Stereoelectroencephalography in Children and Adolescents With Difficult-to-Localize Refractory Focal Epilepsy

**BACKGROUND:** Although stereoelectroencephalography (SEEG) has been shown to be a valuable tool for preoperative decision making in focal epilepsy, there are few reports addressing the utility and safety of SEEG methodology applied to children and adolescents.

**OBJECTIVE:** To present the results of our early experience using SEEG in pediatric patients with difficult-to-localize epilepsy who were not considered candidates for subdural grid evaluation.

**METHODS:** Thirty children and adolescents with the diagnosis of medically refractory focal epilepsy (not considered ideal candidates for subdural grids and strip placement) underwent SEEG implantation. Demographics, electrophysiological localization of the hypothetical epileptogenic zone, complications, and seizure outcome after resections were analyzed.

**RESULTS:** Eighteen patients (60%) underwent resections after SEEG implantations. In patients who did not undergo resections (12 patients), reasons included failure to localize the epileptogenic zone (4 patients); multifocal epileptogenic zone (4 patients); epileptogenic zone located in eloquent cortex, preventing resection (3 patients); and improvement in seizures after the implantation (1 patient). In patients who subsequently underwent resections, 10 patients (55.5%) were seizure free (Engel class I) and 5 patients (27.7%) experienced seizure improvement (Engel class II or III) at the end of the follow-up period (mean, 25.9 months; range, 12 to 47 months). The complication rate in SEEG implantations was 3%.

**CONCLUSION:** The SEEG methodology is safe and should be considered in children/adolescents with difficult-to-localize epilepsy. When applied to highly complex and difficult-to-localize pediatric patients, SEEG may provide an additional opportunity for seizure freedom in association with a low morbidity rate.

**KEY WORDS:** Cortical localization, Epilepsy monitoring, Epilepsy surgery, Epileptogenic zone, Intracranial electrodes

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Various noninvasive tools are available for the preoperative assessment of pediatric patients with medically intractable epilepsy. These tools currently include analysis of seizure semiology, video-scalp electroencephalographic (video-EEG) recordings, high-resolution EEG and magnetoencephalography, magnetic resonance imaging (MRI), other neuroimaging modalities (functional MRI, ictal single-photon emission computed tomography [CT], positron emission tomography techniques), and neuropsychological testing. These methods are usually complementary and are interpreted in conjunction with the main goals of defining and delineating the extent of the anatomic area responsible for the generation and early propagation of the epileptic seizure (epileptogenic zone [EZ]) and establishing the relationship of the EZ with potentially testable functional cortex. When the noninvasive data are insufficient to define the EZ and its proximity to eloquent cortex, invasive
monitoring may be indicated. Indications for invasive monitoring often include (1) conflicting noninvasive data, (2) suspicion of unifocal vs multifocal epilepsy, (3) absence of MRI-identifiable lesion associated with inconclusive noninvasive localization, and (4) proximity to essential eloquent cortex, placing the patient at risk for postoperative neurological impairment.4,6-9

In the United States, subdural grids and strips are the most common invasive method used in pediatric epileptic patients who need extraoperative invasive monitoring procedures.5,10,11 Despite the high spatial resolution provided by the subdural methodology, which allows accurate mapping of superficial cortical areas, relatively deep epileptic foci cannot be localized with adequate spatial and temporal resolution. In addition, subdural grids require relatively large craniotomies and are, in general, limited to exploration of 1 hemisphere, which are important limiting factors when considering the pediatric age group.

In the face of these relative limitations, we explored alternative/complementary methods for invasive monitoring, revisiting the concepts and the techniques of the stereoelectroencephalography (SEEG) methodology,8,12-14 applied to a selected group of pediatric patients with difficult-to-localize epilepsy. We report here our preliminary clinical experience with the SEEG methodology in the extraoperative mapping of refractory focal epilepsy in children and adolescents with difficult-to-localize seizures who were not considered optimal candidates for invasive subdural studies.

