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CRITICAL REVIEW

Depth versus surface: A critical review of subdural and depth electrodes in intracranial electroencephalographic studies

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Abstract

Intracranial electroencephalographic (IEEG) recording, using subdural electrodes (SDEs) and stereoelectroencephalography (SEEG), plays a pivotal role in localizing the epileptogenic zone (EZ). SDEs, employed for superficial cortical seizure foci localization, provide information on two-dimensional seizure onset and propagation. In contrast, SEEG, with its three-dimensional sampling, allows exploration of deep brain structures, sulcal folds, and bihemispheric networks. SEEG offers the advantages of fewer complications, better tolerability, and coverage of sulci. Although both modalities allow electrical stimulation, SDE mapping can tessellate cortical gyri, providing the opportunity for a tailored resection. With SEEG, both superficial gyri and deep sulci can be stimulated, and there is a lower risk of afterdischarges and stimulation-induced seizures. Most systematic reviews and meta-analyses have addressed the comparative effectiveness of SDEs and SEEG in localizing the EZ and achieving seizure freedom, although discrepancies persist in the literature. The combination of SDEs and SEEG could potentially overcome the limitations inherent to each technique individually, better delineating seizure foci. This review describes the strengths and limitations of SDE and SEEG recordings, highlighting their unique indications in seizure localization, as evidenced by recent publications. Addressing controversies in the perceived usefulness of the two techniques offers insights that can aid in selecting the most suitable IEEG in clinical practice.

KEYWORDS

epilepsy surgery, epileptogenic zone, intracranial EEG, SEEG, subdural electrodes

1 | INTRODUCTION

The success of epilepsy surgery requires the resection of the epileptogenic zone (EZ), and the goal of the presurgical evaluation is to identify regions of the brain that could contribute to the EZ. Although concordant localization from semiology, imaging findings, and scalp electroencephalographic (EEG) recordings may be enough to direct surgery, intracranial EEG recording (IEEG) is the gold standard for delineating the epileptogenic focus when noninvasive presurgical data are inconclusive or disconcordant.[1,2] Subdural electrodes (SDEs) and depth electrodes (DEs) are the main sensors used in IEEG. SDEs provide two-dimensional sampling of the neocortical surface with the ability to track seizure propagation in that plane.[3,4] By contrast, stereoelectroencephalography (SEEG) using DEs allows for three-dimensional sampling from both superficial and deep structures, including white matter tracts that might be involved in seizure propagation and crossing multiple lobes. Historically, SDEs have been primarily used in North America, whereas SEEG has been predominantly used in Europe, particularly in France and Italy.[5,6]

It is important to note that the term "epileptogenic zone" has been defined differently by different groups. Lüders et al. defined the EZ as the "minimal area of cortex that must be resected to produce seizure-freedom."[7,8] It is a theoretical construct, and its inclusion in the resection volume can only be inferred from seizure freedom after surgery. Although IEEG can identify the seizure onset zone (SOZ), there is no guarantee that identifying the SOZ localizes the EZ. Conversely, Talairach and Bancaud defined the EZ as "the site of the beginning of the epileptic seizures and of their primary organization."[9,10] With this definition, the EZ can potentially be identified using intracranial recording. Despite the different definitions, the two concepts are not fundamentally different. The deduction of the putative EZ relies on the careful interpretation of the presurgical evaluation data. In cases where noninvasive presurgical evaluation is inconclusive, a well-planned IEEG can often pinpoint seizure onset, identify early propagation pathways, and be used to assess the relationship between the SOZ and eloquent cortex.[11] Overall, approximately 25%–50% of patients with intractable focal onset epilepsy who undergo noninvasive presurgical evaluation require IEEG to define the SOZ and guide surgery.

