Chapter

Stereotactic Electroencephalography (SEEG)

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Abstract

Drug resistant epilepsy (DRE) is not an uncommon clinical condition. DRE could cause disabling seizures and even sudden unexpected death in epilepsy (SUDEP). Pre-surgical evaluation is necessary to for surgical treatment to cure or palliative epilepsy. If feasible, surgical excision of an epileptic focus provides the best chance of cure. However, the standard non-invasive workup could not always identify the epileptic focus. Stereotactic EEG (SEEG) is an invasive EEG that could provide the spatial and temporal progression of epileptic discharge so that we could localize or lateralise the epileptic focus more easily. This chapter aims to illustrate the principle of SEEG, the methods of SEEG electrode insertion, the usual white matter tract pathway that epileptic discharge progresses. It also discusses the therapeutic use of SEEG in lesioning with radiofrequency ablation (RFA), as well as the future potential as part of the brain-computer interface (BCI).

Keywords: stereotactic electroencephalography, drug-resistant epilepsy, radiofrequency ablation, neuroprosthesis, brain-computer interface

1. Introduction

Stereotactic electroencephalography (SEEG) is the study of the electrical activities of the brain by means of implantation of electrodes into brain parenchyma with the aid of stereotactic navigation [1].

It was first developed by Jean Talairach and Jean Bancaud in France in the late 1950s. Talairach was a renowned stereotactic neurosurgeon who developed the frame-based coordinate system of the human brain based on the anatomical AC-PC (anterior commissure – posterior commissure) line, while Bancaud put forth the presurgical evaluation of drug-resistant epilepsy (DRE) with the use of the Talariach method. Bancaud described the organization of temporal lobe seizure with respect to the mesial temporal structures and the temporal neocortex [2]. This laid the foundation of SEEG as the presurgical workup for refractory epilepsy. It was then used in France, Italy and Canada for some time.

Only till 2010s, it was adopted in the United States and gained popularity because of its attractive safety profile and the capacity to perform spatiotemporal analysis

of the progression of the epileptiform discharge and bilateral cerebral hemisphere simultaneously, in comparison with subdural grid and depth electrodes which study cases that were already lateralized and/or partially localized [3].

Moreover, as the technology improves, SEEG could combine with lesioning technique to eradicate the epileptogenic zone, for example, radiofrequency ablation (RFA) [4]. This therapeutic use became more popular since the 2000s. Besides, as the electrodes were getting smaller and smaller, it had its potential in the application in brain-computer interface and the development of neuroprosthesis, in contrast to the traditional use of electrocorticography (ECoG).

Thus, this chapter aims to review the roles of SEEG as:

1. Diagnostic purpose in presurgical workup for drug-resistant epilepsy

2. Therapeutic use to lesion the epileptogenic zone

3. Potential use in brain-computer interface, to create neuroprosthesis

2. Diagnostic use

2.1 Definition and epileptogenesis

To start with, it is important to clarify the concepts of drug-resistant epilepsy (DRE), zonification of epileptogenesis, and a proper presurgical workup.

Drug-resistant epilepsy, aka medical refractory epilepsy, is defined as the failure of adequate trials of two well-tolerated, appropriately chosen and used antiepileptic drug schedules, be it monotherapy or polytherapy, according to the International League Against Epilepsy (ILAE) consensus in 2009 [5]. Patients with DRE is eligible for presurgical evaluation.

In case of focal epilepsy, an *epileptogenic zone* (EZ) may be identified where cure of epilepsy could be achieved if it is resected. For the terminology in epileptogenesis, *epileptogenic lesion* is the anatomical abnormality which could be identified in structural imaging such as MRI [6]. *Ictal onset zone* is the origin of the seizure which could be the brain parenchyma without the lesion. Epileptogenic lesion and the ictal onset zone, together, form the EZ. However, sometimes when the epileptiform discharges propagate to the other parts of the brain causing symptoms. Those part would be named *symptomatogenic zone*. Most of the time, the symptoms could be the more obvious part of the seizure semiology which could make the localization of the EZ confusing. For example, a temporal EZ could transmit the epileptiform discharge to the frontal lobe via white matter tracts such as uncinate fasciculus and arcuate fasciculus, leading to the clinical impression of frontal epilepsy. On the other hand, *irritative zone* refers to the area which produces interictal epileptiform discharge. *Functional deficit zone* refers to the area of hypometabolism in functional imaging i.e. interictal PET scan. Irritative and functional deficit zones could overlap with the EZ but the areas represented are often exaggerated. This zonification concept forms the foundation of *localization* of the culprit of the epilepsy (**Table 1**) (**Figure 1**). On the other hand, *lateralization* of the epilepsy to either left or right side is also crucial but could be difficult at times, especially in frontal epilepsy in which synchronization of the bilateral cerebral hemisphere could be quick via commissural fibers such as corpus callosum.

Epileptogenic lesion	Anatomical abnormality in neuroimaging
Ictal onset zone	Onset of seizure
Epileptogenic zone	Epileptogenic lesion + Ictal onset zone
Symptomatogenic zone	Area which produces symptoms
Irritative zone	Area which produces interictal epileptiform discharge
Functional deficit zone	Area of hypometabolism in interictal functional imaging

Table 1.
Zonification of epileptogenesis.

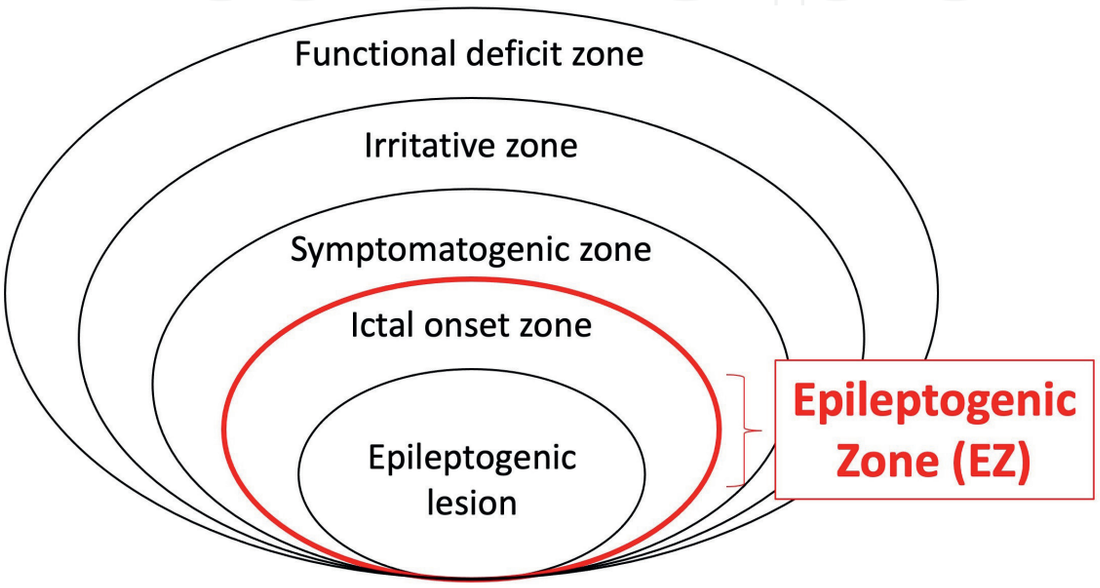

Figure 1.
Zonification of epileptogenesis.

2.2 Presurgical workup

A presurgical workup aims to generate an *anatomical-clinical-electrophysiological (ACE) hypothesis*. MRI, video EEG and neuropsychiatric assessment form the core of it. An MRI with good resolution would offer the *localization* of the epileptogenic lesion, which lays the foundation of good surgical outcome to start with, as lesional epilepsy has a better outcome (by two to three times) than non-lesional epilepsy after neurosurgical intervention [7]. 3-T MRI, which has a higher signal-to-noise ratio, could be more accurate in delineating the lesion as compare with 1.5-T MRI as illustrated in some qualitative studies [8]. An ictal video EEG would be more valuable than an interictal EEG because it offers the appreciation of the clinical semiology with the ictal discharges simultaneously, while interictal EEG could only illustrate the irritative zone. Neuropsychiatric assessment could offer evidence of brain dysfunction secondary to epileptic encephalopathy. For example, frontal lobe epilepsy might cause frontal lobe syndrome such as disinhibition, perseverance, etc. For temporal lobe epilepsy in dominant hemisphere, it causes more verbal memory deficit as compared with the visual memory deficit in the non-dominant hemisphere. It is often how *lateralization* is done in cases such as mesial temporal sclerosis. Bilateral mesial temporal sclerosis is not uncommon.