METHODS

We consecutively studied all pediatric and adolescent patients (<21 years of age) with the diagnosis of medically refractory focal epilepsy who underwent SEEG implantation at the Cleveland Clinic Epilepsy Center between August 2009 and March 2012. Procedures related to the SEEG methodology, which included implantation/removal of electrodes and SEEG-guided resections, were performed by a single surgeon (J.G.M.). All surgeries were part of standard patient care, and no procedures were performed for research purposes. This study was approved by the Cleveland Clinic Institutional Review Board.

Data on age, sex, history, seizure semiology, noninvasive EEG, neuropsychology testing, positron emission tomography, ictal single-photon emission CT, magnetoencephalography, number and location of implanted electrodes, electrophysiological localization of the EZ, complications, and seizure outcome after resection were prospectively collected and analyzed. High-resolution brain MRIs (epilepsy protocol, including volumetric T1, coronal, and axial fluid-attenuated inversion-recovery studies) were performed on all patients with 1.5- or 3-T systems (Siemens, Erlangen, Germany). All scans were evaluated by an experienced, board-certified neuroradiologist. Postoperative clinical data were collected by patient interview, during regular scheduled clinic visits, or by telephone. Postoperative seizure outcome was classified according to Engel classification system.15 Acute postoperative seizures (up to 1 week after surgical resection) were not counted as evidence of recurrent epilepsy.16 None of the studied patients were considered optimal candidates for subdural grid implantation because of a lack of congruency among the noninvasive data (mainly patients with nonlesional imaging and nonlocalizable scalp EEG studies) and because patients failed previous subdural implantations, possibly suggesting a deep located focus missed by the subdural recordings, or required bihemispheric explorations, in whom bilateral craniotomies would likely be associated with excessive morbidity.

All adverse events within a period of 30 days after SEEG implantations were counted as complications. Complications were divided by type (neurological vs nonneurological) and by severity: minor complications (no changes in duration of hospital stay, with minimal modifications in the treatment plan, or no permanent neurological deficits) vs major complications (prolongation of hospitalization and/or permanent neurological deficit, with significant changes in the plan of treatment).17

Selection Criteria for SEEG Implantation

The recommendations for SEEG implantation and the general planning of electrode sites were made during our weekly Epilepsy Center multidisciplinary patient management conference after review and discussion of the results of the previous noninvasive tests and procedures. None of the studied patients were considered ideal candidates for subdural/strips implantation because of the complexity of the epilepsy syndrome. In addition to the general selection criteria for invasive extraoperative monitoring such as absence of precise anatomic delineation of the EZ and its relation to functional cortical areas,7,4,5,11,18 specific indications were used to choose SEEG over other methods of invasive monitoring. These criteria included the following: (1) the possibility of an EZ that is deep-seated or difficult to cover with subdural electrodes such as the mesial temporal lobe, opercular areas, cingulate gyrus, interhemispheric regions, posterior orbitofrontal areas, insula, and depths of sulci; (2) the need for bihemispheric explorations; and (3) presurgical evaluation suggestive of a functional network involvement (eg, limbic system) in the setting of a nonlesional MRI.

SEEG Implantation and Monitoring

The development of an SEEG implantation plan required the clear formulation of a specific anatomo-electro-functional hypothesis to be tested. This hypothesis was based on the results of the various noninvasive evaluation tests and formulated during a multidisciplinary patient management conference. After the anatomic and functional localizing hypotheses for each patient were formulated, tailored implantations strategies were planned, with the goal of confirming or rejecting the preimplantation hypotheses. In this phase, the exploration was focused to sample the anatomic lesion (if present), the more likely structure(s) of ictal onset, and the possible pathway(s) of propagation of the seizures (networks of propagation or epileptic networks).

The desired targets were reached with the use of commercially available depth electrodes (AdTech, Racine, Wisconsin; Integra, Plainsboro, New Jersey) in various lengths and numbers of contacts, depending on the specific brain region to be explored. The electrodes were implanted with the conventional stereotactic technique through 2.5-mm-diameter drill holes. Depth electrodes were inserted using orthogonal or oblique orientation, allowing intracranial recording from lateral, intermediate, or deep cortical and subcortical structures in a 3-dimensional arrangement, thus accounting for the dynamic, multidirectional spatiotemporal organization of the epileptic pathways.