Over the past decade, SEEG has been gaining popularity worldwide due to advances in stereotactic techniques and neurosurgical robots and a shift from large resections to minimally invasive epilepsy surgery.[12] These two techniques possess distinct advantages and limitations, complementing each other in both their indications and applications. There is evidence showing the combination of SDEs and SEEG can be safely undertaken to mitigate the drawbacks of each technique. Comprehensive understanding of their diverse indications, advantages, and ultimate surgical outcomes is still evolving. This review aims to critically assess the emerging evidence regarding their relative risks and benefits, technical considerations, safety, efficacy in localizing EZ, and application in functional mapping. Our goal is to provide practical insights that can assist clinicians in selecting the most suitable IEEG in clinical practice.

Key points

- SEEG is associated with fewer complications and higher patient tolerance.
- SDEs are the preferred option when the suspected EZ is located in the cortical surface, such as perirolandic and interhemispheric areas, requiring intricate functional mapping.
- SEEG has clear advantages in studying an EZ that is deep or involves multiple lobes or both hemispheres.
- SDEs and SEEG offer unique strengths and applications in intracranial EEG recording.

2 | TECHNICAL CONSIDERATIONS AND INDICATIONS FOR SUBDURAL AND DEPTH ELECTRODES

SDEs are embedded in a flexible silastic membrane and placed directly on the brain surface (Figure 1). They are commonly used to identify epileptogenic foci on the cortical convexity, such as lateral frontoparietal and frontotemporal regions, basal cortex, and interhemispheric cortex.[13,14] Subdural grids, with up to 140 contacts, offer extensive sampling from the gyral neocortex, aiding in delineating the EZ and guiding tailored surgical resection. The consecutive arrangement of contacts makes them suitable for electrical stimulation mapping of sensory, motor, and language cortex.[3] However, the placement of SDEs is not always precise, and their position can shift during recording or closing and reopening of the craniotomy if they are not properly secured to the dura.[15] In cases requiring large grids, two separate craniotomies are necessary for implantation and removal, although resection and electrode removal can occur in the same surgery when appropriate. Subdural strips, inserted through burr holes, cover areas such as the curvature of the anterior temporal lobe and basal temporal lobe, but the sampled area is not directly visualized, and the location of the subdural strips may be even less precise.[16] Despite their

