ORIGINAL RESEARCH

A Standardized Electrode Nomenclature for Stereoelectroencephalography Applications

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Purpose: Stereoelectroencephalography (SEEG) is widely performed on individuals with medically refractory epilepsy for whom invasive seizure localization is desired. Despite increasing adoption in many centers across the world, no standardized electrode naming convention exists, generating confusion among both clinical and research teams.

Methods: We have developed a novel nomenclature, named the Standardized Electrode Nomenclature for SEEG Applications system. Concise, unique, informative, and unambiguous labels provide information about entry point, deep targets, and relationships between electrodes. Inter-rater agreement was evaluated by comparing original electrode names from 10 randomly sampled cases (including 136 electrodes) with those prospectively assigned by four additional blinded raters.

Results: The Standardized Electrode Nomenclature for SEEG Application system was prospectively implemented in 40 consecutive patients undergoing SEEG monitoring at our institution, creating unique electrode names in all cases, and facilitating implantation design, SEEG recording and mapping interpretation, and treatment planning among neurosurgeons, neurologists, and neurophysiologists. The inter-rater percent agreement for electrode names among two neurosurgeons, two epilepsy neurologists, and one neurosurgical fellow was 97.5%.

Conclusions: This standardized naming convention, Standardized Electrode Nomenclature for SEEG Application, provides a simple, concise, reproducible, and informative method for specifying the target(s) and relative position of each SEEG electrode in each patient, allowing for successful sharing of information in both the clinical and research settings. General adoption of this nomenclature could pave the way for improved communication and collaboration between institutions.

Key Words: Stereoelectroencephalography, Nomenclature, SEEGA, Electrodes, Epilepsy, Surgery.

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According to the World Health Organization, epilepsy affects approximately 50 million individuals worldwide,[1] with anywhere from 16 to 134 new-onset cases per 100,000 each year.[2,3] Despite treatment, epilepsy produces a profound burden of disease spanning the entire lifespan.[4–7] Although most seizures will respond to various and sometimes multiple antiepileptic agents, medication side effect profiles are often not benign and can lead to poor tolerability.[8–10] In 20% to 40% of those affected by epilepsy, seizures do not respond to medication.[11–13] A subset of patients with medically refractory epilepsy, most notably those with focal onset seizures, are candidates for surgical therapy, including traditional open resection, laser interstitial thermal therapy, and neuromodulation via deep brain stimulation or responsive neurostimulation.[4]

For those eligible for surgery, the chance of achieving better seizure control postoperatively is largely dependent on defining a focal seizure source and accompanying electrical circuit. Noninvasive investigations prove sufficient to adequately localize the seizure focus and guide definitive treatment in many cases.[14] However, in approximately 20% of cases either a clear structural abnormality cannot be detected on imaging, or scalp recordings do not clearly establish a corroborating focal seizure origin.[15,16] In such cases, invasive monitoring with intracranial recordings may be considered.

In many North American centers, open craniotomy with the placement of subdural grid and strip electrodes has traditionally been preferred for intracranial recordings. Although focal cortical gyral surfaces can be densely recorded in this way, a craniotomy is often required to achieve adequate coverage, the topology of the brain, dura, and skull can limit access, and invaginated cortex within sulci and deep structures are poorly sampled.[17] With these limitations in mind, an alternative technique known as stereoelectroencephalography (SEEG) can be considered. Stereoelectroencephalography involves the stereotactic placement of multiple depth electrodes and permits widespread and discontiguous recording of superficial and deep regions of the brain while avoiding the need for a craniotomy.[18–24] This technique, developed in the 1950s and traditionally performed primarily via multiple parallel orthogonal trajectories, has recently gained popularity across the world and in many centers has all but replaced subdural grids.

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TABLE 1. Nomenclature Framework

First Character Group		Second Character Group		
Lobe of Entry (can Add^{L} or^{R} if Bilateral)	**Gyrus/Region**	**Position Relative to Electrodes Within Same Gyrus/Region**	**Standard Distal Electrode Target**	**Position Relative to Electrodes Within Same Target**
Frontal	1—superior	a—most anterior	A—Amygdala	a—most anterior
Parietal	2—subsequent superior	b—2nd most anterior, and so-on	C—Cingulate gyrus	b—2nd most anterior, and so on
Occipital	3—most inferior (if applicable)		H—Hippocampus	
Temporal			I—Insula	
			OF—Orbitofrontal cortex	
			OT—Occipitotemporal gyrus	
			PH—Parahippocampal gyrus	

White columns denote required fields; gray columns denote fields used as required.