As part of our routine practice, patients were admitted to the hospital the day of surgery. The day before surgery, stereo contrasted volumetric T1 sequence MRIs were performed. Images were then transferred to our stereotactic neuronavigation software (iPlan Cranial 2.6, Brainlab AG, Feldkirchen, Germany), and trajectories were calculated the following day. On the day of surgery, while the patient was under general anesthesia, the Leksell stereotactic frame (Elekta, Stockholm, Sweden) was applied.
using standard technique. Once the patient was attached to the angiography table with the frame, a stereo DynaCT and a 3-dimensional digital subtracted angiogram were performed. The preoperative MRIs, the stereo DynaCT, and the angiographic images were then digitally processed with the use of dedicated fusion software (syngo XWP, Siemens Healthcare, Forchheim, Germany). These fused images were used during the implantation procedure to confirm the accuracy of the final position of each electrode and to ensure the absence of vascular structures along the electrode pathway, which were not previously noted with the contrasted MRI. After the planning phase using the stereotactic software, the coordinates of the trajectories were recorded and transmitted to the operating room. Trajectories were, in general, planned in orthogonal orientation in relation to the sagittal plane of the skull to facilitate implantation and later interpretation of the electrode positions. With the use of the Leksell stereotactic system, coordinates for each trajectory were then adjusted in the stereotactic frame, and fluoroscopic images, in the lateral view, were performed in each new position. Care was taken to ensure that the central beam of radiation during fluoroscopy was centered in the middle of the implantation probe to avoid parallax errors. If the trajectory was aligned correctly, corresponding to the planned trajectory and passing along an avascular space, the implantation was then continued, with skull perforation, dura opening, placement of the guiding bolt (AdTech and Integra), and final insertion of the electrode under fluoroscopic guidance.

Postimplantation DynaCT scans were performed while patients were still anesthetized and positioned on the operating table. The reconstructed images were then digitally fused with the MRI data set. The resulting merged data sets were displayed and reviewed in the axial, sagittal, and coronal planes, allowing verification of the correct placement of the electrodes.

After surgery, patients were transferred to the pediatric epilepsy monitoring unit. After the necessary information was obtained, depth electrodes were removed in the operating room during procedures performed under local anesthesia and sedation. Patients were discharged the next morning, and resective surgeries, if indicated, were scheduled in approximately 6 weeks.

**Strategies of Exploration**

As originally described by Bancaud et al., the SEEG method demands a tailored, individualized strategy of exploration, rejecting any form of standardized placements. However, we recognized similarities and typical patterns of coverage in many of our patients, expressing the need to explore similar nodes and structures in specific epileptic networks. In patients with preimplantation hypotheses suggesting temporal lobe limbic seizures, we consistently covered the mesial structures of the temporal lobe, temporal pole, entorhinal cortex, orbitofrontal cortex, insula cortex, posterior and anterior cingulate gyri, and mesial parietal areas (precuneus). When hypotheses pointed to the frontal lobes, the orbitofrontal, frontal polar, anterior insula, superior and inferior frontal...
sulci, mesial surface of the superior frontal gyri (supplementary motor areas), rolandic areas, and parietal cortical areas were covered. In posterior quadrant implantations, supracalcarine and infracalcarine implantations were frequently explored, in conjunction with parietal and posterior temporal areas, commonly in bilateral fashion (Figure 1).

RESULTS

Patient Demographics

Thirty consecutive pediatric patients with refractory focal epilepsy underwent extraoperative invasive monitoring using the SEEG methodology during the review period. During the same period, 34 children and adolescents were implanted with subdural grids and/or strips with a total of 64 invasive implantations. All patients had the diagnosis of medically refractory focal epilepsy with an average failure of 5 antiepileptic drugs. The mean age was 14.9 years (range, 6-20 years), and 18 of the patients (60%) were male. In total, 402 depth electrodes were implanted in all lobes, averaging 13 electrodes per patient. Implantations were bilateral in 11 patients (Figure 2), right hemispheric in 10 patients, and left hemispheric in 9 patients (Table 1). The average estimated blood
loss per SEEG implantation procedure was 5 cm³. The average hospital stay for the SEEG implantations was 9.7 days.