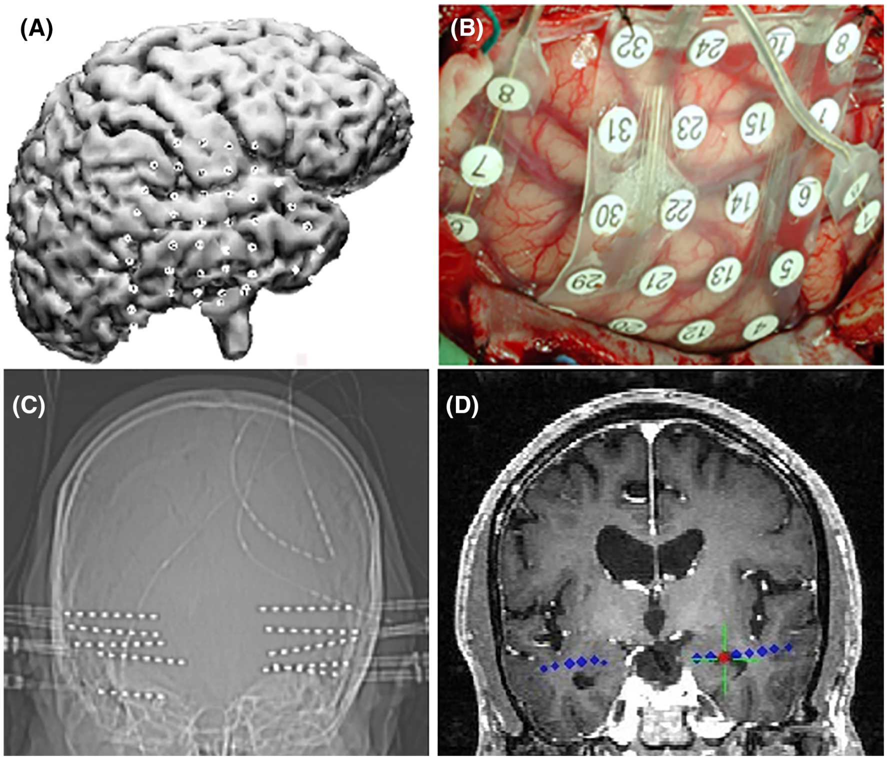

FIGURE 1 Illustration of subdural and depth electrodes. (A) Three-dimensional view of subdural electrodes coregistered with presurgical magnetic resonance imaging (MRI) and postimplantation computed tomography (CT) in a patient with temporal lobe epilepsy. (B) Intraoperative view of implanted subdural electrodes. (C) Postimplantation CT in a patient with bitemporal lobe epilepsy. (D) Precise location of depth electrodes coregistered with MRI and postimplantation CT.

advantages, SDEs are not commonly used to record or map the function of the sulcal cortex, cannot record from deeper brain structures, and are typically not well suited for bihemispheric implantation.[17]

Although all intracranial EEG methodologies are based on anatomo-electro-clinical correlation to some extent, SEEG uniquely offers the capability to study this correlation from both surface and subcortical structures simultaneously, aiming to better reveal the three-dimensional spatiotemporal organization of local field potentials within the brain.[18] DEs are commonly placed using a stereotactic frame, frameless neuronavigation, or a stereotactic robot through small twist drills or burr holes. After recording, they can be removed under local anesthesia at the bedside.[18] SEEG is particularly valuable for identifying deep epileptogenic foci, such as sulcal cortex, mesial temporal lobe, insula, cingulate, and hypothalamic lesions. SEEG are also especially beneficial in cases involving multiple noncontinuous lobes or bihemispheric epilepsy, for example, bitemporal epilepsy, seizures related to bihemispheric tuberous sclerosis complex, and bilateral periventricular heterotopias. When combined with minimally invasive epilepsy surgery techniques like magnetic resonance imaging (MRI)-guided laser interstitial thermal therapy, SEEG allows for epilepsy surgery without a craniotomy, reducing associated risks, discomfort, cosmetic concerns, and complications. DEs are also valuable for studying the role of the thalamus in seizure genesis or as an early propagation site, allowing thalamic recording and open or closed loop stimulation.[19] Therefore, it is uniquely positioned to identify distributed epileptic networks, which is essential for the use of thalamus-targeted neuromodulation. SEEG is also preferred when patients have previously undergone implantation of subdural grids or had previous epilepsy surgery and arachnoid adhesions are present.[20]

Studies have suggested that the average recording volumes per contact are similar for SEEG and SDEs, but SEEG may facilitate larger overall recording volumes due to the routine implantation of more electrodes.[21] Nevertheless, concerns have been raised regarding the relatively sparse sampling of the gyral surface with DEs compared to SDEs, which can restrict the precise identification of the boundaries of an SOZ in neocortical regions.[2] Additionally, interpreting SEEG mapping results can be challenging due to the stimulation of both gray and white matter tracts during functional mapping. Finally, in general, DEs are not implanted in children younger than 2 years due to the thinness of their skulls, which prevents the anchoring of bolts.[22] However, some centers have safely performed SEEG in children younger than 2 years.[23,24] It is important to emphasize that the success of epilepsy surgery relies not only on the technique of SEEG implantation, but also on the implantation planning. Effective implantation strategies, based on the anatomo-electro-clinical information, are fundamental in determining the implantation target and identifying the EZ. Example images of SDEs and SEEG are shown in Figure 1, and indications are summarized in Table 1.

A recent economic evaluation study involving adult patients has demonstrated that despite differences in

TABLE 1 Specific brain targets and suitable intracranial electrodes.

