist be sensitive to small, subtle changes that may be present on the scan and therefore raise the suspicion of this abnormality being present. Only on high-quality, thin-cut images obtained with sequences that optimize gray-white matter differentiation is it possible to detect these abnormalities. Even so, the majority of abnormalities seen by the pathologist in this subgroup are only at the microscopic level. They are abnormalities of the cytoarchitecture and thus below the level of MR detection but can still be detected as functional abnormalities by FDG-PET.

Detection of Potential Postoperative Complications

CT and MR appear to be equally good in the detection of potential early postoperative findings such as the develop-

<table>
<thead>
<tr>
<th>Stage</th>
<th>Electroencephalography</th>
<th>Positron Emission Tomography</th>
<th>CT</th>
<th>MR</th>
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<tbody>
<tr>
<td>Before surgery*</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Immediately after surgery*</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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<td>6 months after surgery</td>
<td>Yes</td>
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<td>Yes</td>
<td></td>
</tr>
<tr>
<td>1 year after surgery</td>
<td>Yes†</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
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<tr>
<td>2 years after surgery</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td>3 years after surgery</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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* CT and/or MR.
† CT or MR.
‡ Research.
ment of infected or noninfected fluid collections or hydrocepha-
lus. In these situations, it may be easier to obtain a CT scan in
the medically unstable child. Later, patients who have undergone
total hemispherectomy are at some risk for the development of recurrent intracranial hemorrhage, which may lead to the development of obstructive hydrocephalus and intracranial hemosiderosis. This latter syndrome is well
described in the literature [10, 12, 34–36] and leads to progressive
clinical deterioration and eventual death. Clinical manifesta-
tions in such patients include hearing loss, cerebellar
dysfunction, pyramidal signs, and mental retardation.

This complication is less commonly seen today, possibly for several reasons, including improved surgical techniques, insertion of ventriculopercutaneous shunts into the hemisph-
erectomy cavity, and the performance of "functional" hemi-
spherectomy at some centers. In the latter procedure, por-
tions of the frontal and occipital lobes are functionally
disconnected from surrounding brain areas, but left in place
to improve anchorage of the remaining brain tissue.

Because MR demonstrates good anatomic detail and is
extremely sensitive to the demonstration of hemosiderin depo-
sition [35–38], it is an ideal technique with which to follow
these patients and to identify at an early stage those who are
most at risk for the development of these potentially devas-
tating complications. Gradient-echo sequences or phase-
mapping techniques should be used if available whenever
children with total hemispherectomies are evaluated post-
operatively because of their higher sensitivity for demonstrat-
ing hemosiderin deposition [39–41] (Pennon JK et al., SMRM, August 1987). Although only one patient had had surgery more than 3 years prior to the present study, evidence
of both septations and subarachnoid hemorrhage was already
present in three patients (Figs. 8 and 9). None of these
patients, however, have any of the clinical symptoms of
intracranial siderosis at this time. It is particularly important
that this subgroup be closely monitored both clinically and by
serial MR studies.

Patients in our surgical protocol are studied in the immedi-
ate postoperative period by either CT or MR, but on subse-
quently evaluations, MR is performed at 6-month intervals
(Table 4).

Enthusiasm for hemispherectomy surgery is rising, and the
procedure appears to be achieving excellent initial results.
Only when large series of children at various epilepsy surgery
centers are sequentially followed up both clinically and by
imaging techniques will the true success of the different surgical
techniques currently used be established. It is clear, however,
that a closely coordinated combination of neuroim-
aging studies is required in the evaluation of this group of
patients. Such studies play an essential role both in the
appropriate initial selection of these patients and in alerting
the clinician to the presence of complications.

ACKNOWLEDGMENT

We thank Harry Vinters for information on the pathology of these cases.

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