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# Stereoelectroencephalography in children with cortical dysplasia: technique and results

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**Abstract** The stereoelectroencephalophraphy (SEEG) method was developed in France by Jean Tailarach and Jean Bancaud during the 50s and has been mostly used in France and Italy, as the method of choice for extraoperative invasive mapping in refractory focal epilepsy. Subsequently, for more than 60 years, SEEG has shown to be a valuable tool for preoperative decision-making in focal epilepsy. Nevertheless, there are few reports addressing the utility and safety of the SEEG methodology applied to children and adolescents. In this chapter, we will discuss the current results of SEEG in pediatric patients with difficult to localize epilepsy. Details regarding surgical technique and clinical results will be presented.

**Keywords** Stereoelectroencephalography · Cortical dysplasia · Stereotactic implantation

## Introduction

The principle of SEEG is based on anatomo-electro-clinical (AEC) correlations with the main aim to conceptualize the three-dimensional spatial-temporal organization of the epileptic discharge within the brain based mainly on seizure semiology. The implantation strategy is individualized, with electrode placements based on a preimplantation hypothesis that takes into consideration the primary organization of the epileptiform activity and the hypothetical functional epileptic network that may be involved in the primary organization and early propagation of the epileptic activity. For these reasons, the preimplantation AEC hypothesis is the most important element in the process of planning for SEEG electrodes placement. If the preimplantation hypothesis is incorrect, the placement of the depth electrodes will be inadequate and the interpretation of the SEEG recordings misleading. The most important characteristic of SEEG methodology is that it enables precise recordings of deep cortical and subcortical structures, from multiple noncontiguous lobes, allowing the mapping of three-dimensional aspects of specific epileptic networks. In addition, it allows bilateral explorations while avoiding the need for large craniotomies [2, 5–7, 14].

The SEEG technique was originally described as a multiphase and complex method, using the Talairach stereotactic frame and the double grid system in association with teleangiography [13, 15]. Despite its long reported successful record, with almost 60 years of clinical use, the technical complexity regarding the placement of SEEG depth electrodes may have contributed to its limited widespread use in centers outside Europe. Taking advantage of new imaging and computational innovations, commonly available in many surgical centers, more modern and less cumbersome methods of stereotactic implantation of depth electrodes can be applied in routine basis.

## SEEG methodology principles and clinical indications

The development of an SEEG implantation plan requires the clear formulation of a specific anatomo-electro-functional hypothesis to be tested. This hypothesis is typically generated during the patient management conference based on the results of the various noninvasive evaluation tests. At Cleveland Clinic, a final tailored implantation strategy is generated during a separate presurgical implantation meeting. Depth electrodes would sample the anatomic lesion (if identified), the more likely structure(s) of ictal onset, the clinically active regions, and the possible pathway(s) of onset propagation of the electrical seizure activity (functional networks). The EZ

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could be the one corresponding to the first clinical sign or may be a spread area from a "clinically silent" ictal onset zone within a functional network. For these reasons, a three-dimensional "conceptualization" of the network nodes upstream and downstream from the hypothesized clinical onset region is an essential component of the presurgical implantation strategy.

In addition to the general indications for invasive monitoring, specific indications can be considered to choose SEEG in detriment to other methods of invasive monitoring. These criteria included:

1. The possibility of a deep-seated or difficult to cover location of the EZ in areas such as the mesial structures of the temporal lobe, opercular areas, cingulate gyrus, interhemispheric regions, posterior orbitofrontal areas, insula, and depths of sulci.
2. A failure of a previous subdural invasive study to clearly outline the exact location of the seizure onset zone. The failure to identify the EZ in these patients may be due to multiple reasons that include the lack of adequate sampling from a deep focus or a clinically silent focus upstream from the EZ.
3. The need for extensive bihemispheric explorations (in particular in focal epilepsies arising from the interhemispheric or deep insular regions).
4. Presurgical evaluation suggestive of a functional network involvement (e.g., limbic system) in the setting of normal MRI.