Targeted brain area	SDEs	SEEG
Frontal, parietal, temporal, occipital lobe convexity, near or in eloquent cortex	✓✓	✓
Mesial frontal, mesial temporal	✓	✓✓
Deep structures, such as cingulate, insular, thalamus, hypothalamus	X	✓
Bottom of sulcus	X	✓
Multilobes and bihemispheres	✓	✓✓

Abbreviations: SDE, subdural electrode; SEEG, Stereoelectroencephalography.

complication rates and effectiveness, SEEG and SDE monitoring have comparable cost-effectiveness. The most influential factors affecting their relative cost-effectiveness are the costs of SDEs and SEEG, rather than differences in complication rates or postresection seizure freedom rates.[25] In another study involving pediatric patients, total perioperative charges for invasive monitoring and resection were approximately 2% higher for SEEG patients, likely due to some SEEG patients undergoing two separate hospitalizations for SEEG evaluation and resective surgery compared to patients with SDEs. However, the difference was not statistically significant.[26]

3 | HYBRID USE OF SUBDURAL AND DEPTH ELECTRODES

The EZ can encompass multiple spatially distributed structures. Several studies have demonstrated that the combination of SDEs and SEEG can be complementary in their strengths, overcoming their individual limitations. This synergy between the two techniques can result in more precise localization of the SOZ and propagation patterns.[27–31] For example, Nagahama et al.[32] both implanted SDEs and conducted SEEG in 91 patients. Their findings revealed that the SOZ was identified through both modalities in 50% of the cases, solely by SDEs in 34% of patients, and solely by SEEG in 16%. Among the 79% of patients who underwent resective surgery, 65% achieved Engel I outcomes and 25% achieved Engel II outcomes with 4 years of postoperative follow-up. Clinically symptomatic complications occurred in 8.8% of patients, including hemorrhage in 3.3% of cases, infections in 3.3%, cerebral edema in 2.2%, and one patient with a permanent neurological deficit. No mortality was reported.[32] In a case series reported by Lee et al.,[33] 113 patients underwent combined SDE and SEEG monitoring, with a mean (±SD) of 125 ± 32 contacts placed and a mean monitoring duration of 7.3 ± 3.2 days. Hemorrhage occurred in 5.1% (seven patients) cases initially but decreased to 0% with experience and adoption of new surgical techniques in the last 4 years of the study. Of the seven patients who experienced hemorrhage, six had transient neurological deficits that had resolved by discharge. No infections or permanent deficits were reported. Seizures were successfully localized in 95% of cases. At 1 year, Engel I outcomes were observed in 64% cases with resection, 29% with responsive neurostimulator (RNS), and 60% with both interventions.[33] Despite successful cases, the hybrid approach presents technical challenges, primarily because DEs are difficult to anchor with 1-mm precision through a craniotomy and may result in unreliable electrode localization due to brain shift.

A potential promising alternative is the combination of SEEG and intraoperative electrocorticography (ECoG). In this approach, SEEG electrodes are implanted to validate hypotheses concerning the SOZ and propagation pathways, and intraoperative ECoG is used to delineate the boundaries of the cortical irritative zone and eloquent cortex without adding the risks associated with chronic SDE recording. It is known that generalized anesthesia could alter seizure activity; therefore, it may be advisable to have awake mapping if possible.

4 | SAFETY ASPECTS OF SUBDURAL AND DEPTH ELECTRODES

Complications associated with both SDEs and SEEG are overall infrequent. Rates of adverse effects associated with SDE implantation vary widely in literature, ranging from 1% to 23%.[4,14,34,35] In a systematic review and meta-analysis of 21 studies encompassing 2542 patients with an average of 52–95 of SDE contacts per patient and 5–17 days of monitoring,[36] the most common complications were cerebral spinal fluid leaks (12%), followed by infections (5.3%); intracranial hemorrhage (4.0%), which was mainly subdural, caused by tearing cortical bridging vein during electrodes insertion; and elevated intracranial pressure (2.4%). There were five deaths (.2%) directly related to subdural EEG studies due to refractory elevated intracranial pressure (ICP). Up to 3.5% of SDE patients required additional surgical procedures to manage these complications. Transient or permanent neurological deficits (motor and language) have also been reported.[4,37–39] Moderate to significant headaches and nausea were commonly reported post-implantation, presumably secondary to increased ICP or pain due to incision and craniotomy. Management of this condition may require analgesics, fluid restriction, and sometimes corticosteroids, which can delay the recording of habitual seizures.[39] The risk of complications increased with the number of subdural electrode contacts and duration of intracranial monitoring, doubling if >67 SDE contacts were placed and rising by 4% per day after 7.8 days of monitoring.[36]

