Stereoelectroencephalography before 2 years of age

Raphia K. Rahman, MBS, Samuel B. Tomlinson, MD, Joshua Katz, MD, Kathleen Galligan, MS, PA-C, Peter J. Madsen, MD, Alexander M. Tucker, MD, Sudha Kilaru Kessler, MD, and Benjamin C. Kennedy, MD

Division of Neurosurgery, Children's Hospital of Philadelphia, Pennsylvania; Rowan University School of Osteopathic Medicine, Stratford, New Jersey; Department of Neurosurgery, Perelman School of Medicine at the University of Pennsylvania, Philadelphia, Pennsylvania; Rutgers Robert Wood Johnson Medical School, New Brunswick, New Jersey; Division of Neurology, Children's Hospital of Philadelphia, Pennsylvania; Departments of Pediatrics and Neurology, Perelman School of Medicine at the University of Pennsylvania, Philadelphia, Pennsylvania

OBJECTIVE Stereoelectroencephalography (SEEG) is a widely used technique for localizing seizure onset zones prior to resection. However, its use has traditionally been avoided in children under 2 years of age because of concerns regarding pin fixation in the immature skull, intraoperative and postoperative electrode bolt security, and stereotactic registration accuracy. In this retrospective study, the authors describe their experience using SEEG in patients younger than 2 years of age, with a focus on the procedure’s safety, feasibility, and accuracy as well as surgical outcomes.

METHODS A retrospective review of children under 2 years of age who had undergone SEEG while at Children’s Hospital of Philadelphia between November 2017 and July 2021 was performed. Data on clinical characteristics, surgical procedure, imaging results, electrode accuracy measurements, and postoperative outcomes were examined.

RESULTS Five patients younger than 2 years of age underwent SEEG during the study period (median age 20 months, range 17–23 months). The mean age at seizure onset was 9 months. Developmental delay was present in all patients, and epilepsy-associated genetic diagnoses included tuberous sclerosis (n = 1), KAT6B (n = 1), and NPRL3 (n = 1). Cortical lesions included tubers from tuberous sclerosis (n = 1), mesial temporal sclerosis (n = 1), and cortical dysplasia (n = 3). The mean number of placed electrodes was 11 (range 6–20 electrodes). Bilateral electrodes were placed in 1 patient. Seizure onset zones were identified in all cases. There were no SEEG-related complications, including skull fracture, electrode misplacement, hemorrhage, infection, cerebrospinal fluid leakage, electrode pullout, neurological deficit, or death. The mean target point error for all electrodes was 1.0 mm. All patients proceeded to resective surgery, with a mean follow-up of 21 months (range 8–53 months). All patients attained a favorable epilepsy outcome, including Engel class IA (n = 2), IC (n = 1), ID (n = 1), and IIA (n = 1).

CONCLUSIONS SEEG can be safely, accurately, and effectively utilized in children under age 2 with good postoperative outcomes using standard SEEG equipment. With minimal modification, this procedure is feasible in those with immature skulls and guides the epilepsy team’s decision-making for early and optimal treatment of refractory epilepsy through effective localization of seizure onset zones.

KEYWORDS stereoelectroencephalography; seizure; epilepsy surgery; pediatric; functional neurosurgery

Stereoelectroencephalography (SEEG) is a minimally invasive technique for characterizing the spatial and temporal characteristics of seizure onset and propagation and has been utilized in children for decades.1–6 Beyond its proposed advantages over subdural grids for mapping seizure networks, its tolerability and low rate of cerebrospinal fluid (CSF) leakage make it particularly attractive for use in children.7–11 Although its use has been shown to be safe and efficacious in older children, SEEG is rarely used in children younger than 2 years of age given safety concerns regarding pin fixation in the developing skull, intraoperative and postoperative electrode bolt security, and stereotactic registration accuracy.6,12–14 Only 3 patients under the age of 2 have been reported to undergo SEEG at other institutions, and individual outcomes in these patients are not available.15–19 In a recent national survey, only 31% of pediatric epilepsy surgeons in the US had performed SEEG in children under age 3, and

ABBREVIATIONS CSF = cerebrospinal fluid; ICH = intracranial hemorrhage; SDG = subdural grid–based; SEEG = stereoelectroencephalography; TPE = target point error.

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only 10% reported performing it before age 2. Furthermore, children younger than 2 years of age have not been included in most pediatric series of invasive monitoring, and if included, they have not undergone SEEG. Reports and experiences with SEEG in children under 2 years of age are sparse, with no treatment outcomes reported. In this case series and review of the literature, we present the surgical outcomes of SEEG in 5 children under age 2, demonstrating the technique’s safety, feasibility, and accuracy, as well as epilepsy outcomes in this age group.