If these three investigations provide concordant findings, in which an EZ could be concluded, then surgical excision might be proceeded. The most often encountered

example would be temporal lobe epilepsy secondary to mesial temporal sclerosis. Indeed, mesial temporal resection (i.e. amygdalohippocampectomy), via either transtemporal (anterior temporal lobectomy) or transsylvian approach, offer some of the best outcome in terms of seizure control.

Functional images such as interictal PET-CT could provide supportive information but often it is not conclusive due to its lack of spatial resolution. Nowadays, a PET-MRI could be done in the same setting to provide the simultaneous appreciation of anatomical and functional data, which might be more superior than fusing, by software, the interictal PET-CT with the MRI which were done in two settings. Ictal SPECT is also valuable to evaluate the part of brain with the greatest perfusion which is often the EZ. It is the most useful when there is more than one lesion, and the clinician could not conclude which one is the culprit. However, it is technically demanding as the radioactive isotope should be injected once the ictal event starts, in terms of seconds. Also, if the electrophysiological onset precedes the clinical one, the ictal event has started for some time before clinical semiology happens. For lateralization of dominant hemisphere, functional MRI by means of blood oxygen level dependent (BOLD) might be helpful to lateralize the language area. Yet, there could be bilateral activation at times especially in those who were agitated or intellectually disabled. Of note, even functional MRI could lateralize the language area, it has relatively poor spatial resolution as it is all about the adjustment of the threshold in the software. It could not replace the language assessment in awake craniotomy in case of proximity of the EZ to the language areas. Magnetoencephalography (MEG) is to detect dipoles which occur in the EZ. It is similar to SPECT but it is not as time-dependent.

If the above measures (some refer them as level 1) provide discordant findings (**Table 2**), and *lateralization* and *localization* could not be achieved, invasive workup (i.e. level 2) might have to be considered [9]. Wada test involves the endovascular injection of barbiturate to internal carotid artery (ICA) to temporarily suppress the activity of one cerebral hemisphere to see if it causes verbal or visual memory deficits, as mentioned, which then points to left or right-side temporal lobe epilepsy respectively. If ICA Wada test fails to lateralize the dominant hemisphere, then selective posterior cerebral artery (PCA) Wada test could be considered to selectively suppress the activity of the hippocampus [10].

2.3 Invasive EEG

Here comes to the invasive EEG. If an epilepsy is lateralized and partially localized in the level 1 presurgical workup, craniotomy for putting in subdural grid or depth electrodes (SDE) was the commonest method for invasive EEG. Subdural grid offers

MRI	to localize the *epileptogenic lesion*
Ictal Video EEG	to localize the *ictal onset zone* and characterize the semiology which helps to localize the *symptomatogenic zone*
Interictal EEG	to localize the *irritative zone*
Neuropsychiatric assessment	to lateralize the epilepsy
Interictal PET	to localize the *functional deficit zone*
Ictal SPECT and MEG	to localize the *epileptogenic zone*

Table 2.
Level 1 presurgical workup.

examination of epileptiform discharges across the cerebral convexity while depth electrodes provide the assessment of epileptiform discharges from deep to superficial. Yet, it involves the risks of bleeding and infection, especially in those with prior craniotomy. It might also cause unhabitual seizure events during the recording which might confuse the clinical picture.

Stereotactic EEG (SEEG) involves the minimally invasive approach to implant multiple electrodes with twist drill to cover different areas of a cerebral hemisphere. Bilateral implantation is also feasible. Simultaneous deep and superficial assessment of multiple sites is one of its greatest advantages [11]. The spatial and temporal relationship of the epileptiform discharges as in a 3D coordinate system could be delineated. The epileptic network could be determined. It causes less unhabitual seizure event. In the series by McGonigal A, *et al*., SEEG localizes the EZ in non-lesional epilepsy cases as effective as in lesional ones [12]. In the meta-analysis published by Mullin, *et al.*, the bleeding and infection rate was found to be 1% and 0.8% respectively [13]. In the meta-analysis by Arya R. *et al.*, the rate was 4% and 2.3% respectively [14]. In some lesional cases with anatomical discordance (e.g., right temporal lobe epilepsy with a deeper pathology hypothalamic hamartoma), or when there are multiple pathologies (e.g., polymicrogyria, periventricular nodular heterotopia), SEEG could be helpful to identify or confirm the true pathology that is responsible for the epileptogenesis [15]. At the moment, there is no head-to-head series to compare the seizure control rate between SEEG and SDE. According to the review by Katz JS *et al.*, there is no definite superiority of SEEG vs. SDE (Engel class I rate 56–68% vs. 30–70%) with reference to different case series [16].

There are three ways to implant SEEG, namely frameless, frame-based and robotic-assisted stereotactic navigation. Frameless navigation system makes use of guidance by neuroimaging with surface matching registration. Frame-based approach involves the application of stereotactic frame to patient's head. Fusion of post-frame CT scan with the initial planning MRI will provide the coordinates with reference to the stereotactic frame to navigate the intended trajectory. Robotic-assisted stereotactic navigation also involves registration but it differs by having robot to bring neurosurgeons to the intended trajectory, which could speed up the procedure when there are multiple electrodes to be inserted, as in the case of SEEG. In the meta-analysis performed by Vejay N. Vakharia *et al.* in 2017, the mean error of the entry point and target point was 2.45 and 2.89 mm for frameless approach, 1.43 and 1.93 mm for frame-based approach, and 1.17 and 1.71 mm for robotic-assisted approach [17]. Despite the apparently smaller mean error in frame-based and robotic-assisted approaches, there was high heterogeneity among studies and the parameters used were different (Euclidean distance vs. lateral deviation). This precluded meaningful comparison of the different approaches.

2.4 SEEG planning

The flow of the SEEG planning and implantation procedures is as follows. At the combined epilepsy meeting, the findings of the presurgical workup are presented and the plan for SEEG is confirmed in selected cases with discordant findings. Multidisciplinary discussion to generate the anatomical-clinical-electrophysiological hypothesis would be essential. Implantation of electrodes would depend on the best hypothesis generated and important alternative hypothesis to be rejected. A 2D grid coordinate system (aka Talairach Stereotactic System) might be helpful for communication among the team (**Figure 2**). Fine-cut MRI brain with contrast would be

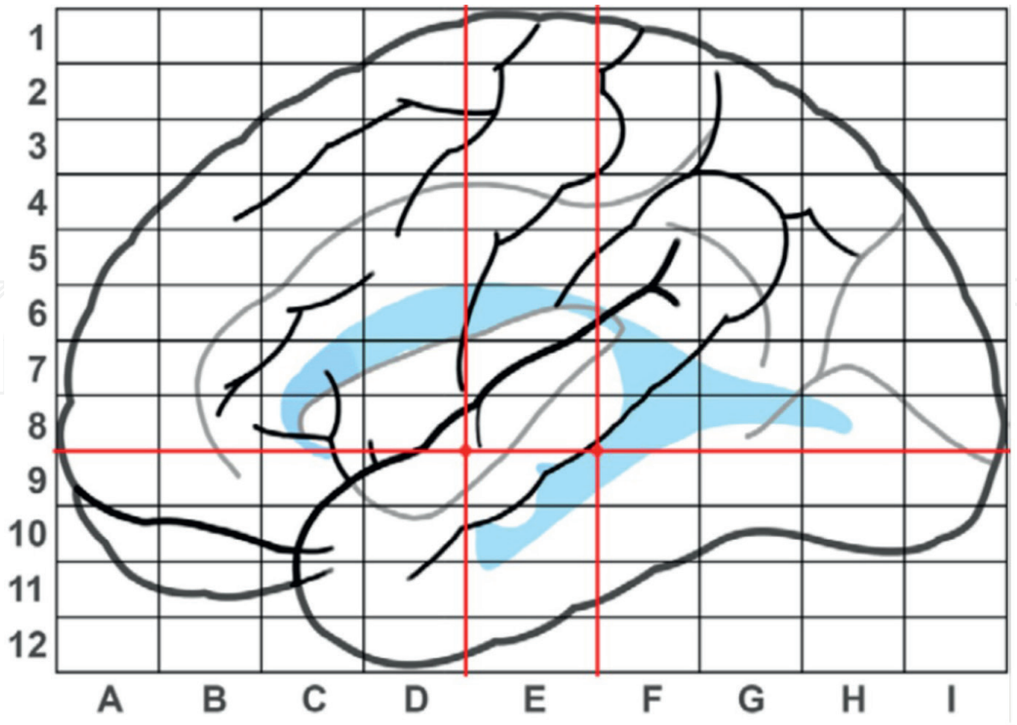

Figure 2.
Talairach stereotactic system.

used for stereotactic navigation and trajectory planning. A CT cerebral angiogram would be useful to appreciate the bony architecture as well as the cortical and Sylvian vessels. MRI with cerebral angiogram (MRA) fusing with a plain CT brain is also an alternative to reduce contrast use.