In a comprehensive meta-analysis of 30 studies involving 2624 patients with SEEG monitoring, each patient, on average, had 10 DEs (ranging from 2 to 20 DEs) and was monitored for an average of 11 days (ranging from 2 to 33 days).[40] Hemorrhage was the most common complication, with a pooled prevalence of 1.0%, primarily intracerebral hemorrhage (ICH; .7%), followed by subdural hematomas (.4%) and epidural hematomas (.3%). Infections were found in .8% of cases, mainly as cerebral abscesses. Headaches following SEEG implantation were generally mild to moderate. A 30% lower rate of opioid use was observed after SEEG compared to SDE placement.[41] The prevalence of transient and permanent neurological deficits was .6%, although the cause of permanent deficits might not be directly attributable to SEEG implantation. Five deaths (.3%) were reported, with two resulting from ICH, two from preimplantation ventriculography (which is no longer performed at most centers), and one from severe cerebral edema believed to be due to an underlying metabolic derangement.[40] Notably, postexplantation computed tomographic scans revealed frequent subclinical bleeding in patients with SEEG implantation, ranging from 3% to 19%, suggesting that previous SEEG studies might have underinvestigated hemorrhagic complications.[42,43]

Several recent comparative studies have found that the overall complication rate was significantly higher with SDEs compared to SEEG (Table 2). In a meta-analysis of 48 studies involving 4009 patients (2036 SDE and 1973 SEEG), the complication rate was 16% for SDEs versus 4.8% for SEEG ($p = .001$).[44] Additionally, in a large international cohort of 1468 patients (526 SDE and 942 SEEG) from 10 epilepsy centers with >12 months of postoperative follow-up, Jehi et al. found that the overall complication rate was 9.6% in the SDE group and 3.3% in the SEEG group (odds ratio = 2.24).[45] Overall, most comparative studies suggest that SEEG carries a substantially lower complication rate, less pain, shorter intensive care unit stays, and fewer cosmetic concerns compared to SDEs.

5 | IDENTIFICATION OF THE EZ AND SEIZURE OUTCOMES WITH SUBDURAL AND DEPTH ELECTRODES

The goal of IEEG is to identify the EZ and assess its proximity to the eloquent cortex.[7] Over recent decades, the concept of the EZ has evolved from a localized area to encompass the region of seizure onset plus early propagation, now understood as part of a seizure network.[7,46,47] This evolving understanding of the EZ has influenced the selection of invasive recording techniques. SDE investigations conceptualize the EZ as a two-dimensional focus with abutting ictal spread, whereas SEEG enables a three-dimensional assessment of both deep and superficial cortex simultaneously, using strategically placed DEs. This three-dimensional approach is particularly valuable for sampling distributed elements in a seizure network.

With the increasing use of SEEG in the past decade, many centers have gained experience in both SDE and SEEG recordings. Studies have compared the rate of seizure outcomes between the two modalities within single centers (Table 2). However, retrospective studies have reported mixed seizure outcomes in patients who underwent SDE or SEEG recordings. Some outcome studies have suggested a similar seizure freedom rate for the two techniques. For example, in the cohort of 66 patients with a mean postoperative follow-up of 42 months, Kim et al. demonstrated that seizure freedom was achieved in 35% of patients with SDEs and 29% of patients with SEEG, with no significant difference between the two modalities ($p = .79$).[48] Similar conclusions were drawn from studies by Remick et al. (134 SDE, 42 SEEG patients) and Talai et al. (47 SDE, 53 SEEG patients; Remick: 60% SDEs vs. 75% SEEG, $p = .55$; Talai: 71% SDEs vs. 81% SEEG, $p = .76$).[49,50] On the contrary, in a meta-analysis by Sacino et al. that included 974 pediatric patients (697 SDE vs. 277 SEEG patients), seizure freedom rate was achieved in 66.5% of patients with SEEG monitoring (95% confidence interval [CI] = 58.8–73.4), which was higher than 52% of patients with SDE monitoring (95% CI = 43.0–61.1).[51] Tandon et al. reported a significantly greater proportion of better outcomes (Engel I and II) in the SEEG cohort than SDE cohort in both lesional (30/36, 83% vs. 50/79 63%, $p = .03$) and nonlesional cases (27/39, 69% vs. 9/26, 35%, $p = .006$) at 12-month follow-up.[52]