Methods

A retrospective chart review was performed to identify pediatric patients treated with SEEG from November 2017 through July 2021 at the Children’s Hospital of Philadelphia. Data on demographic characteristics, clinical presentation, presurgical workup, surgical procedure, imaging results, and clinical course were extracted from the electronic medical record. Patients were selected using the following inclusion criteria: 1) age less than 2 years, and 2) SEEG surgery. Prior to SEEG, all cases were discussed in a multidisciplinary epilepsy conference. Candidacy for invasive monitoring in the form of SEEG was based on meeting the following criteria: 1) the presence of drug-resistant epilepsy as defined by the International League Against Epilepsy; 2) focal or likely focal epilepsy; and 3) a noninvasive presurgical evaluation, including MRI, magnetoencephalography, and positron emission tomography when indicated, which failed to indicate an appropriate resection strategy but did suggest potential strategies requiring further data from intracranial EEG recording.

Placement of SEEG Electrodes

Preoperative trajectory planning utilized a volumetric postcontrast T1-weighted MR image and volumetric postcontrast CT scan. Trajectory planning for the patient in case 1 was performed using the Medtronic StealthStation, as this occurred prior to our robotic surgery program. The other 4 patients’ trajectories were planned using ROSA planning software (Zimmer Biomet). Care was taken to avoid all vessels on trajectory planning. The patient in case 1 underwent Leksell frame placement, followed by CT scanning, and then the frame was reset in all dimensions for each trajectory. The other 4 patients were fixed in a Mayfield skull clamp with pediatric pins (Integra LifeSciences; Fig. 1). Prior to fixation, each patient’s CT was reviewed for areas of maximum skull thickness. For the Leksell frame, occipital bone and the lateral superior orbital rim were used because of their bone thickness. For the Mayfield clamp, the mastoid, occipital bone, and anterior superior temporal line were used for the same reason. For both the Mayfield and Leksell pins, pressure was increased slowly, feeling the nearby skull for any indentation. The Mayfield clamp was tightened to 40 psi. This was watched for any loss of pressure. If some pressure was lost, the skull was then assessed for indentation, and feeling none, the clamp was tightened to 40 psi again. The Mayfield clamp was affixed to the ROSA robot (Zimmer Biomet), and contactless laser registration of the face was performed using the preoperative CT scan with contrast as a reference scan. PMT SEEG electrodes were placed (PMT Corp.). The robot arm was driven close to the skull for the drilling portion of the procedure. Twenty-five × 2.4-mm PMT bolts were secured into the skull approximately 1–2 mm deeper than the inner table of the skull. This was estimated by watching the bolt’s progress as it was screwed in, coupled with knowledge of the patient’s skull thickness, and was measured and recorded preoperatively for each trajectory. As part of our usual workflow, this is confirmed as a negative discrepancy; that is, discrepancy = robot to target distance − robot to bolt distance − bolt length − intracranial planing length. When this discrepancy is −2 mm, the depth of the bolt is 2 mm deep to the inner table of the skull. Xeroform gauze was tightly wrapped around the base of each bolt, and substantial gauze padding was placed around the bolts beneath a headwrap. After electrode placement, a postoperative CT scan was obtained to confirm accurate placement and to assess for any acute hemorrhage. At the time of this retrospective study, planning data were not available for the patient whose trajectory had been planned on the StealthStation, so his CT scan was reviewed. Customary quality assurance had been performed on the StealthStation on the day of surgery with satisfactory results. For the 4 patients who had undergone robot-assisted surgery, target point error (TPE) measurements were made using a...
cross-sectional view of the merged postoperative CT with the preoperative plan on ROSA planning software. The distance between each planned target point and the center of the electrode was recorded as the TPE (Fig. 2A). Continuous intracranial EEG activity was recorded using a 128-channel Natus Xltek/NeuroWorks digital video-EEG system (Natus Medical Inc.).

### Results

Five patients (3 boys) younger than 2 years of age underwent SEEG recording (median age 20 months, range 17–23 months). Clinical characteristics are summarized in Table 1. The mean age at seizure onset was 9 months (range 2–14 months). All patients had multiple seizures daily and developmental delay. Four patients had MRI abnormalities, and 3 had associated genetic etiologies.

