Stereotactic placement of depth electrodes in medically intractable epilepsy

Technical note

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Object. Despite its long-reported successful record, with almost 60 years of clinical use, the technical complexity regarding the placement of stereoelectroencephalography (SEEG) depth electrodes may have contributed to the limited widespread application of the technique in centers outside Europe. The authors report on a simplified and novel SEEG surgical technique in the extraoperative mapping of refractory focal epilepsy.

Methods. The proposed technique was applied in patients with medically refractory focal epilepsy. Data regarding general demographic information, method of electrode implantation, time of implantation, number of implanted electrodes, seizure outcome after SEEG-guided resections, and complications were prospectively collected.

Results. From March 2009 to April 2012, 122 patients underwent SEEG depth electrode implantation at the Cleveland Clinic Epilepsy Center in which the authors’ technique was used. There were 65 male and 57 female patients whose mean age was 33 years (range 5–68 years). The group included 21 pediatric patients (younger than 18 years). Planning and implantations were performed in a single stage. The time for planning was, on average, 33 minutes (range 20–47 minutes), and the time for implantation was, on average, 107 minutes (range 47–150 minutes). Complications related to the SEEG technique were observed in 3 patients. The calculated risk of complications per electrode was 0.18%. The seizure-free rate after SEEG-guided resections was 62% in a mean follow-up period of 12 months.

Conclusions. The authors report on a safe, simplified, and less time-consuming method of SEEG depth electrode implantation, using standard and widely available surgical tools, making the technique a reasonable option for extraoperative monitoring of patients with medically intractable epilepsy in centers lacking the Talairach stereotactic armamentarium.

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Key Words • epilepsy surgery • stereotaxy • stereoelectroencephalography • surgical technique

The stereoelectroencephalography (SEEG) method was developed and popularized in France by Jean Talairach and Jean Bancaud during the 1950s and has been mostly used in France and Italy as the method of choice for invasive mapping in cases of refractory focal epilepsy.1,2,19 According to previous European reports, SEEG methodology enables precise recordings from deep cortical and subcortical structures, multiple noncontiguous lobes, and bilateral explorations while avoiding the need for large craniotomies.7,10,11,14

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.4,10 Despite its long-reported successful record, with almost 60 years of clinical use, the technical complexity involved in the placement of SEEG depth electrodes may have contributed to the limited widespread application of the technique in centers outside Europe.

Taking advantage of new radiological and computational innovations, commonly available in many surgical centers, we report on a simplified and novel SEEG surgical technique in the extraoperative mapping of refractory focal epilepsy.

Methods

The recommendations for SEEG depth electrode implantation and the general planning of electrode sites were
made during our weekly Epilepsy Center multidisciplinary patient management conference following detailed review and discussion of results of the noninvasive localization methods (and, at times, previous invasive tests and other surgical procedures). In addition to the general criteria used for invasive extraoperative monitoring, additional specific criteria were considered in choosing SEEG instead of other methods of invasive monitoring. These criteria included: 1) the possibility of a deep-seated or difficult-to-cover location of the epileptogenic zone 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) the failure of a previous subdural invasive study to clearly outline the exact location of the seizure-onset zone; 3) the need for extensive bihemispheric explorations; and 4) a presurgical evaluation suggestive of a functional network involvement (for example, the limbic system) in the setting of normal MRI findings.

All the SEEG procedures were performed by a single neurosurgeon (J.G.M.). Data regarding general demographic information, method of implantation, time of implantation, number of implanted electrodes, types of resections, SEEG-guided resection outcome, and complications were prospectively collected. All adverse events within a period of 30 days following SEEG electrode implantations were counted as complications. Complications were categorized by type (neurological vs nonneurological) and by severity (minor complications [no changes in duration of stay in the epilepsy monitoring unit, with minimal modifications in the treatment plan, or no permanent neurological deficits] versus major complications [prolongation duration of stay in the epilepsy monitoring unit and/or permanent neurological deficit, with significant changes in the plan of treatment]). This research was approved by the Cleveland Clinic Institutional Review Board. All surgeries were part of standard patient care and no procedures were performed for research purposes.

Results

From March 2009 to April 2012, 122 patients underwent SEEG depth electrode implantation at the Cleveland Clinic Epilepsy Center. There were 65 male and 57 female patients whose mean age was 33 years (range 5–68 years). The group included 21 pediatric patients (younger than 18 years). All the patients had the diagnosis of refractory focal epilepsy, and, on average, 5 antiepileptic drugs/patient had failed to resolve symptoms.

The SEEG implantation patterns were individualized, reflecting the differences in the preimplantation hypothesis formed for each patient. On average, 13 electrodes were implanted per patient (range 7–22 electrodes, total 1586 electrodes). Planning and implantations were performed in a single stage, on the same day. The time for planning was, on average, 33 minutes (range 20–47 minutes), and the time for implantation was, on average, 107 minutes (range 47–150 minutes). Implantations were bilateral in 49 patients, right hemispheric in 43 patients, and left hemispheric in 30 patients. Implantations involved at least 2 lobes (at times noncontiguous), which included a combination of frontal, temporal, parietal, occipital, and/or insular lobe explorations. The large majority of electrodes were inserted in orthogonal orientation in relation to the sagittal plane, with 51 electrodes implanted in oblique orientation (for targeting the insular cortex, posterior orbitofrontal cortex, superior frontal gyrus, and superior parietal lobule).