These results must be interpreted cautiously due to the differences between the two techniques. Based on the currently available data, a significant distinction between the two techniques lies in their respective indications. For instance, seizures of superficial perirolandic onset are better

TABLE 2 Clinical characteristics of comparative studies for SDEs and SEEG.

First author	Publication year	Design	Patients, *N*	SDEs	SEEG	Mean age at surgery, years, SDEs vs. SEEG	Gender, male, %, SDEs vs. SEEG	Mean epilepsy duration, years, SDEs vs. SEEG	Postresection follow-up, months, SDEs vs. SEEG	Resection or ablation rate, %, SDEs vs. SEEG	Complication rate, %, SDEs vs. SEEG	Seizure outcome, %, SDEs vs. SEEG
Yan[44]	2019	Meta-analysis	4009	2036	1973	24.9 vs. 24.9	54.8 vs. 52.5	5.2 vs. 10.5	22 vs. 18	81.6 vs. 76.9, $p = .001$	15.5 vs. 4.8, $p = .001$	Engel I: 56.4 vs. 61, $p = .001$
Sacino[51]	2019	Meta-analysis	974	697	277	12.1 vs. 7.4	52.9 vs. 62	NA	18–83 vs. 12.4–198	NA	10.7 vs. 2.9, $p =$ NA	Engel I: 66.5 vs. 52.1, $p =$ NA
Toth[54]	2019	Meta-analysis	1999	1025	974	NA (range = 2–69)	53 vs. 49	NA	18.2 vs.10	88.8 vs.79, $p < .001$	NA	Engel I: 55.9 vs. 64.7, $p = .02$
Tandon[52]	2019	Retrospective cohort	260	139	121	30.6 vs. 30.1	43.9 vs. 47.1	17.2 vs. 16.4	12 vs. 12	91.4 vs.74.4, $p < .001$	7.2 vs. 0, $p = .003$	Engel I & II: 54.6 vs. 76, $p = .003$
Kim[48]	2021	Retrospective cohort	66	19	47	33.4 vs. 35.6	61.1 vs. 59.6	15.1 vs. 19.9	42.2 vs. 39.8	94.4 vs. 87.2, $p =$ NA	10.5 vs. 17, $p = .51$	Engel I & II: 64.7 vs. 61, $p = .79$
Joswig[66]	2020	Retrospective cohort	500	145	355	32.5 vs. 34	50.1 vs. 49	17.6 vs. 18.2	36 vs. 36	NA	Infection: 2.3 vs. 0, hemorrhage: 1.4 vs. 2.8, $p =$ NA	No difference in Engel I & II outcomes, $p = .12$
Talai[50]	2021	Retrospective cohort	108	61	47	12 vs. 14	54 vs. 68	6 vs. 7	12 vs. 12	93 vs. 60, $p < .001$	Infection: 33 vs. 4, $p = .01$ Hemorrhage: 1.6 vs. 4.3, $p = .55$	Engel 1 & II: 71 vs. 81, $p = .76$
Jehi[45]	2021	Retrospective cohort	1468	526	942	33 vs. 31.5	50.6 vs. 53.8	19 vs. 17.4	>12 vs. >12	78.6 vs. 66.5, OR = 1.4	9.6 vs. 3.3, OR = 2.24	Engel I: 41 vs. 55, OR = 1.66
Remick[49]	2022	Retrospective cohort	176	134	42	10.9 vs. 13.9	52.4 vs. 56.1	NA	12 vs. 12	75.4% vs. 21.4%, $p < .001$	17.9 vs. 7.1, $p = .09$	Engel I: 60.2 vs. 75, $p = .55$

Note: Retrospective studies conducted prior to 2019 have been included in the meta-analysis studies presented in the table; they are not individually listed.