None of the patients studied with SEEG had a single clear focal epileptogenic lesion that could be targeted for resection on the basis of results of noninvasive testing. Equivocal or complex MRI abnormalities, in conjunction with discordant or nonlocalizing findings on noninvasive testing, were observed in 12 patients (40%) and included subtle blurring of the gray-white transition with increased T2 and fluid-attenuated inversion-recovery signals, decreased volume of the hippocampal formation associated with increased T2 and fluid-attenuated inversion-recovery signals, complex and bilateral congenital cortical abnormalities, previous surgical resections, bilateral tubers, and periventricular nodules. Eighteen patients (60%) had nonlesional MRIs.

Electrographic Localization of the Hypothetical EZ, Surgical Resections, and Postresection Seizure Outcome

Results are summarized in Table 2. The hypothetical EZ was localized in 26 patients (86.6%). Among these patients, 18 (69.2%) underwent resection. Reasons for not undergoing resection despite localizing the hypothetical EZ included multifocal EZ (4 patients); EZ located in eloquent cortex, preventing resection (3 patients); and improvement in seizures after the implantation (1 patient).

The mean follow-up after SEEG-guided resections was 25.9 months (range, 12 to 47 months). From the group of 18 patients who underwent surgical resections, preoperative MRIs were nonlesional in 11 patients (61%). Eleven patients (61%) had resections on the right side, and 7 patients (39%) had resections on the left side. Temporal lobe resections were performed in 5 patients.
(27.7%), unilobar extratemporal resections in 5 patients (27.7%), and multilobar resections in 8 patients (44.6%). Of the extratemporal resection group, 3 patients underwent frontal resections, 1 patient underwent a parietal resection, and 1 patient underwent a posterior cingulate gyrus resection. The multilobar resections consisted of 5 frontotemporal resections, 2 fronto-temporo-insular resections, and 1 fronto-insular resection (Figure 3).

Of the 18 patients who underwent resection, 10 patients (55.5%) were seizure free at the last follow-up (Engel class I), and 5 patients (27.7%) experienced seizure improvement (Engel classes II and III). Regrettably, 3 patients (16.6%) had no improvement in seizures after resections (class IV). Surgical pathology from resected specimens showed subtle forms of cortical dysplasia (focal cortical dysplasia Ia and Ib) in 13 patients (72.2%); 3 patients (16.6%) were found to have unspecific findings as gliosis, 1 patient with encephalomalacia and 1 patient with hippocampus changes consistent with mesial temporal sclerosis (Table 2). The histopathology of 3 patients with no seizure improvement showed gliosis in 2 and a mild form of cortical dysplasia in the remaining patient.

Each patient underwent 2 or 3 surgical procedures (12 and 18 patients, respectively), which included SEEG implantations, SEEG electrode removals, and SEEG-guided resections. In total, 78 procedures were performed. In the SEEG implantation series, no child experienced serious or permanent morbidity. One patient developed a small and asymptomatic intraparenchymal hematoma during implantation, which required no surgical intervention or prolonged hospital stay. No complications were observed in the SEEG removal series. The complication rate related to the implantation procedures was 3.3%. The rate of hemorrhagic complications per implanted electrode was 0.2%. The total complication rate related to SEEG procedures (implantations and removals) was 1.3%. In the SEEG-guided resection series, 1 patient developed a right internal capsule ischemic stroke after posterior insular resection, resulting in hemiparesis; the patient partially recovered after 6 months. Another patient developed an incisional cerebrospinal fluid leak after SEEG-guided frontal lobectomy, which was successfully treated with lumbar drainage.