Developing the SEEG Depth Electrode Implantation Strategy

The development of an SEEG electrode implantation plan required a clear formulation of a specific anatomo-electro-functional hypothesis to be tested. The hypothesis was typically generated during the patient management conference and was based on the detailed review of results of the various noninvasive evaluation tests. After the anatomo-functional localizing hypothesis was formulated, a tailored implantation strategy was planned, with the goal of confirming or rejecting the preimplantation hypothesis. In this phase, the exploration was focused on sampling the anatomical lesion (if present), the more likely structure(s) of ictal onset, and the possible pathway(s) of propagation of seizures.

Technique of SEEG Electrode Implantation

The desired targets are reached using commercially available depth electrodes (AdTech and Integra) 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 3D 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 before surgery, a stereo-contrasted volumetric T1-weighted MRI sequence is performed. Images are then transferred to our stereotactic neuronavigation software (iPlan Cranial 2.6, Brainlab AG), where trajectories are calculated the following day. The day of surgery, while the patient is under general anesthesia, the Leksell stereotactic frame (Elekta AB) is applied using standard technique. Once the patient has been attached to the angiography table with the frame, stereotactic DynaCT (Siemens AG) and 3D digital subtraction angiography are performed. The preoperative MR images, the stereotactic DynaCT scans, and angiographic images are then digitally processed using a dedicated fusion software (syngo XWP, Siemens). These fused images are 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 on contrast-enhanced MRI. Following the planning phase that involved the stereotactic software, trajectory coordinates are recorded and transmitted to the operating room. Trajectories are in general planned in an orthogo-
nal orientation in relation to the skull’s sagittal plane to facilitate implantation and, later on, interpretation of the electrode positions. Using the Leksell stereotactic system, coordinates for each trajectory are then adjusted in the stereotactic frame and a lateral fluoroscopic image is acquired in each new position. Care is taken to ensure that the central beam of radiation during fluoroscopy is centered in the middle of the implantation probe to avoid parallax errors. If the trajectory is aligned correctly, corresponding to the planned trajectory and passing along an avascular space, the implantation is then continued, with skull perforation, dura opening, placement of the guiding bolt (AdTech and Integra), and final insertion of the electrode under fluoroscopic guidance. If a vessel is recognized along the pathway during fluoroscopy, the guiding tube is manually moved a few millimeters until the next avascular space is recognized and implantation is then continued. The electrode insertion progress is observed under live fluoroscopic control in a frontal view to confirm the straight trajectory of each electrode. For additional guidance, a coronal MRI slice corresponding to the level of each electrode implantation is overlaid on the fluoroscopic image.

Postimplantation DynaCT scans are obtained while the patient is still anesthetized and positioned on the operating table. The reconstructed images are then fused with the MRI data set using the previously described fusion software. The resulting merged data sets are displayed and reviewed in axial, sagittal, and coronal planes, which allows verification that the electrodes have been correctly placed (Figs. 1 and 2).

After surgery, patients are transferred to the epilepsy monitoring unit. The duration of stay in the epilepsy monitoring unit varies from patient to patient, depending on several factors including number, quality, and ictal and interictal patterns of recordings. The average length of stay in the epilepsy monitoring unit of patients who have undergone SEEG electrode implantation is 7 days (range 3–28 days). After we obtain the necessary information, electrodes are removed in the operating room, in a procedure performed under local anesthesia and sedation. Patients are discharged the next morning and resection is scheduled for 2–3 months following SEEG electrodes removal.

Minor neurological complications related to the described SEEG technique were observed in 3 patients: an asymptomatic subdural hematoma in 1 patient and intraparenchymal hemorrhages in 2 patients. All hemorrhages were located in the frontal lobe following placement of the following: 1) an oblique electrode targeting the insula, resulting in a subdural hematoma and minimal local mass effect centered within the left frontal region; 2) a frontal electrode targeting the orbitofrontal cortex, resulting in a hemorrhagic hematoma in the lateral orbital gyrus, at the electrode entry point; and 3) another frontal electrode, targeting the posterior mesial frontal cortex, resulting in

![Fig. 1. Method of SEEG depth electrode implantation. A: Preoperative MR image and intraoperative digital angiogram fused. B: Example of live fluoroscopic image fused with the digital angiogram during SEEG electrode implantation. The radioscopic beam is aligned at the center of the implantation probe, confirming the avascular trajectory to be penetrated. C: Live fluoroscopic image fused with preoperative MR image during implantation of SEEG electrodes. Note the insertion of hippocampal electrodes bilaterally. The intraoperative images provide the surgeon an additional degree of certainty and precision regarding the final position of every trajectory. D: Intraoperative postimplantation image showing the preoperative volumetric T1-weighted coronal image fused with the intraoperative DynaCT images. The implanted electrodes are depicted in yellow. E: Final implantation aspect (right side).](image)
a small hemorrhagic hematoma at the target point. There were no angiography-related complications, and no other complications were observed in this series. Given the total number of implanted electrodes (n = 1586), the calculated risk of complications per electrode was 0.18%. The morbidity rate was 2.5% (3 of 122 patients).