In these scenarios, the SEEG methodology may be considered a more appropriate and safer option, mainly in the pediatric population. As mentioned above, the SEEG methodology has the advantages of allowing extensive and precise deep brain recordings and stimulations with minimal associated morbidity. In reoperations, mainly in patients who underwent a previous subdural evaluation, possibilities are that the majority of these patients failed epilepsy surgery because of difficulties in accurately localizing the EZ. These patients pose a significant dilemma for further management, having relatively few options available. Further open subdural grid evaluations may carry the risks associated with encountering scar formations, and still having limitations related to deep cortical structure recordings. A subsequent evaluation using the SEEG method may overcome these limitations, offering an additional opportunity for seizure localization and sustained seizure freedom [14]. The main disadvantage of the SEEG method is the more restricted capability for performing functional mapping. Due to limited number of contacts located in the superficial cortex, a contiguous mapping of eloquent brain areas cannot be obtained as in the subdural method mapping. In order to overcome this relative disadvantage, the functional mapping information extracted from the SEEG method is frequently complemented with other methods of mapping, as DTI images or awake craniotomies [7].

## The SEEG technique

Once the preimplantation hypothesis is conceptualized, the desired targets and trajectories are reached using commercially available depth electrodes in various lengths and number of contacts, depending on the specific brain region to be explored. The electrodes are implanted using conventional stereotactic technique through 2.5-mm diameter drill holes. Depth electrodes are inserted using orthogonal or oblique orientation, allowing intracranial recording from lateral, intermediate, or deep cortical and subcortical structures in a three-dimensional arrangement, thus accounting for the dynamic, multidirectional spatiotemporal organization of the epileptic pathways.

As part of our routine practice, the patient is admitted to the hospital the day of surgery. The day prior to surgery, volumetric preoperative MRIs (T1, contrasted with Multihance®; 0.1 mmol/kg) were obtained. DICOM format images were then digitally transferred to a robotic assistant device's (ROSA®, Medtech®. Montpellier, France) native planning software. Three-dimensional volumetric reconstructions were then created (axial, coronal, and sagittal), reformatted based on the topographic location of the AC-PC line. Individual trajectories were planned within the three-dimensional imaging reconstruction according to predetermined target locations and intended trajectories. Trajectories were selected to maximize sampling from superficial and deep cortical and subcortical areas within the preselected zones of interest and were oriented orthogonally in the majority of cases to facilitate the anatomo-electrophysiological correlation during the extraoperative recording phase and to avoid possible trajectories shifts due to excessive angled entry points. Nevertheless, when multiple targets were potentially accessible via a single nonorthogonal trajectory, these multitarget trajectories were selected in order to minimize the number of implanted electrodes per patient.

All trajectories were evaluated for safety and target accuracy in their individual reconstructed planes (axial, sagittal, and coronal), and also along the reconstructed "probe's eye view." Any trajectory that appeared to compromise vascular structures was adjusted appropriately without affecting the sampling from areas of interest. A set working distance of 150 mm from the drilling platform to the target was initially utilized for each trajectory, been later adjusted in order to maximally reduce the working distance and, consequently, improve the implantation accuracy. The overall implantation schemas were analyzed using the three-dimensional cranial reconstruction capabilities and internal trajectories were checked to ensure that no trajectory collisions were present.

External trajectory positions were examined for any entry sites that would be prohibitively close (less than 1.5 cm distance) at the skin level.

### Positioning and image registration

On the day of surgery, patients were placed under general anesthesia. For each patient, the head was placed into a three-point fixation head holder. The robot was then positioned such that the working distance (distance between the base of the robotic arm and the midpoint of the cranium) was approximately 70 cm. The robot was locked into position, and the head holder device was secured to the robot. No additional position adjustments were made to the operating table during the implantation procedure. After positioning and securing the patient to the robot, image registrations were performed. Semiautomatic laser-based facial recognition was utilized to register the preoperative volumetric MRI with the patient. The laser was first calibrated using a set distance calibration tool. Preset anatomical facial landmarks were then manually selected with the laser. The areas defined by the manually entered anatomic landmarks subsequently underwent automatic registration using laser-based facial surface scanning. Accuracy of the registration process was then confirmed by correlating additional independently chosen surface landmarks with the registered MRI.

### Robotic-guided electrode placement

The patients were then prepped and draped in a standard sterile fashion. The robotic working arm was also draped with a sterile plastic cover. A drilling platform, with a 2.5-mm-diameter working cannula was secured to the robotic arm. The desired trajectories were selected on the touch screen interface. After trajectory confirmation, the arm movement was initiated through the use of a foot-pedal. The robotic arm automatically locked the drilling platform into a stable position once reaching the calculated position for the selected trajectory.