Functional mapping with electric stimulation of SEEG electrodes was attempted in 24 patients at the end of the monitoring period. In this series, electric stimulation of SEEG electrodes was not performed to define the EZ. Stimulation pulses were delivered in biphasic mode, in 30-second trains, at a frequency of 25 Hz, with 0.3 milliseconds of pulse width and pulse intensity varying from 1 to 10 mA. Stimulation retrieved detailed functional mapping information from cortical areas, in addition to white matter fiber mapping from subcortical areas. Motor and sensory mapping (supplementary motor cortex, primary motor and sensory cortical and subcortical areas) was obtained in 10 patients; language mapping (productive and receptive speech) was obtained in 5 patients; 2 patients were mapped for cortical and subcortical visual pathways; and multiple functional mappings were retrieved in 3 patients (motor, sensory, language, and/or vision). No functional mapping responses were obtained in 4 patients who had electrodes located in noneloquent cortical areas or did not cooperate during the test. No provoked seizures or adverse effects were observed during the functional mapping acquisition procedure.

**Table 2. Stereoelectroencephalography-Guided Resections**

<table>
<thead>
<tr>
<th>Patient</th>
<th>Age, y</th>
<th>Sex</th>
<th>Type of Resection</th>
<th>Seizure Outcome (Engel Class)</th>
<th>Pathology</th>
<th>Complications (Resections)</th>
<th>Follow-up, mo</th>
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<td>LT</td>
<td>I</td>
<td>HS</td>
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<td>19</td>
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<td>12</td>
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<td>6</td>
<td>16</td>
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<td>35</td>
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<tr>
<td>18</td>
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<td>M</td>
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<td>II</td>
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<td>I</td>
<td>FCDIa</td>
<td>CSF leakage</td>
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</tr>
</tbody>
</table>

*C, cingulate gyrus; CSF, cerebral spinal fluid; F, frontal; FCD Ia, focal cortical dysplasia type Ia; HS, hippocampus sclerosis; I, insula; IC, internal capsule; L, temporal; P, parietal.*
DISCUSSION

The SEEG method was developed almost 60 years ago in France,\textsuperscript{12} and several European studies have shown it to be efficacious and safe for EZ localization,\textsuperscript{8,13,19,20} but it was not widely and systematically used in the United States until the beginning of 2009.\textsuperscript{21,22} To the best of our knowledge, this is the first pediatric SEEG series from a single American epilepsy center.
with extensive experience in invasive monitoring using the subdural methodology. The fact that the studied patients were not considered optimal candidates for subdural grids and/or strips makes the present results unique in the literature.

The rationale for indicating SEEG over other methods of invasive monitoring in the pediatric age group makes the core of the discussion. On the basis of our preimplantation analyses, patients were not considered ideal candidates for subdural implantations (and consequently favoring SEEG) for 4 main reasons. First, there was the hypothesis of a deep-seated or difficult-to-cover location of the EZ in areas such as the mesial structures of the temporal lobe, perisylvian opercular areas, cingulate gyri and other interhemispheric regions, posterior orbitofrontal areas, insula, and depths of sulci, which could not be adequately mapped by the subdural method. Based on our clinical experience with subdural grids, such cortical and deep structures areas are difficult to be properly covered with superficial electrodes, likely resulting in misleading ictal patterns manifested as exit patterns recordings. Second, previous subdural invasive studies have failed to clearly outline the exact location of the seizure-onset zone. The reasons for failure to identify the EZ in these patients could include the deficiency in adequate sampling of deep epileptic foci or a clinically silent focus upstream from the hypothetical EZ. Third, the noninvasive data, although pointed to 1 hemisphere, were insufficient to discard the possibility of bihemispheric seizure onsets or to completely exclude a false lateralization clinical scenario. In consequence, bihemispheric explorations (although always favoring 1 hemisphere over the other) were indicated. Fourth, the presurgical evaluation was suggestive of a functional network involvement (eg, limbic system) in the setting of normal MRI. In this circumstance, the application of the subdural method could have resulted in a false localization patterns owing to the intrinsic limitation of the method in mapping the 3-dimensional dynamics of the epileptic network. In the above settings, the SEEG method was considered a more appropriate and safer option, offering advantages in relation to the subdural method. The SEEG methodology has the advantages of allowing extensive and precise deep brain recordings and stimulations with minimal associated morbidity. The main disadvantage is the more restricted capability for performing functional mapping because of the limited number of contacts located in the superficial cortex. The results presented in this particular group of patients reflect our preliminary impressions regarding the application of SEEG in pediatric patients with difficult-to-localize epilepsy.