Although no formal accuracy tests were performed, electrodes trajectories (entry zone, course, and target zone) precisely matched the preimplantation trajectories (with maximal error of 2 mm in any orientation) in most of the trajectories. Among the 1586 placed electrodes, 32 (2%) were misplaced. However, among the misplaced electrodes, intraoperative repositioning was performed on only 5 occasions. Although the remaining 27 electrodes from this group were misplaced, they were still positioned in the anatomical area of interest for recordings and this did not require repositioning.

Based on the SEEG recordings, the hypothetical epileptogenic zone was localized in 115 patients (94%). Ninety patients underwent SEEG-guided resections and had a minimal follow-up of 6 months. From this group, 56 patients (62%) had sustained seizure control. Temporal lobe resections were performed in 37 patients (41.1%) and extratemporal resections in 53 patients (58.9%). In the extratemporal resections group, 26 patients underwent frontal resections (28.9%) and 12 underwent parietal resections (13.3%). Multilobar resections were performed in 15 patients (17%) and included frontal-temporal resections in 11 patients, frontal insular resections in 2, and insular-perisylvian resections in 2. The mean follow-up after SEEG-guided resection was 12 months.

Discussion

The SEEG implantation method and technique we have described, which departs from the more traditional technique used for SEEG electrode implantation (that mainly uses the double Talairach grid and frame, in as-
Stereoelectroencephalography in the United States

association with teleangiography), proved to be safe, comparable to the traditional method of implantation. In our series, the total complication rate was 2.5%. Other groups have reported similar results.5,6,8,16 Cossu et al. reported a morbidity rate of 5.6%, with severe permanent deficits from intracerebral hemorrhage in 2 patients (1%).5 In our series, all 3 complications were hemorrhagic, which has been reported in several studies to be the most common complication related to depth electrode placement.5,8 Other series reporting complications across invasive monitoring procedures (subdural grids and depth electrodes) have rates ranging from 0% to 26%.3,12,17,28,21 Interestingly, subdural monitoring with grid electrodes has historically been shown to have a low permanent morbidity rate (range 0%–3%) compared with depth electrodes (range 3%–6%) since there is no intraparenchymal passage.18 Although it is difficult to compare morbidity rates between subdural grids and SEEG depth electrodes due to the variability in patient selection, different institutions, and variable number of implanted electrodes, it is our preliminary impression that the SEEG method provides at least a similar degree of safety when compared with subdural grids or strips. This impression is also shared by others.5,6,16

The rate of hemorrhagic complications per electrode was low (0.18%). The rate of hemorrhagic complications per patient was 2.5%. We believe that the low rate of complications may be in part related to the implantation technique, specifically to the use of the intraoperative cerebral angiography. The use of angiography during the implantation allowed us to perform extensive stereotactic explorations in highly vascularized and eloquent cortical areas, such as the insula, the perisylvian area, and the rolandic cortex, with minimal morbidity. No complications were associated with the angiographic procedure. However, the use of angiography for SEEG depth electrode implantation remains controversial. Many groups have reported acceptable complication rates without angiography but with the use of a double-dose Gd-enhanced MRI, on which vessels can be clearly visualized and electrode trajectories can be planned accordingly.20 Nevertheless, when reviewing the literature, the rate of complications when using the MRI-only technique (without angiography) tends to be higher. De Almeida et al., using the MRI-only technique in most of SEEG electrode implantations, reported a rate of hemorrhagic complication to be almost 3-fold higher (0.7% per electrode) compared with other groups using the angiographic technique.8 However, despite promising safety and efficacy results, the proposed method has not proved its superiority to other depth electrode placement techniques. Consequently, further prospective studies are necessary to validate our preliminary results.

Conclusions

The proposed method for stereotactic placement of depth electrodes is a reliable and safe alternative to the more standard method of SEEG depth electrode implantation. This study reports a simplified and less time-consuming method of implantation that involves using standard and widely available surgical tools, making the technique a reasonable option for extraoperative monitoring of patients with medically intractable epilepsy in centers that do not have the Talairach stereotactic armamentarium.

Disclosure

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 to the study and manuscript preparation include the following. Conception and design: Gonzalez-Martinez. Acquisition of data: Gonzalez-Martinez, Mullin, Vadera, Bulacio, Hughes, Enatsu. Analysis and interpretation of data: Gonzalez-Martinez, Mullin, Vadera, Bulacio, Jones, Najm. Drafting the article: Gonzalez-Martinez. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Gonzalez-Martinez. Administrative/technical/material support: Gonzalez-Martinez. Study supervision: Gonzalez-Martinez, Najm.

References

10. Guenot M, Isnard J: [Epilepsy and insula.] Neurochirurgie 54:374–381, 2008 (Fr)

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