Abbreviations: NA, nonapplicable; OR, odds ratio; SDE, subdural electrode; SEEG, stereoelectroencephalography.

TABLE 3 Summary of the differences between SDEs and SEEG.

Aspect	SDEs	SEEG
Implantation technique	Placed directly on the brain surface	Inserted using stereotactic frame or robot through small burr holes
Craniotomy	Yes	No
Coverage area	Extensive surface gyral coverage	Focused sampling of surface and deep structure, multiple lobes, bihemispheric coverage
Spatial precision	Electrodes can shift during recording or craniotomy if not properly secured to the dura	Precise placement, anchored with bolts
Disadvantages	Cannot reach deep structures and are not suitable for bihemispheric implantation	Sparse spatial coverage, "needle in a haystack"
Safety	9.6% complication rate,[45] more pain-related issues, larger scar, longer hospital stays	3.3% complication rate,[45] less pain, small scar, shorter hospital stays
Functional mapping	"Pure" cortical stimulation	May stimulate gray or white matter tract
Mapping parameters	50 Hz, pulse width .2–.3 ms, maximum 15 mA for 3–5 s[58]	50 Hz, pulse width .5-1 ms, maximum 8 mA for 3–8 s or 1 Hz, pulse width .5–3 ms, maximum 4 mA for 20–60 s[60,61]

Abbreviations: CSF, cerebrospinal fluid; SDE, subdural electrode; SEEG, Stereoelectroencephalography.

evaluated by SDEs because of their extensive coverage, allowing functional mapping and providing a clear margin for resection. In contrast, SEEG evaluation is better suited to assessing deep foci, multifocal onset, or bilateral seizures. For example, seizure foci associated with periventricular heterotopias are best identified by SEEG, leading to 76% seizure freedom despite bilateral lesions, which usually have poor outcomes.[53] Additionally, SDEs and SEEG were used during different epochs. Using SDEs was the mainstream IEEG technique in North America from the 1930s until the 2010s, whereas SEEG only became widely used in North America in the past 2 decades. Many factors other than the method of IEEG may have affected outcomes with the two IEEG cohorts. Advances in imaging and neurophysiological testing (e.g., magnetoencephalography, source localization, MRI) mean that different diagnostic and localizing information has been available in the epoch of SEEG use than was available while SDE use was prevalent, potentially contributing to different outcomes. Changes in surgical techniques (e.g., resection vs. laser ablation), the development and certification of neuromodulation options, the expertise and biases of clinical teams, and patient preferences can all also influence surgery outcomes. Specific brain targets and suitable intracranial electrodes and a comparison of SEEG and SDEs are summarized in Tables 1 and 3.

Interestingly, studies have reported a 20% higher resection or ablation rate with SDEs compared to SEEG.[44,52] This could be because palliative resections could have occurred during the same craniotomy for SDE removal even if the IEEG data were suboptimal.[52,54] On the other hand, patients with suboptimal SEEG localization might be more likely to opt for nondestructive palliative treatment options such as neuromodulation therapies or no intervention. Notably, there was a 114% increase in RNS implantation in the United States in 2019 compared to 2016.[55]