Our results demonstrate that in children and adolescents who have exhausted treatment options and are suspected to have highly complex medically intractable focal epilepsy amenable to surgical treatment, the SEEG method provides an additional opportunity for seizure freedom in approximately 50% of resected patients. Additionally, the SEEG method, once considered cumbersome and perhaps associated with excessive morbidity in this age group, was found to be an effective and safe invasive method in selected pediatric and adolescent patients with difficult-to-localize and medically intractable focal epilepsies. In this challenging group of patients, SEEG may represent a reliable alternative method of invasive extraoperative monitoring by allowing extensive and bihemispheric implantations in association with minimal morbidity.

The placement of intracerebral depth electrodes has a reputation of being excessively morbid, with a relatively high morbidity rate as pointed out by Lee et al. Conversely, probably as a result of methodological and technological advances, the experience with our recent adult and pediatric series does not indicate that this reputation is deserved any longer. This impression, now validated by our results reporting minimal morbidity in SEEG procedures, is shared by others. In previously published series, the only adverse event reported was breakage of an electrode during a seizure, but no neurological complication was observed. In a more recent series, 1 death was reported in a child implanted with SEEG electrodes, likely unrelated to the implantation of electrodes but resulting from electrolytic disturbances and secondary brain edema. Unfortunately, previous studies in children evaluated with other methods of invasive monitoring (mainly subdural grids) have reported a complication rate of up to 25% for intracranial bleeding, 6% for infection, and up to 14% for cerebral edema. Considering these published data, SEEG implantation may be particularly appealing for the pediatric group because it avoids the need for larger craniotomies, resulting in minimal postoperative pain and negligible blood loss during the implantations. Despite its relatively less invasive features with potential advantages when applied to the pediatric population, SEEG is underused in this age group, with most of the SEEG literature involving the adult population. The use of conventional cerebral angiograms may be considered a potential disadvantage of the described method, although complications related to it were not seen in this series. Nevertheless, we are currently developing a new method that will use CT angiography and CT video digitally fused with the preimplantation MRI to avoid, in the near future, the use of conventional cerebral angiograms.

Although the inclusion of children and adolescents can be cumbersome because of possible differences in specific clinical features such as semiology, electrophysiology, and pathology, our studied group reflects the clinical experience from a subspecialty group of neurologists because all patients were referred by pediatric epileptologists, more realistically representing their routine clinical practice. In addition, the patients’ characteristics and seizure outcome results did not differ between these subgroups (small children and older children and adolescents). A review of the literature shows that only a few studies from a single institution have focused on reporting surgical results in children resected under SEEG guidance. In these 2 studies, Cossu et al noted significant seizure improvement in 74% of children and 80% of infants after SEEG-guided resections. Their high seizure-free rate may reflect aspects of patient selection; almost 80% of their children studied with SEEG had unifocal brain lesions seen on preoperative MRI. At our center, such pediatric patients are often operated on based on results from noninvasive testing with similar outcome results.
From an effectiveness aspect, the applied SEEG methodology was effective in electrophysiologically defining the hypothetical EZ in challenging cases; the hypothetical localization was accomplished in 86% of studied patients. It is important to emphasize that despite the high rate of hypothetical EZ localization, the “true” EZ can be confirmed only by long-term seizure outcomes after SEEG-guided resections because misinterpretations of invasive monitoring recordings can occur. In fact, in this series, only 55.5% of the hypothetical localizable EZs achieved sustained seizure freedom, clearly revealing the false-positive results of SEEG recordings. Conversely, the possibility of unmasked false-negative results cannot be disregarded because patients not considered optimal candidates for resective surgery by SEEG recording standards could have gained seizure freedom status after resection. Consequently, the efficacy of SEEG recordings must be interpreted with reservations.