In the planning software, we could put the trajectories in an orthogonal manner i.e., perpendicular to mid-sagittal plane of the brain. It is similar to the Talairach approach, yet the latter made use of 2D angiography (digital subtraction angiography). The patient would be positioned laterally during the implantation procedure. Orthogonal approach has the advantage of easier interpretation of the spread of the epileptiform discharges as the 3D system could be more regular in shape if all the electrodes are parallel to each other. However, the more peripheral the SEEG electrodes are, there could be greater deviation as the electrode direction is not perpendicular to the skull and the brain surface which could lead to deviation towards the periphery. Therefore, the region of interest of the procedure must be determined and marked during the planning and the setup of the navigation system. Of course, the region of interest is often the proposed EZ. On the other hand, orthogonal insertion to insula could be difficult. Insula is often the important alternative to exclude in both frontal and temporal epilepsy. Anatomically it is covered by frontal, temporal, and parietal operculum with Sylvian fissure and middle cerebral artery (MCA) branches on the surface. Therefore, the orthogonal insertion to insula region needs great care not to pass through important vasculature. However, it allows the simultaneous assessment of both operculum and the insula on the same electrode. The other way to implant the SEEG would be a 3D approach, adjusting to the skull shape at the entry site (**Figures 3** and **4**) and to avoid MCA branches in Sylvian fissure in case the insula is one of the targets (**Figure 5**). Yet, as the electrodes are not parallel to each other, interpretation could be more difficult.

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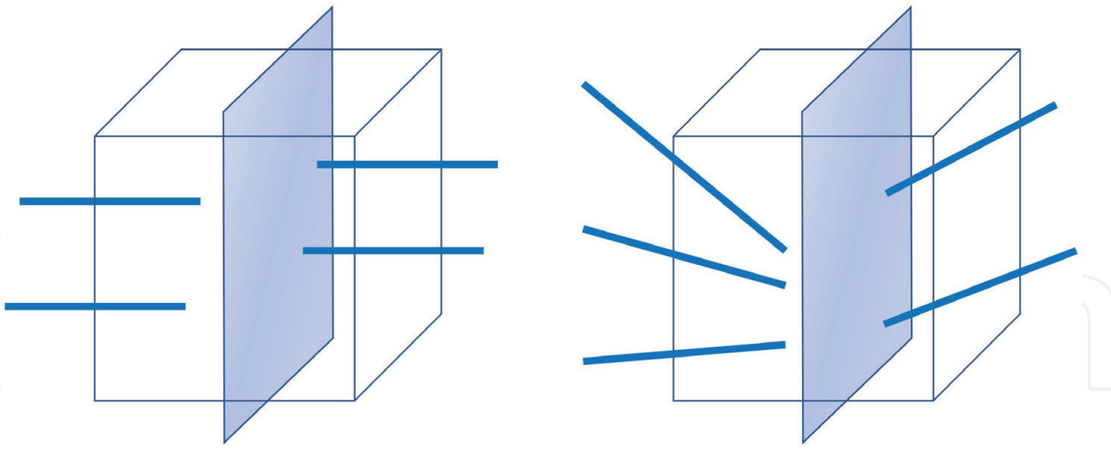

Figure 3.
Comparison of orthogonal (left) with 3D (right) approach.

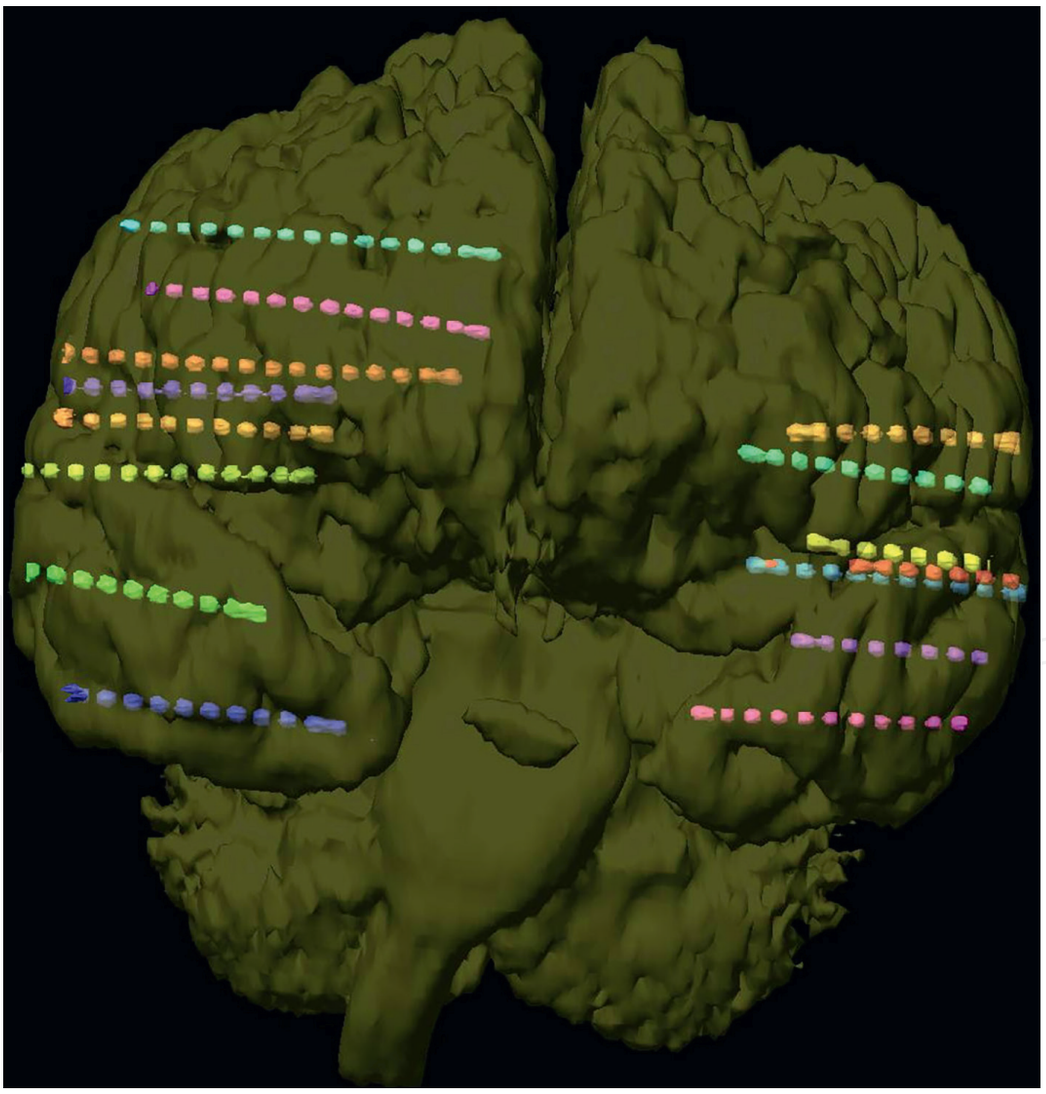

Figure 4.
3D reconstruction from real case MRI to illustrate the orthogonal approach of SEEG placement. (Left: anterior-posterior, right: lateral-oblique) This is a case of right temporal non-lesional epilepsy with bilateral temporal EEG onset and MEG dipoles with semiology of cephalic aura, bilateral hearing loss followed by left side twitching.