6 | FUNCTIONAL MAPPING WITH SUBDURAL AND DEPTH ELECTRODES

Electrical stimulation mapping (ESM) is the gold-standard procedure during presurgical evaluation to determine the function of the stimulated area and its relationship with the adjacent eloquent cortex. ESM is pivotal for predicting and minimizing functional deficits during epilepsy surgery.[56] Typically, ESM is done with trains of bipolar, biphasic square waves with pulse widths of 250–350 μs at a frequency of 50 Hz. The stimulus intensity starts at 1–2 mA, with stepwise increments of .5–2 mA until a functional response, afterdischarges (ADs), seizure, or a maximum stimulus current has been achieved.[57] The maximum current usually remains <10 mA, although currents up to 15 mA have been used with SDEs. Train durations of 2–3 s are used for sensorimotor mapping and 5 s for receptive language mapping.[58] Due to the smaller size of SEEG contacts compared to SDEs, the resulting charge densities from stimulation at any given current are greater with SEEG. The maximum current strength for SEEG is based on the accepted safety limits for charge density (<30 μC/cm^2/phase) and the lack of current shunting into the cerebrospinal fluid, as observed in SDEs.[59,60] A maximum stimulation of 8 mA is typically used with SEEG to stay near this recommended charge density limit in contrast to the 15-mA limit often used in subdural ECoG.[60] Two types of stimulation protocols have been recommended in ESM with SEEG. High-frequency stimulation at 50 Hz, with a phase width of .5–1 ms, intensity of .5–5 mA, and stimulation duration of 3–8 s, is best suited for functional mapping outside the primary cortices.[61] Low-frequency stimulation using 1 Hz, with a phase width of .5–3 ms, intensity of .5–4 mA, and stimulation duration of 20–60 s, is more suitable for functional mapping of the primary cortices to minimize the risk of triggering generalized tonic–clonic seizures. However, the low-frequency protocol tends to lack sensitivity for language mapping.[62] Aungaroon and colleagues investigated 67 mapping cases with SEEG and 106 mapping cases with SDGs, finding a similar incidence of language and motor responses between the two techniques. However, SEEG exhibited greater sensitivity in eliciting sensory responses than SDEs. Additionally, the SEEG group showed a lower occurrence of ADs and stimulation-induced seizures, suggesting superior safety and neurophysiological validity for SEEG stimulation.[63]

7 | CONCLUSIONS AND FUTURE DIRECTIONS

Although IEEG is now considered the standard practice for seizure localization, it does not guarantee complete seizure control after the surgery. Seizures may persist or recur despite optimal seizure localization and resection or ablation.[64] IEEG study can often define the SOZ and spread zone, but may not fully delineate the EZ. Any type of IEEG should be approached with careful consideration and realistic expectations for achieving seizure freedom. The putative EZ from presurgical evaluation relies on careful interpretation of noninvasive and IEEG data. There is substantial evidence supporting the safety and better tolerance of SEEG compared to SDEs. SEEG demonstrates clear benefits in cases where the hypothesized EZ involves deep structures and multiple lobes, and in mapping seizure distant propagation. Furthermore, with combined macro−/microelectrodes now available for SEEG, seizure generation and propagation can be studied on a cellular level with depth electrodes.[65] Conversely, SDEs remain advantageous when extensive surface gyri coverage is necessary, such as evaluating seizure foci at the lateral frontoparietal convexity and the interhemispheric gyrus. SEEG and SDEs are technically complementary and not mutually exclusive. As class I evidence from randomized clinical trials may never exist, the choice of electrode type for IEEG studies should be based on the hypotheses generated before planning electrode placement, rather than center preference, cost, or solely morbidity. Registry data are likely to be more valuable in better defining the complication profile, drawing on a more heterogeneous population than would controlled trial data.

Due to its multiple advantages, SEEG is likely to remain the primary IEEG type in the future. Therefore, the primary focus should be enhancing implantation strategies and overcoming limitations in studying early propagation due to limited spatial coverage. Because there is significant variation in ESM techniques across centers, particularly when mapping with SEEG, developing ESM guidelines based on best practices would help optimize the role of ESM in presurgical evaluation. Finally, long-term outcome studies are warranted to determine whether increased use of SEEG would result in more patients undergoing epilepsy surgical evaluation and subsequently benefit more patients in achieving long-term seizure freedom.

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CONFLICT OF INTEREST STATEMENT

None of the authors has any conflict of interest relevant to this article to disclose. We confirm that we have read the Journal's position on issues involved in ethical publication and affirm that this report is consistent with those guidelines.

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