Despite the relatively high hypothetical efficacy, our localization success in the pediatric group is still inferior to that of our adult SEEG series (with 98% success). We can speculate that this difference could be explained by the challenges in formulating an adequate implantation hypothesis in the pediatric group as a result of complex or nonspecific semiology and electrophysiological unspecific features compared with adults, preventing precise and adequate implantations and consequently resulting in nonlocalizable procedures. This was particularly true in 3 patients from our series with very severe, life-threatening epilepsy who failed the SEEG explorations (patients 15, 20, and 24). All of them had nonlesional MRIs with nonlocalizable scalp EEG features and difficult-to-interpret semiology, resulting in a paucity of congruent preimplantation data and consequently erroneous preimplantation hypotheses. In contrast, we have found SEEG to be especially useful in patients without a lesion on MRI. Seizure freedom after resective surgeries in patients with normal preoperative MRI has been significantly worse in the literature, with seizure-free rates as low as 17%. In our series, 18 patients had nonlesional MRIs, of whom 11 underwent surgical resection after SEEG monitoring. In the nonlesional patients undergoing resection, the seizure-free rate was 45.5%. We conclude that nonlesional MRIs should not prevent further invasive investigation as long as reasonable preimplantation hypotheses can be formulated on the basis of video-EEG and ancillary tests such as positron emission tomography, magnetoencephalography, and ictal single-photon emission CT.

Our studied population corresponded to a highly difficult-to-localize group of pediatric patients who were not considered to be ideal candidates for other methods of invasive monitoring because of the complexity of their epilepsy syndrome: 66% of the patients had nonlesional MRIs or equivocal or bilateral MRI abnormalities, 80% had multifocal scalp EEGs, and 36.6% had noninvasive data and semiology that did not clarify even the laterality of the seizures, justifying bilateral implantations. However, although bilateral implantations were applied in a significant number of patients, implantations were always preferential to 1 side, being guided by a clear implantation strategy that favored 1 side. Even with the paucity of noninvasive data, preimplantation hypotheses were formulated, guiding the placement of the electrodes, which resulted in resective strategy followed by sustained seizure control or a reduction of seizures in 50% of the studied group with minimal morbidity.

CONCLUSION

The SEEG method, when individualized through careful and meticulous analysis, is a possible option for pediatric and adolescent patients who present with clinical features of medically intractable focal epilepsy and difficult-to-localize seizures. In performing SEEG in this highly selected group, we were able to partially overcome the relative limitations related to the current standard methods of invasive monitoring, offering to these challenging children an additional opportunity for seizure freedom without safety compromises that would not likely be possible with other methods of extraoperative invasive monitoring. Our early outcome parallels that of previous pediatric series using the same method. Nevertheless, to validate our results and conclusions, a long-term longitudinal study enrolling a larger number of patients is mandatory.

Disclosure

The authors have no personal, financial, or institutional interest in any of the drugs, materials, or devices described in this article.

REFERENCES


**COMMENTS**

This is an important series because the authors show the utility of a stereoelectroencephalography system in the often complicated question of localization of pediatric foci. Although their method may localize only to a particular lobe because of the necessary limitation in sampling, this would often be an extremely important conclusion in this population. It appears that this method will now join other established methods as a potential approach to localization in pediatric epilepsy surgery. The authors also are to be congratulated on their low complication rate. I hope the authors will follow the lead of the pediatric neurosurgery community and pursue imaging methods other than conventional angiogram to plan trajectories that avoid blood vessels, especially as the public becomes increasingly concerned about justifying radiation that would not be present in other approaches such as magnetic resonance angiography/venography.