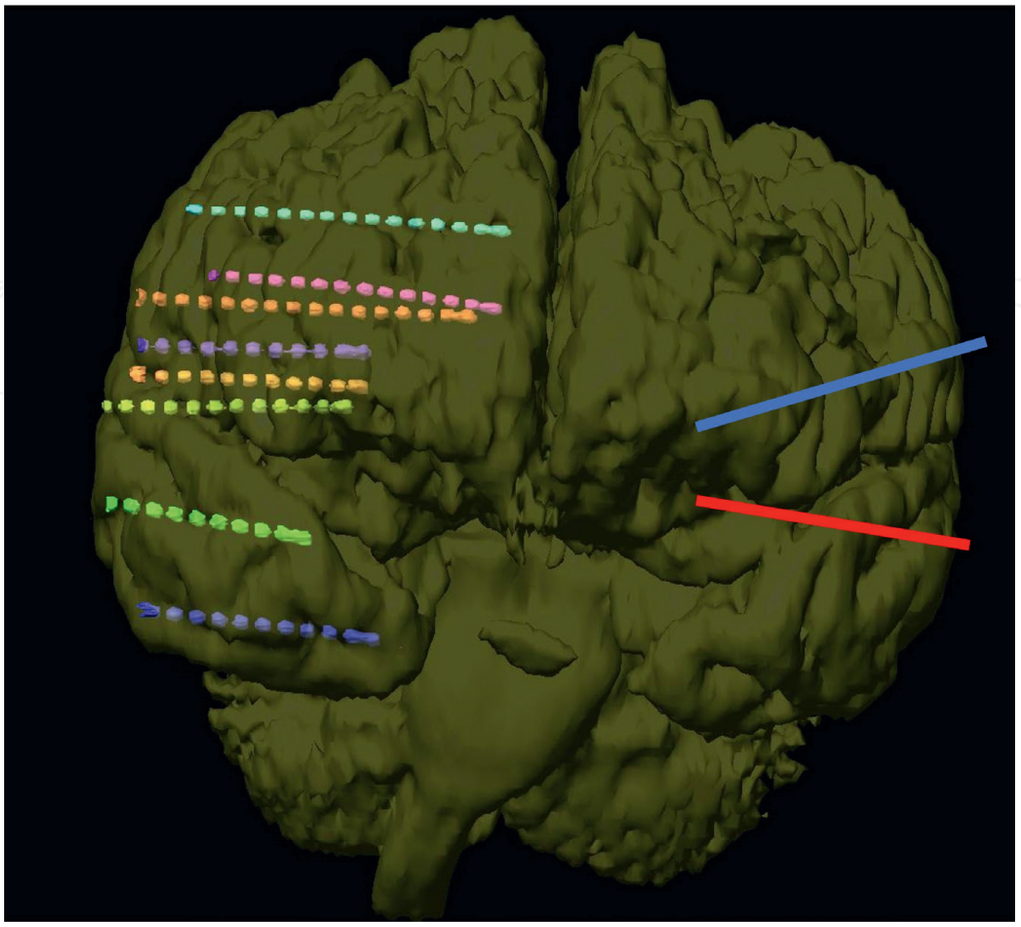

Figure 5.
This is an anterior-posterior view of the 3D-reconstructed brain parenchyma. Blue line represents the 3D approach which avoids the Sylvian fissure while the red line represents the orthogonal approach which punctures through the Sylvian fissure.

The planning strategy in different epilepsy would be discussed in later part. During the planning, entry sites and target sites must be determined. Then the length from dura to target should be measured. Many of the planning software could customize the lead contact size and intervals. With reference to the insert of the electrodes, one could decide the length of different electrodes to be used. After planning the trajectories in the planning software, either frameless stereotactic navigation system or robotic-assisted system could be used directly. Frame-based approach would require a post-frame CT.

2.5 SEEG implantation

Patient is then put under general anesthesia and intubation. Head is secured by clamp and navigation system is set. Skin is prepared and draped. Adjustment of the guiding system is performed (**Figure 6**). The length inserted would be calculated with reference to the different parts of the system (**Figure 7**). Skin-dura distance is measured in navigation system (**Figure 8**). Stopper-skin distance is measured intraoperatively. Adding the two up we would have the length of drill needed to puncture the skull. Stab wound is made on the scalp. Drill with length marked by stopper is brought in. Skull is drilled (**Figure 9**). Sometimes 1–2 mm more might be needed to puncture the inner table. A sense of give-way under careful control is often the sign

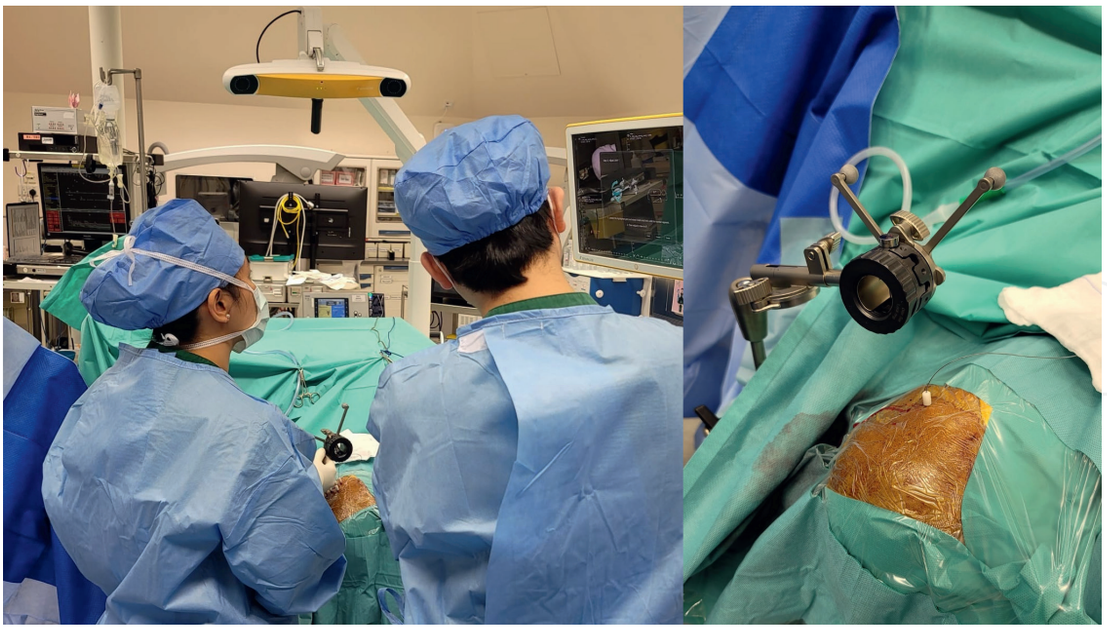

Figure 6.
Guiding system is adjusted by frameless stereotactic navigation.