Details of SEEG placement and findings are also provided in Table 1. The mean number of placed electrodes was 11 (range 6–20 electrodes). One patient (case 5) un-

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![Figure 2A](image-url) **FIG. 2.** A: Demonstration of accuracy. ROSA software showing preoperative postcontrast T1-weighted MR image merged with postoperative CT scan and demonstrating an electrode (white) aligned with its preoperative plan (orange) at the target point in cross-section. Accuracy is demonstrated by the overlap between the plan and the white image of the electrode. Another plan closely aligned with another electrode is nearby. B: Appearance of a TPE measurement in cross-section for a typical electrode measured at 1.00 mm, the mean and median TPE. Radius of the plan circle is 1 mm.

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### Table 1. Clinical characteristics and outcome in 5 children who underwent SEEG

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Age (mos)</th>
<th>Sex</th>
<th>Impaired Development</th>
<th>MRI Lesion</th>
<th>Localization of Electrode (no. of Electrodes)</th>
<th>Mean/Max TPE (mm)</th>
<th>Engel Class After Resection</th>
<th>Length of FU (mos)</th>
<th>Therapeutic Surgery</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20</td>
<td>M</td>
<td>Mild</td>
<td>Normal</td>
<td>Rt parietal, occipital</td>
<td>—</td>
<td>IC</td>
<td>53</td>
<td>Occipital lobectomy &amp; pariagonal resection</td>
</tr>
<tr>
<td>2</td>
<td>17</td>
<td>F</td>
<td>Mild</td>
<td>Abnormal</td>
<td>Lt fronto-temporal</td>
<td>0.8/1.88</td>
<td>IA</td>
<td>25</td>
<td>Focal mesial and superior parietal resection</td>
</tr>
<tr>
<td>3</td>
<td>22</td>
<td>M</td>
<td>Mild</td>
<td>NPRL3 deletion, FCD type IIa &amp; MTS</td>
<td>Lt temporal, insula</td>
<td>0.9/1.45</td>
<td>IA</td>
<td>6</td>
<td>Temporal lobectomy</td>
</tr>
<tr>
<td>4</td>
<td>23</td>
<td>F</td>
<td>Moderate</td>
<td>Abnormal</td>
<td>Rb fronto-temporal, parietal, insula</td>
<td>0.9/2.21</td>
<td>IA</td>
<td>10</td>
<td>Hemispherotomy &amp; partial lobectomy</td>
</tr>
<tr>
<td>5</td>
<td>18</td>
<td>M</td>
<td>Abnormal</td>
<td>FCD type IIa, KAT6B pathogenic variant</td>
<td>Bilateral frontal, parietal, insula</td>
<td>1.3/3.75</td>
<td>IA</td>
<td>8</td>
<td>Motor-sparing frontal lobectomy &amp; partial insulectomy</td>
</tr>
</tbody>
</table>

FCD = focal cortical dysplasia; FU = follow-up; mod = moderate; MTS = mesial temporal sclerosis; pst = posterior.
nderwent bilateral SEEG monitoring. Seizure onset zones were identified, and resection was performed in all cases (3 frontal, 1 temporal, 1 occipital).

Regarding accuracy, the patient in case 1 did not have planning data available, but his postoperative CT demonstrated electrodes without any obvious misplacement and bolts were aligned with electrode trajectories, which were all straight. Among the 4 patients with available preoperative planning data, there were 48 total electrodes. The mean and median TPEs for all electrodes were 1.0 mm with a range of 0.04–3.75 mm. The range of individual patients’ mean TPE was 0.8–1.3 mm. The 3.75-mm TPE was an outlier and was attributable to a bend at the very distal tip of the electrode. This was the only TPE above 3 mm, and only one other TPE was above 2 mm (2.21 mm). Figure 2B demonstrates a typical 1.00-mm error measurement.

There were no SEEG-related complications, including skull fracture, electrode misplacement, hemorrhage, infection, CSF leakage, electrode pullout, neurological deficit, or death. The mean follow-up after SEEG was 21 months (range 8–53 months). All patients experienced immediate cessation of seizures after resection. The patients in cases 3 and 5 had an Engel class IA outcome with no seizures since surgery. The patient in case 1 had an Engel class IC outcome, the patient in case 4 had an Engel class ID outcome, and the patient in case 2 had 2 provoked episodes of seizures in 25 months and had an Engel class IIA outcome.