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This article reports the pediatric experience with stereo-electroencephalography (SEEG) at the Cleveland Clinic since this technique was adopted there in 2009. As correctly stated by the authors, there are decades of experience with SEEG in many specialized centers in Europe, particularly in France and Italy. However, this is a new and different approach to intracranial monitoring for most North American epilepsy centers. It is not simply putting in many depth electrodes as a “fishing expedition” alternative to subdural or subdural and depth monitoring in combination. The philosophical shift is to record from multiple locations within brain networks that are interconnected to one another. The interictal and ictal recording results are interpreted and integrated to reflect the behavioral spread of seizure activity in an individual patient. The ability to record from deeper structures such as the depths of suki, the peri-insular/peripheral regions, and multiple areas of the frontal and parietal interhemispheric regions differentiates this technology from standard subdural array monitoring. However, similar to subdural monitoring, SEEG recordings are only as successful as the seizure localization hypothesis that is used to guide their placement and the technical success in the surgical placement of the electrodes.

The patients described in this report are very difficult epilepsy surgery patients, with many of them negative on magnetic resonance imaging and/or having failed prior surgical explorations. In this complex patient population, the SEEG technique as reported by the authors compares favorably with subdural monitoring in terms of surgical safety, peri-operative morbidity, and seizure freedom. SEEG is not an either/or decision compared with subdural monitoring in the surgical management of epilepsy. Rather, patients requiring intracranial monitoring for seizure lateralization and localization should be evaluated on a case-by-case basis by an experienced team of epilepsy neurologists and neurosurgeons to determine the best strategy. The authors are to be congratulated for working to break down the transatlantic barriers and biases that have largely prevented the acceptance of SEEG technology by North American epilepsy surgery centers.

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The authors present the first-ever series of North American children and adolescents evaluated by means of invasive recordings with stereo-electroencephalography (SEEG). The study highlights the increasing interest in this diagnostic methodology by centers that previously used only subdural electrodes.

This report stimulates a closer confrontation between the 2 methodologies for invasive recordings. The study is therefore interesting for users of both subdural grids and SEEG, allowing all of them to consider the drawbacks and benefits of the 2 approaches. Although the authors come...
from a different culture, they have perfectly acquired the deep meaning of the SEEG methodology and have learned how to take advantage of the peculiarities of this approach. In fact, the strategy of implantation is aimed at the verification of a previous hypothesis on the location of the epileptogenic zone. Moreover, the technical possibility of recording the brain activity directly from every point of the brain, including the bottom of the sulci, the mesial surface, or the deep seated structures, allows the 3-dimensional definition of the epileptogenic zone, exploring the possible epileptogenic networks. Thus, they can merge their very important experience with subdural grids and choose which one they consider the best possible alternative in terms of invasive recordings.

Pediatric cases are the most difficult to treat because of the characteristics peculiar to the young age and because the epileptogenic zone is very often extratemporal. Nonetheless, the authors obtained excellent results: The SEEG complication rate is very low and the results on seizures are satisfactory. These outcomes testify to the very good mastery of the newly adopted approach.

The authors, after a long history of subdural grid monitoring, successfully faced the complexity of the SEEG methodology, and this report highlights their open-mindedness and foresight also in a very demanding field such as pediatric epilepsy surgery. The pathway they have taken, in a fertile and receptive culture in North America, will certainly find proselytes.

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CME QUESTIONS

1. When investigating the limbic network with a stereo-EEG intracranial implant for a putative epileptogenic focus, what structure is among the investigated regions?
   A. Cingulate cortex
   B. Peri-calcarine cortex
   C. Rolandic region
   D. Superior parietal lobule
   E. Supramarginal gyrus

2. When performing invasive monitoring for epilepsy, when is stereo-EEG monitoring preferred over subdural grids and strips?
   A. Putative involvement of a functional network
   B. Need to perform language mapping
   C. Greater than average skull thickness
   D. Desire to perform resection during the same admission
   E. Desire to reduce the need for continuous antibiotics

3. What is the approximate seizure freedom rate in patients following frontal lobe epilepsy surgery?
   A. 0-10%
   B. 20-30%
   C. 40-50%
   D. 60-70%
   E. 80-90%