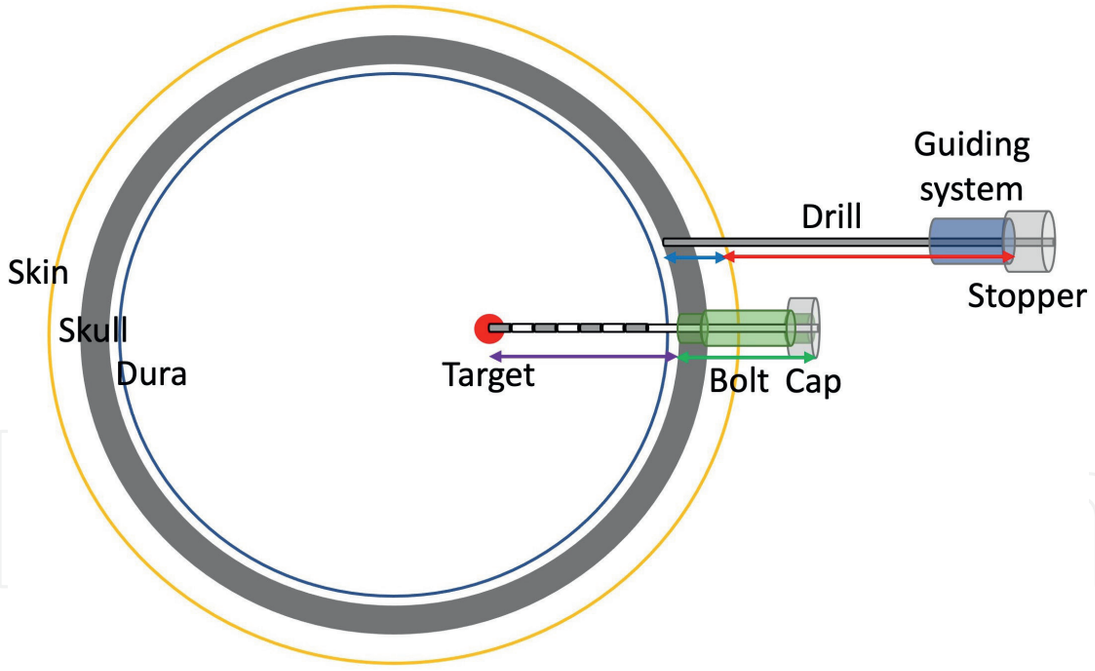

Figure 7.
Blue arrows = skin-dura distance. Red arrows = stopper to skin distance. Blue + red = length of drill to puncture the skull. Purple arrows = dura-target distance. Green arrows = bolt-dura distance. Purple + green = length of electrode.

of complete puncture. Dura and pia are cauterized and punctured by monopolar (**Figure 10**). The bolt is anchored to the skull. Length of electrode is needed is the sum of dura-target distance and the bolt-dura distance (i.e., from bolt to target). The electrode with length marked by the cap is inserted with the cap screwed to the bolt (**Figure 11**). Opposition of the scalp wounds might be needed to prevent CSF leak. The whole procedure is repeated in different electrodes. In case of bilateral

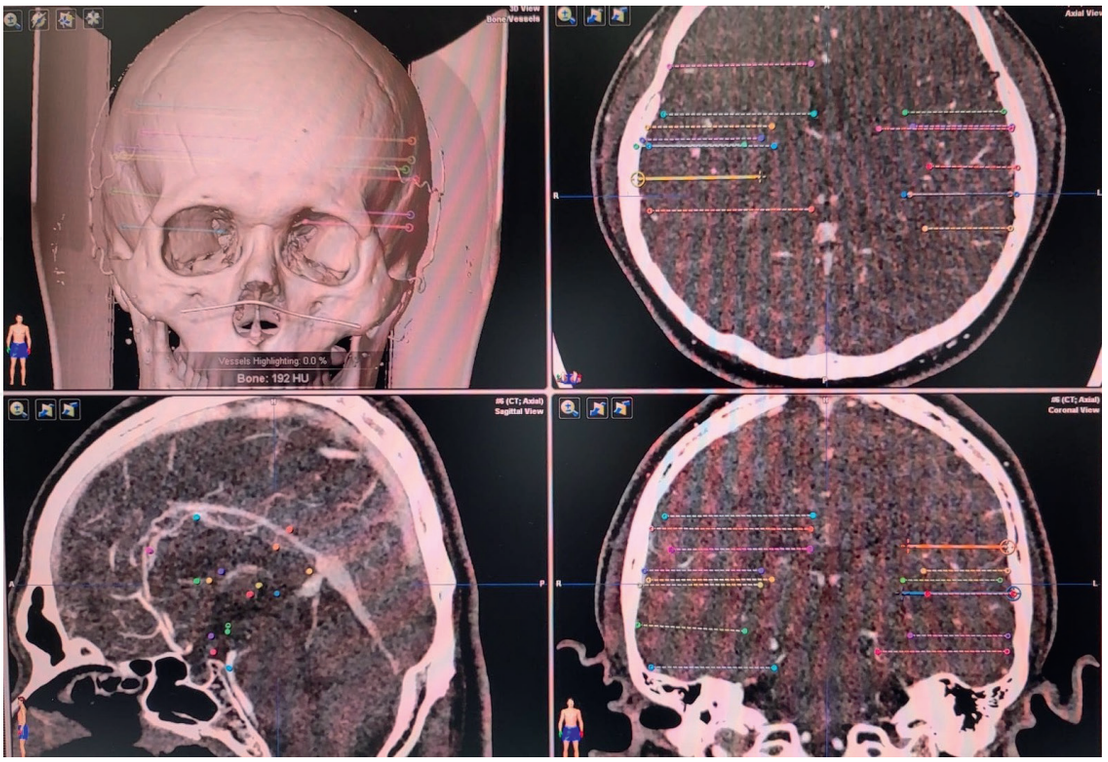

Figure 8.
Electrodes are planned in orthogonal manner. Skin-dura distance could be measured.

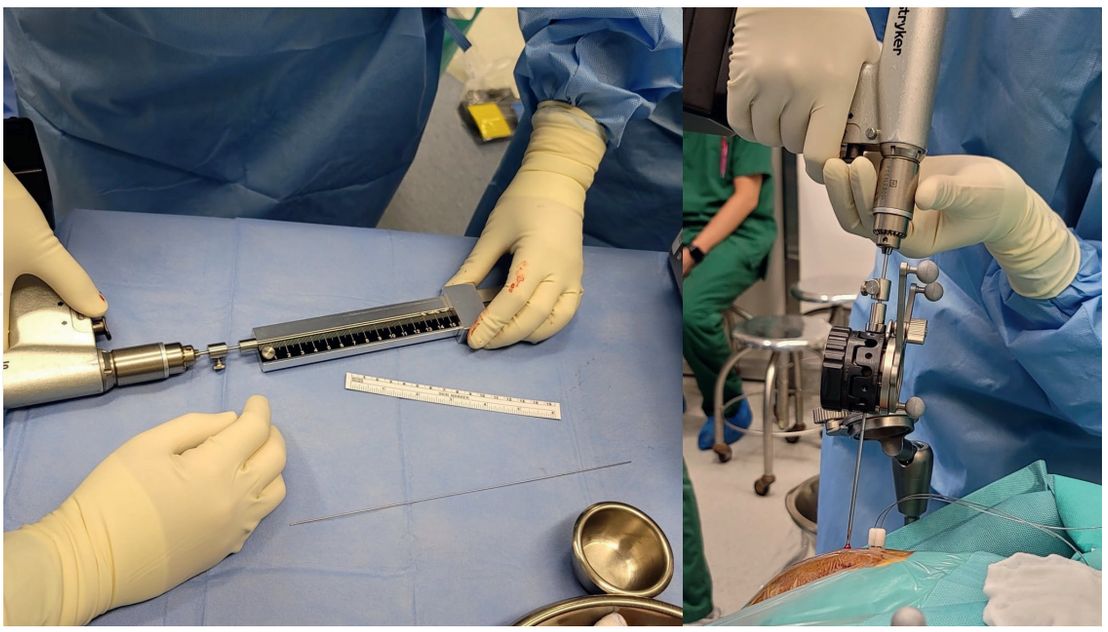

Figure 9.
Stopper-dura distance is set. Bone drilling.

implantation, the patient would be repositioned in the contralateral side, in lateral position, with navigation system set again. It should be reminded that the EEG signals recorded intraoperatively might be affected by the general anesthesia. Patient would be transferred back to the ward for monitoring of the SEEG signals (**Figure 12**). In author's center, we put patients on empirical antibiotics when the patient is under the