Discussion

We report the first case series of SEEG in children younger than age 2. Our results show that SEEG can be accurately and safely performed with high diagnostic yield and excellent postoperative outcomes in these very young children with thin bone. In children with drug-resistant epilepsy, early surgical treatment reduces the detrimental effects of early life epilepsy as well as anti-seizure medications, thereby optimizing neurodevelopmental outcomes, especially in patients with severe epilepsy, such as those reported in our series.14,15,18 In cases in which noninvasive diagnostic investigations do not lead to a clear therapeutic surgical plan, invasive EEG monitoring becomes a critical method for delineating the epileptogenic zone with optimal spatial resolution. Subdural grid–based (SDG) monitoring has attendant risks, including CSF leakage, infection, and cerebral edema, with a reported morbidity rate as high as 25% for intracranial bleeding.15,29,30 SDG monitoring also results in a large incision with associated pain and swelling postoperatively, as well as subdural scarring, which can add risk and difficulty to subsequent surgery. Additionally, SDG monitoring cannot sample areas of cortex other than those on the brain surface and may be inadequate for testing hypotheses generated by the evaluation of seizure semiology, interictal and ictal scalp EEG, and multimodal imaging.

The safety and efficacy of SEEG has been investigated in children.6,25,31 In comparison to SDG monitoring, SEEG is associated with a decreased incidence of adverse events (i.e., infection, intracranial hemorrhage [ICH], CSF leakage, and the need for blood transfusions) in children, along with a decreased operative time and hospital length of stay.7,10,32 SEEG can also monitor deep or medial structures directly and precisely, makes monitoring of multiple lobes or hemispheres more feasible, and avoids craniotomy altogether for patients who will undergo minimally invasive surgery or no surgery.25,33–36 As a result, the use of SEEG has become widespread in North American pediatric epilepsy centers over the past decade.1,23,24 However, most centers avoid SEEG in the very young, especially those younger than age 2. Concerns include thin bone without fused suture, which could lead to skull fracture from fixation pins; registration inaccuracy once fixation pins are applied, leading to inaccurate placement or hemorrhage; and electrode misplacement, migration, or pullout due to poor bony fixation of the electrode bolts.6,12–14 A recent survey of pediatric epilepsy neurosurgeons in the US revealed that only 31% had ever performed SEEG in a patient under age 3, and only 10% had performed SEEG in a patient under age 2.1 This survey also indicated that the reported annual patient volume was inversely correlated to the age of the youngest SEEG patient in that surgeon’s experience.1 Our literature search revealed 3 patients under the age of 2 who had undergone SEEG outside our institution, 1 patient from each of three author groups (Table 2).15,16,18 The youngest of these was 20 months old.16 These reports were part of larger series including all ages, the individual patients were not discussed in detail, and complications, accuracy, and outcomes were not individually reported. Thus, outside of our prior case report (case 2 in the present report),19 our literature search revealed little to no guidance about whether this technique can or should be performed in this age group.

In the present series, our indications for epilepsy surgery were clear: highly drug-resistant severe epilepsy and many seizures per day in all cases. The need for invasive monitoring was present, with each patient having focal onset, but none having an MRI lesion that was clearly delineated as responsible for the epilepsy according to noninvasive workup. From a monitoring perspective, SEEG as a technique compared to SDG monitoring was specifically helpful in monitoring the medial occipital lobe in case 1; multiple medial tubers in multiple lobes in case 2; the hippocampus, amygdala, and insula in case 3; the insula in case 4; and the insula and contralateral hemisphere in case 5. No patients at our institution underwent SDG monitoring during the study period. Monitoring of each of these structures was critical for decision-making. As expected, all our patients tolerated the procedure well, with minimal discomfort.

SEEG complications have been reported in the literature, including hemorrhage, infection, hardware-related complications, and neurological complications.9,37,38 However, our patients had no SEEG-related complications, including skull fracture, electrode misplacement, hemorrhage, infection, CSF leakage, electrode pullout, neurological deficit, or death. The avoidance of hemorrhage is accomplished by careful preoperative planning and by maintaining accuracy. Accuracy was high with a mean TPE of 1.0 mm. One outlier TPE of 3.75 mm was attributable to a bend in the distal tip of an electrode and cannot
be attributed to the age of the child, a registration error, the slipping of pins, or skull thickness. The electrode was left in place and recorded well. Our error measurements in this very young cohort compare favorably with reports of error in older patients.5,39–42

The patients reported here had severe epilepsy with many seizures per day and developmental delay, and 3 had experienced regression because of their epilepsy. Three patients had genetic epilepsy, making this study group a particularly difficult-to-treat cohort. In large part because of the results of their SEEG, none of the patients are currently having seizures, and all experienced developmental acceleration. The fact that multiple seizures per day stopped immediately upon SEEG-guided resection suggests that SEEG did accurately delineate seizure onset zones in all 5 patients.