A 2-mm-diameter handheld drill (Stryker®) was introduced through the platform and used to create a pinhole. Dura was then opened with an insulated dural perforator using monopolar cautery at low settings. A guiding bolt (Ad-Tech, Racine, WI, USA) was screwed firmly into each pinhole. The distance from drilling platform to the retaining bolt was measured. This value was subtracted from the standardized 150-mm platform to target distance. The resulting difference was recorded for later use as the final length of the electrode to be implanted. This process was repeated for each trajectory. All pinholes and retaining bolts were placed prior to beginning electrode insertion. A small stylet (2 mm in diameter) was then set to the previously recorded electrode distance. The stylet was passed gently into the parenchyma, guided by the implantation bolt, followed immediately by the insertion of the premeasured electrode (Fig. 1).

After implantation of all electrodes, the patient was removed from the fixation device. The head was positioned into a soft foam headholder on a radiolucent table. Fluoroscopy was then utilized in the AP plane to confirm the general accuracy of implanted electrode trajectories. A post implantation volumetric CT of the brain without contrast, with 1-mm cuts, was obtained for each patient.

Following the surgical electrode implantation, patients are transferred to the pediatric epilepsy monitoring unit (pEMU). The duration of admission at the epilepsy monitoring unit varies from patient to patient, depending on several factors including number, quality of recorded ictal and interictal patterns. The average length of stay of patients in the EMU who underwent SEEG implantation at Cleveland Clinic over the last 4 years is 7 days (range from 3 to 28 days). After obtaining the necessary information, electrodes are removed in the operating room, in a procedure performed under local anesthesia and sedation. The results of the SEEG evaluation are discussed during another patient management conference and recommendations for surgical resection are made. Patients are discharged next morning and resective surgery is scheduled 2 to 3 months following SEEG electrodes removal.

## SEEG morbidity and efficacy results

Results regarding SEEG-guided resections demonstrate that in children and adolescents who have exhausted treatment options and are suspect to have highly complex medically refractory epilepsy amenable to surgical treatment, the SEEG method provides an opportunity for seizure freedom in approximately 50 % of resected patients. Additionally, the placement of depth electrodes, 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 caused by focal cortical dysplasia. In this challenging group of patients with refractory epilepsy associated with mild forms of cortical dysplasia, SEEG may represent a reliable alternative method of invasive extraoperative monitoring by allowing extensive exploration of widespread functional networks in association with minimal morbidity [8].

As a general concern regarding morbidity associated with the SEEG method, the placement of intracerebral depth electrodes has a reputation to be excessive morbid, with a relative high morbidity rate as previously pointed by Lee and colleagues [10]. Conversely, probably due to methodological and technological advances, the experience in recent adult [7] and pediatric series [8] does not indicate that this reputation is deserved any longer. In previously published series [4, 5], the only adverse event reported was a breakage of an electrode during a seizure, but no neurological complication was observed. In a more recent series,