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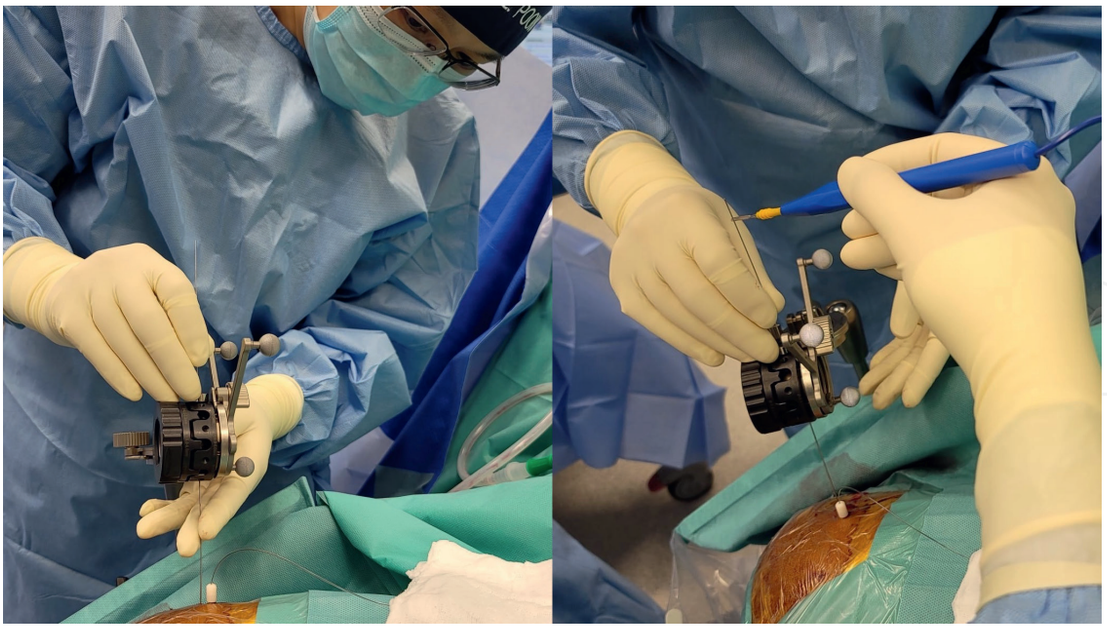

Figure 10.
Dura cauterization and puncture.

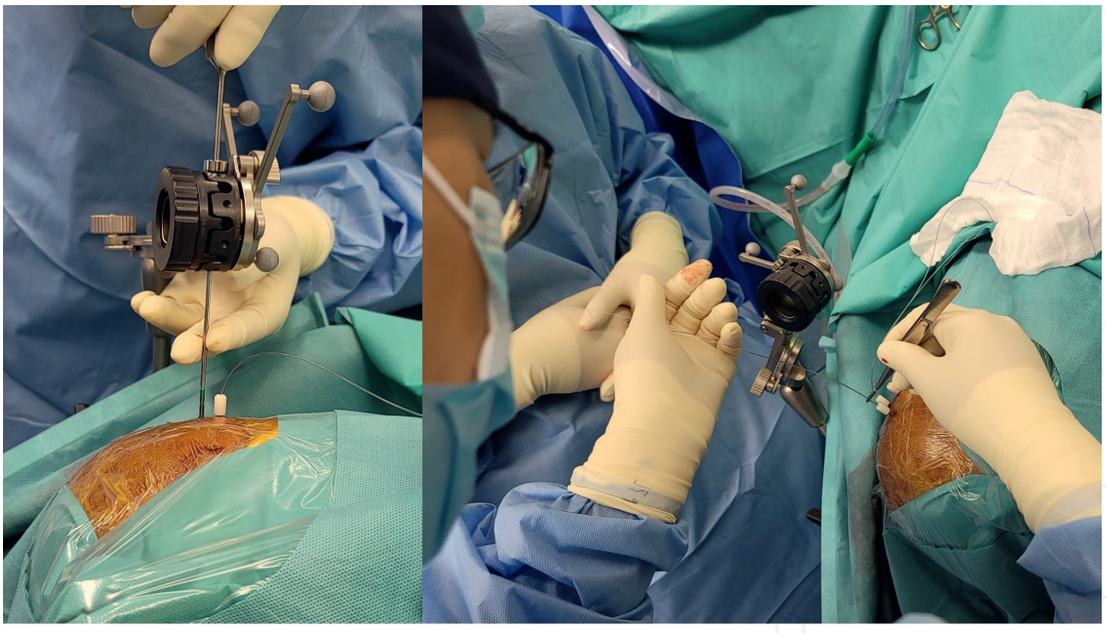

Figure 11.
Bolt anchoring and electrode insertion.

SEEG monitoring. Antiepileptics would be withheld according to the patient's semiology and seizure frequency. CSF leak is what one should carefully watch out for.

2.6 SEEG signal recording and stimulation

Post-operative CT scan would be fused to the preoperative MRI. First, we assess the accuracy of electrodes placement. Second, the electrodes are segmented, and the anatomical position of different contacts are marked. SEEG signals would be recorded by 4–5 days. By then stimulation might be performed. On one hand seizure events

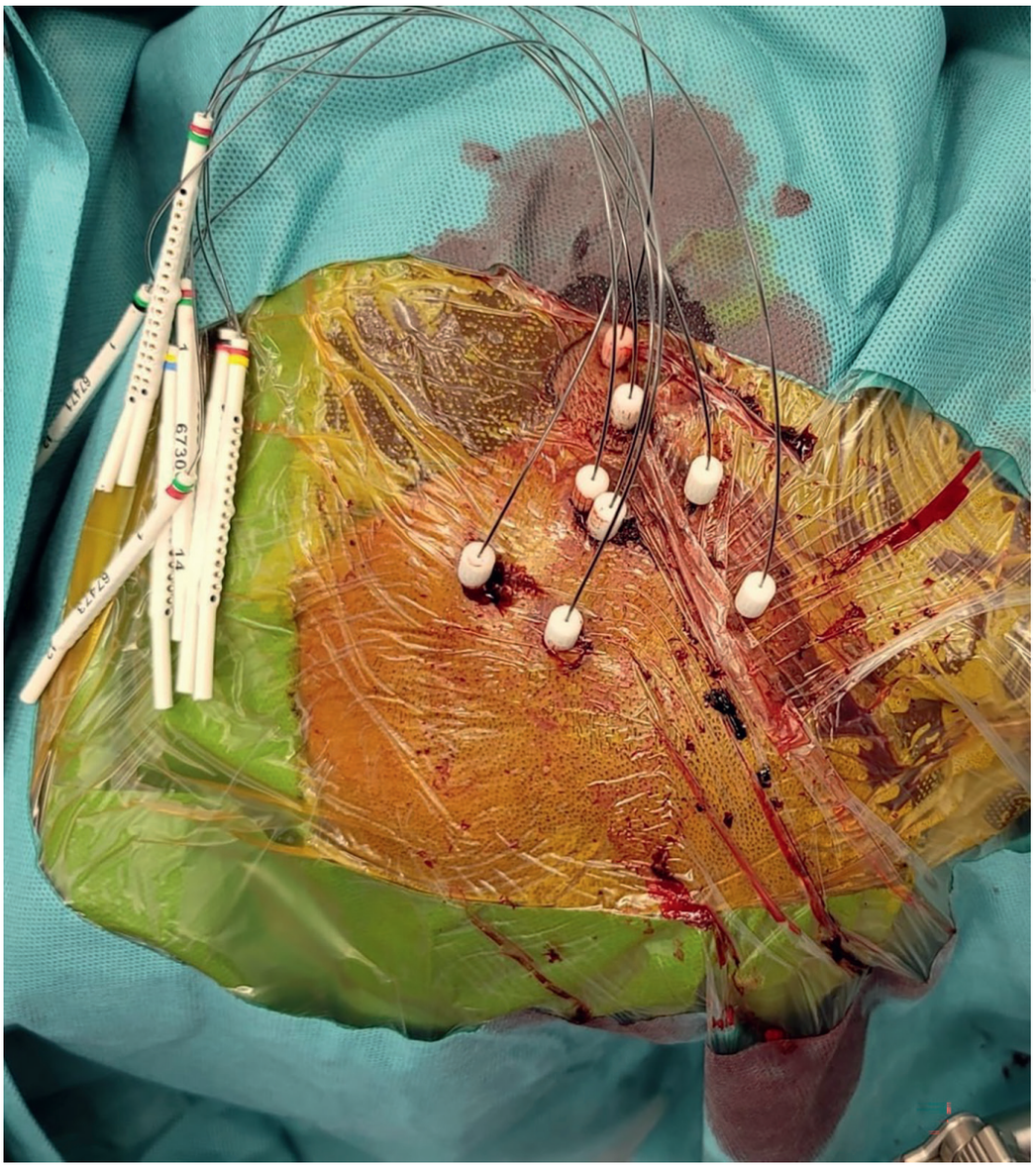

Figure 12.
Electrodes are ready for connection to EEG montage. Betadine-soaked dressing is applied.

could be triggered to give clinicians a hint on the location of the ictal onset zone. Yet, the events might be unhabitual. On the other hand, some eloquent areas might be located by the stimulation. Concerning the stimulation technique, low frequency stimulation (1 Hz frequency, 0.5-4 mA pulse intensity, 0.5-3 ms pulse width, 20–60s duration) is suitable for areas of low after-discharge threshold such as primary auditory cortex, primary motor cortex, hippocampus, and areas with focal cortical dysplasia. High frequency stimulation (50 Hz, 0.5-5 mA, 0.5-1 ms, 3–8 s) would be suitable to areas elsewhere [18]. Stimulation might be helpful for clinicians to understand the epileptic network better (**Figure 13**).