Methodological considerations for SEEG in very young children include addressing fixation, placement, wrapping, and postoperative care. Cranial fixation pins, whether from a 4-point frame, as used in case 1, or a Mayfield clamp, should be inserted in structurally sound regions of the skull, including the mastoid, occipital bone, superior temporal line, or lateral superior orbital rim. Using pediatric skull pins and limiting tightening to 40 psi helps avoid fracture or penetration. To prevent targeting errors, care should be taken to avoid movement during prepping and drilling. Great care is warranted when placing electrode bolts and screwing on caps. We estimate screwing our bolts in 1–2 mm past the inner table to ensure bony purchase. A gentle yet tight Xeroform wrap and extensive padding under the headwrap can help hold the electrodes in place in the setting of very thin bone. Lastly, working with parents and nurses to maintain minimal impact or pulling on the headwrap can be helpful in avoiding migration or pullout.

Limitations of this study include its retrospective nature, the small cohort of 5 patients, and the data from a single surgeon, all limiting generalizability and introducing sampling bias. A larger, multinstitutional, prospective study is required to determine the safety, accuracy, and efficacy of SEEG in this age group and to detect rare SEEG-related complications, such as ICH, CSF leakage, infection, and postoperative neurological deficits, as well as incidence and risk factors.

**Conclusions**

While the conclusions that can be drawn from this retrospective report of a small patient cohort from a single center and single surgeon are limited, we provide preliminary evidence that SEEG in children younger than 2 years of age can be safe and feasible. Future larger studies are needed to determine the incidence and risk factors for complications and to uncover more information regarding the diagnostic utility of this method in lesional and nonlesional epilepsies in very young children.

**References**


7. Talai A, Eschbach K, Stence NV, et al. Comparison of sub-

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**TABLE 2. Institutional series and case reports on SEEG in children younger than 2 years of age**

<table>
<thead>
<tr>
<th>Authors &amp; Year</th>
<th>Study Type</th>
<th>Age at SEEG Procedure (mos), Sex</th>
<th>Seizure Frequency</th>
<th>Neurological Deficit</th>
<th>MRI Findings</th>
<th>SEEG Strategy: Side (lobe/no. of electrodes)</th>
<th>Total No. of Electrodes</th>
<th>SEEG-Related Complication</th>
<th>Seizure Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liu et al., 2020</td>
<td>Retrospective series</td>
<td>21.6, NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>Unspecified</td>
</tr>
<tr>
<td>Taussig et al., 2014</td>
<td>Retrospective cohort</td>
<td>20, NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>Nr</td>
<td>NR</td>
<td>Unspecified</td>
</tr>
<tr>
<td>Cosu et al., 2012</td>
<td>Retrospective series</td>
<td>21, M</td>
<td>Daily</td>
<td>Lt hemiparesis</td>
<td>Large rt open-lop schizencephaly</td>
<td>Rt (P/2, T1, O/1, F/2)</td>
<td>6</td>
<td>No hemorrhagic or infectious complications</td>
<td>Unspecified</td>
</tr>
<tr>
<td>Katz et al., 2022</td>
<td>Case report</td>
<td>17, F</td>
<td>2–16/day</td>
<td>None</td>
<td>Multiple tubers in every lobe</td>
<td>Lt (F, T)</td>
<td>10</td>
<td>None</td>
<td>Complete seizure remission after resection</td>
</tr>
</tbody>
</table>

F = frontal; NR = not reported; O = occipital; P = parietal; T = temporal.
dural grid and stereoelectroencephalography in a cohort of pediatric patients. Epilepsy Res. 2021;177:106758.

Disclosures
The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author Contributions
Conception and design: Kennedy, Kessler. Acquisition of data: Kennedy, Rahman, Katz, Galligian. Analysis and interpretation of
data: Kennedy, Rahman, Tomlinson, Katz, Kessler. Drafting the article: Kennedy, Rahman, Tomlinson, Katz, Kessler. Critically revising the article: Kennedy, Rahman, Tomlinson, Madsen, Tucker, Kessler. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Kennedy. Administrative/technical/material support: Katz, Galligan. Study supervision: Kennedy, Tomlinson, Galligan, Madsen, Tucker, Kessler.

Correspondence
Benjamin C. Kennedy: Children’s Hospital of Philadelphia, PA. kennedybc@chop.edu.