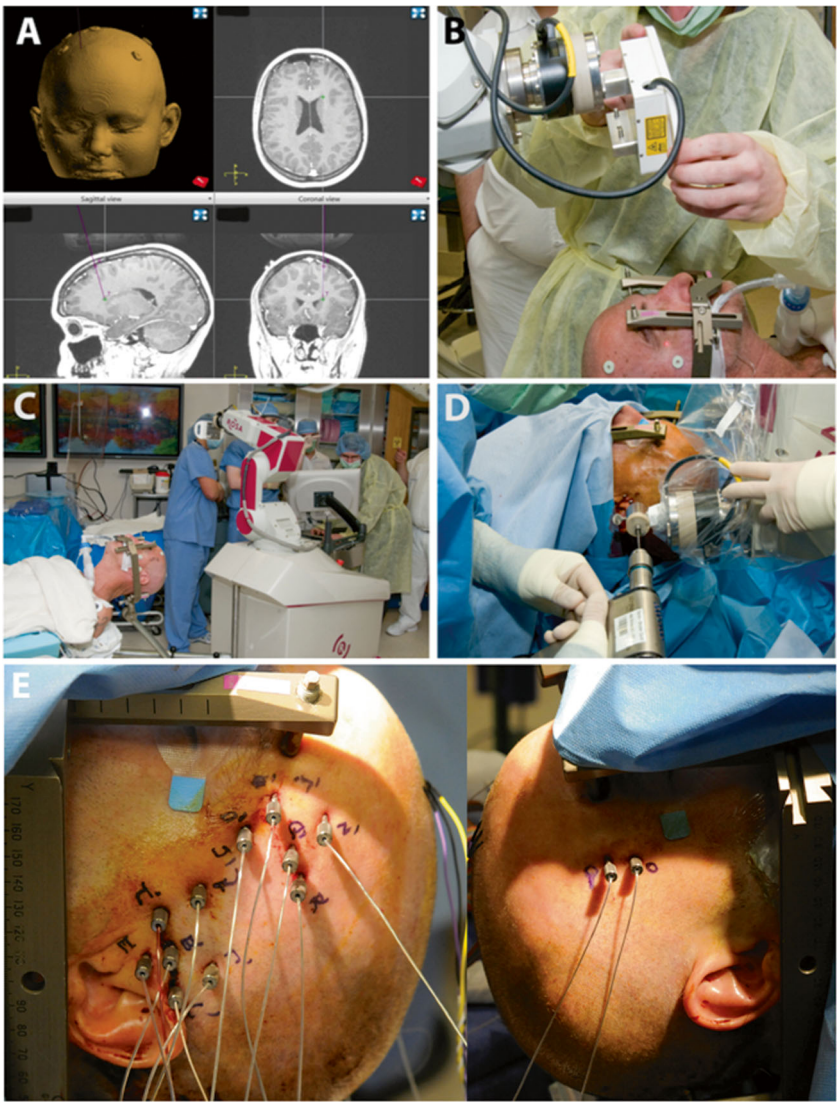


**Fig. 1** Method of SEEG implantation. **a** Planning SEEG trajectory using robot's native implantation software. **b** Registration using face recognition method. **c** Operating room set up with patient anesthetized and robot positioned. **d** Drilling phase using robotic guidance. **e** Final aspect of a bilateral SEEG implantation

one death was reported in a child implanted with SEEG electrodes, likely unrelated to the implantation of electrodes but due to electrolytic disturbances and secondary brain edema [3]. 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 [1, 12]. Considering these published data, SEEG implantation may be particularly appealing for the pediatric group, as it avoids the need for larger craniotomies, resulting in minimal postoperative pain and the negligible blood loss during the implantations.

From an effectiveness aspect, the SEEG method has shown to be effective in electrophysiologically defining the hypothetical EZ in challenging cases, since localization is accomplished in approximately 80 to 98 % of children across the literature [5, 7]. Particularly in this clinical aspect, the authors have found SEEG to be especially useful in pediatric patients without a lesion on MRI, with most of these patients generally presenting with mild forms of focal cortical dysplasia [8]. Seizure freedom following resective surgeries in patients with normal preoperative MRI has been significantly worse in the literature, with seizure-free rates as low as 17 % of patients who were previously implanted with subdural grids/strips [9, 11]. In a recent published series from the Cleveland Clinic group, of the 18 pediatric patients who underwent SEEG-guided resection, 10 patients (55.5 %) were seizure-free at last follow-up (class I) and 5 patients (27.7 %) experienced seizure improvement (Engel classes II and III). Regrettably, three patients (16.6 %) had no improvement in seizures following resections (class IV). Surgical pathology from resected specimens showed mild forms of cortical dysplasia 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. The histopathology of three patients with no seizure improvement showed gliosis in two and mild form of cortical dysplasia in the remaining patient. The authors conclude that nonlesional MRIs should not prevent further

invasive investigation as long as reasonable preimplantation hypotheses can be formulated based on video-EEG and ancillary tests as PET, MEG, and ictal SPECT [8]. Furthermore, the comparison data might suggest the potential superiority of the SEEG method in seizure localization in patients with nonlesional MRI associated with mild forms of cortical dysplasia. The better localization ratio provided by the SEEG method may be related to its intrinsic capacity that is better characterizing the three-dimensional aspect of a specific functional network, likely responsible for the primary organization and early propagation of the epileptic activity.

## 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 in the setting of nonlocalizable scalp EEG recordings and with nonlesional MRIs, likely associated with mild forms of cortical dysplasia. In performing SEEG in this highly selected group, it is possible to partially overcome the relative limitations related to other methods of invasive monitoring, offering to these challenging children an additional opportunity for seizure freedom without safety compromises.

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