2.7 Removal of leads and resection epilepsy surgery

Once the anatomical-clinical-electrophysiological hypothesis is made after the discussion in the multidisciplinary team, one could proceed to removal of the SEEG

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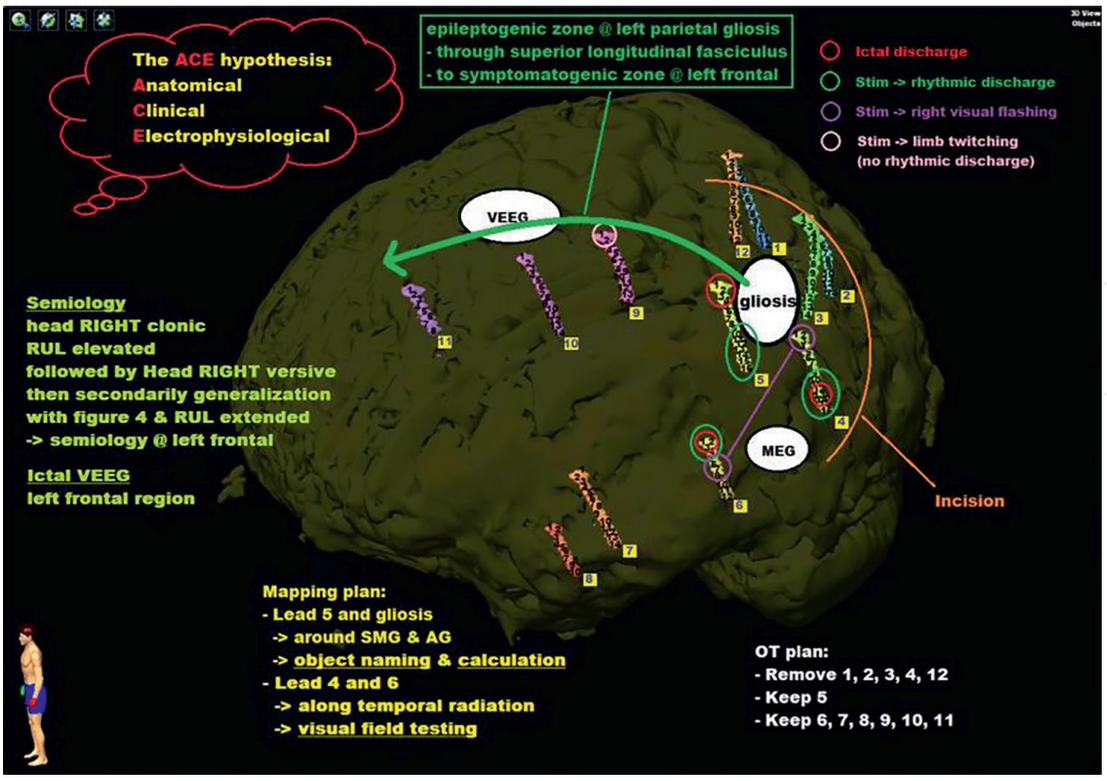

Figure 13.
This diagram illustrates a case with epileptogenic zone confirmed with direct electrical stimulation. The epileptogenic lesion was the gliosis with T2 hyperintensity in MRI in the temporoparietal junction. Yet, the patient's semiology was often a frontal one. SEEG electrodes were implanted around the gliosis and the dipoles found in MEG. They were also implanted across the superior longitudinal fasciculus. Stimulation triggers rhythmic discharge in the superficial contacts around the gliosis and thus identifies the ictal onset zone. Visual pathway was also identified in the deeper contacts of one adjacent electrode.

leads and excision of the EZ. Usually, the leads inserted to the proposed EZ would be removed first to provide the surgical exposure. The remaining leads could be left to detect any interictal signals. If they are present, they could serve as a guide to successful disconnection of the EZ once they disappeared. However, one should not compromise the surgical exposure which is critical to adequate excision of the EZ and careful hemostasis. Awake craniotomy might be needed for assessment of the eloquent areas with direct electrical stimulation to avoid neurological deficits after the operation. Awake craniotomy might even need a larger exposure for adequate assessment. Details of awake craniotomy would be out of the scope of this chapter. As the leads have been implanted for 1–2 weeks before the concluding procedure, risk of infection could be higher than usual craniotomy cases. Therefore, intra-operative wound irrigation and post-operative antibiotics might also be helpful.

2.8 Implantation strategy

SEEG electrodes should be implanted according to the anatomical-clinical-electrophysiological hypothesis [19]. It is also important to place electrodes, apart from the proposed EZ, the symptomatogenic and functional deficit zones.

Temporal lobe epilepsy (TLE), as mentioned, with mesial temporal sclerosis and concordant presurgical workup, could have resection surgery proceeded right away. However, the following four situations might warrant SEEG implantation.

1. Presurgical workup is discordant (e.g. a left TLE semiology with right mesial temporal sclerosis)

2. TLE is bilateral.

3. TLE with extratemporal epileptic generator e.g.

    a. Orbitofrontal structures (spread via uncinate fasciculus)

    b. Posterior cortices i.e. parietal and occipital (spread via inferior frontal-occipital fasciculus or inferior longitudinal fasciculus)

4. TLE-plus with early involving of neighboring structures

    a. Orbitofrontal structures

    b. Insular cortex, frontal operculum

    c. Temporo-parieto-occipital junction

From these one could appreciate in TLE, orbitofrontal structures and insula are two very important structures to have the electrodes stationed. Understanding the connectome with the white matter tracts is also essential as it is often how epileptiform discharges spread. (**Figure 14**).

For frontal lobe epilepsy, the epileptiform discharges often spread quickly within the frontal lobe, and it has high connectivity with the extra-frontal structures and the contralateral frontal lobe. SEEG is mainly to compartmentalize the seizure pattern. The frontal operculum could be divided into the pars orbitalis, pars triangularis and opercularis. Orthogonal insertion of the SEEG electrode into the pars orbitalis could provide assessment of the orbitofrontal structures. On the other hand, mesial frontal structures are often underrepresented in scalp EEG. Orthogonal insertion of the SEEG electrodes via middle frontal gyrus often provide assessment of that with the deeper contacts. Therefore, if frontal lobe is of concern and mesial frontal structures must be assessed, a longer electrode might have to be used.

Posterior quadrant epilepsy is a less frequently encountered type. It involves parietal and occipital lobes. Clinical polymorphism is present due to high density of brain connections to the insula and temporal as well as contralateral posterior quadrant. It is often some challenging cases and multi-lobar and bilateral electrodes might have to be used to assess the propagation pathways and assessment of the functional areas such as Wernicke's area, reading, calculation, vision, and face recognition. Tractography study such as diffusion tensor imaging (DTI) might be helpful to look for the ventral and dorsal white matter tracts through the occipital lobe. SEEG electrodes could be implanted according to the white matter tracts and see if the epileptiform discharge propagates from one to another electrode via the pathway.

Insular epilepsy has the semiology mimicking frontal and temporal lobe epilepsy. As mentioned, it is often an important alterative to exclude. Again, it is underrepresented in scalp electrodes. Difficulty to plan trajectories of the SEEG electrodes is often encountered due to the vascular constraints, especially with the orthogonal approach. The comparison of orthogonal and 3D approaches is discussed in previous part.

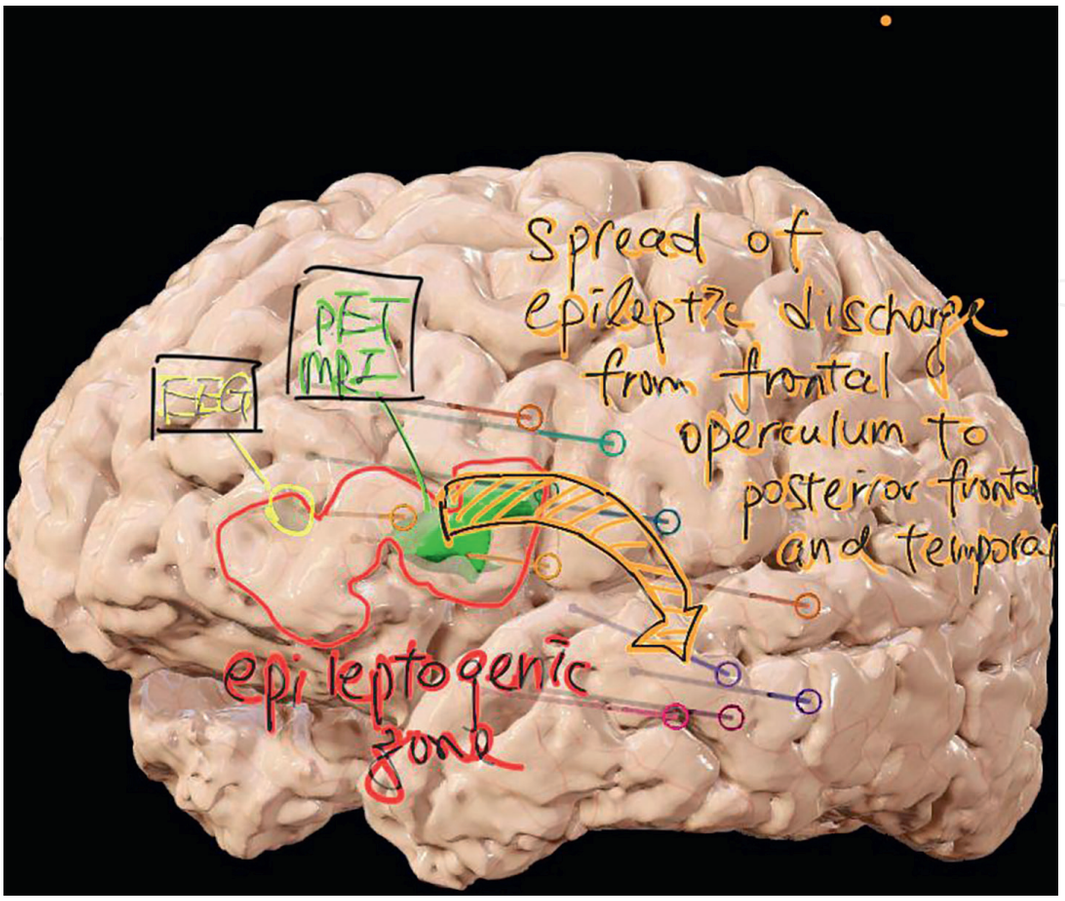

Figure 14.
An illustration of a case of temporal lobe epilepsy semiology with hand and oral automatism followed by post-ictal drowsiness yet EZ concluded to be in the orbitofrontal structures with spread to temporal lobe via pathways such as uncinate fasciculus or arcuate fasciculus. SEEG concluded the ictal onset zone (yellow) while the PET-MRI confirmed the functional deficit zone (green). Electrodes were also inserted in an orthogonal approach to the insula as it is an important alternative hypothesis to exclude.

3. Therapeutic use

3.1 Radiofrequency ablation (RFA)

Stereotactic lesioning has long been a surgical treatment to focal epilepsy. Examples include laser interstitial thermal therapy (LITT) and SEEG-coupled RFA. Lesioning technique is more suitable for lesional epilepsy as the lesion could be identified and approached by the SEEG electrode, whereas in non-lesional epilepsy, the electrodes are often placed according to the epileptogenic network. It could be helpful in cases when open surgery is relatively contraindicated. For example, in temporal lobe epilepsy in dominant hemisphere, stereotactic lesioning might be able to treat the mesial temporal structure where a dominant hippocampectomy is contraindicated. On the other hand, deeply located pathology such as hypothalamic hamartoma and periventricular nodular heterotopia could be treated by stereotaxic lesioning instead of making large corticotomy or passing through important structures such as basal ganglia. More importantly, stereotactic lesioning is *not* a contraindication to subsequent surgery i.e., resection or neuromodulation. SEEG-guided RFA is done by applying radiofrequency thermocoagulation between two contiguous electrode contacts to

make a precise lesion. SEEG signals would be recorded and the likely ictal onset zone together with the MRI-found epileptogenic lesion would be concluded to be the EZ. Direct electric stimulation as previously discussed could also give us the guidance of where the EZ is and if any eloquent areas are nearby. When the target of lesioning is decided, power would be applied with patient being awake until impedance increases i.e., when the coagulum is formed. The duration would usually be less than 1 minute. Sometimes, patient could even hear the crackling sound when the coagulum is made. In an in vitro study by Staudt MD, *et al.* in Operative Neurosurgery found that smaller power, longer duration, closer distance, bipolar thermocoagulation form a larger lesion [20].

3.2 Outcomes

In the systematic review of Pierre B, *et al.* in Epilepsia in 2018, six retrospective studies and 296 patients were included. Permanent neurological deficit was charted in 2.5% patients. Seizure-free outcome was achieved in average 23% while seizure response rate was up to 58% [21]. Greatest efficacy was observed in periventricular nodular heterotopia while lowest in non-lesional cases. Studies showed high heterogeneity concerning case selection and, therefore factors for good outcome are still unknown.

In the cohort study done by Alexis Moles, *et al.* in 2018, patients with temporal epilepsy with SEEG done was selected to the group of anterior temporal lobectomy and RFA as what procedure the patient had undergone. Three-quarters of patients in lobectomy group achieve seizure freedom in contrast to 0% in the RFA group [22]. Yet around half of the patients in the RFA were responder with no memory impairment recorded. In the cohort, SEEG-RFA is the first choice of treatment after SEEG implantation in the patients who were enrolled later after this treatment policy is employed. They would perform anterior temporal lobectomy if there is failure of the RFA and this would regard as treatment failure. So, the difference in the treatment outcome is not due to the different characteristics, but the treatment per se. Therefore, SEEG-RFA for temporal epilepsy could never achieve the same outcome as the well-established anterior temporal lobectomy and amygdalohippocampectomy but could offer some improvement in seizure control in the patients where lobectomy is contraindicated e.g., temporal lobe epilepsy in dominant hemisphere, apart from directly subjecting patients to neuromodulation. The target of this treatment is the ictal onset zone identified in the SEEG recordings instead of dealing with the entire EZ.

4. Brain-computer interface

Brain-computer interface (BCI) is a rapidly developing field in neuroscience. One area would the neuroprosthesis which receives electrical signals from the brain and perform tasks that patients with neurological deficits are not able do e.g., speech and movement. The hardware to receive the electrical signals include scalp EEG, ECoG and, of course, SEEG. Motor imagery, P300 and steady-state visual evoked potential (SSVEP) are some of the types of BCI [23]. Motor neuroprosthesis is the one that is better developed but recently the study by Moses DA, *et al.* showed the possibility of decoding the brain speech areas and produce speech for patient who was anarthric for a long time [24].

Currently scalp EEG and ECoG are the mainstay. However, like presurgical workup in epilepsy, SEEG provides a network analysis not only including the superficial structures but also the deep structures. It also provides a spatial and temporal appreciation of the electrical signals. Most importantly, it has a lower hemorrhagic or infective complication rates as compared with craniotomy. It probably leads to fewer gliosis as compared with subdural grid and provides better longevity. When the technology improves, the diameter of the electrodes as well as the intervals between electrodes become smaller [25]. The in vivo implantation could likely be successful as what functional neurosurgeons had been doing in deep brain stimulation.

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