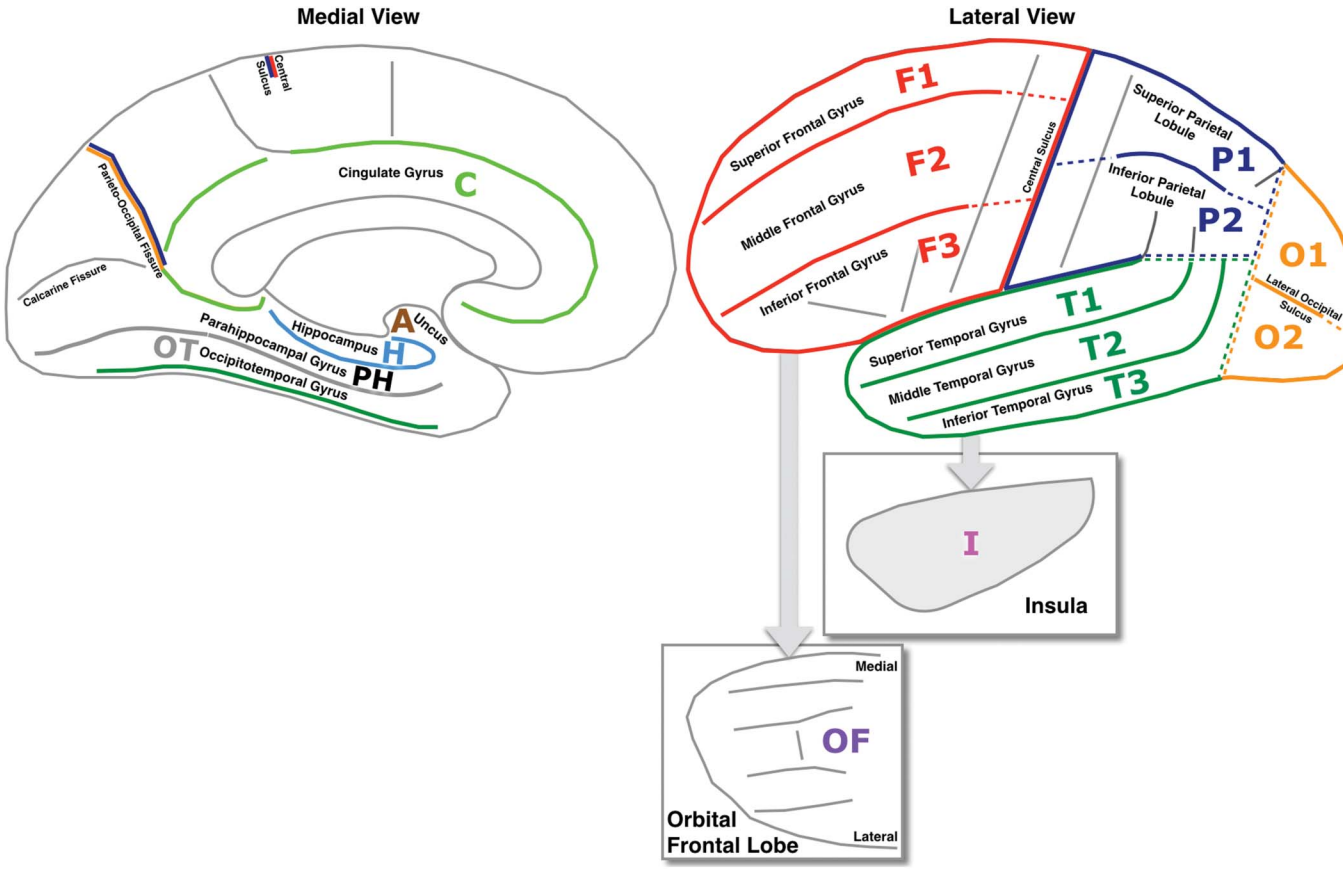

FIG. 1. Gyral/region and target labeling in the Standardized Electrode Nomenclature for the Stereoelectroencephalography Application scheme. For illustration purposes, the left hemisphere is depicted, including lateral surface (right image), mesial surface (left image), orbitofrontal surface (middle inferior image), and insular surface (inferior right image). Frontal and temporal lobes are divided into superior, middle, and inferior frontal/temporal gyri (F1/T1, F2/T2, and F3/T3). The parietal lobe is divided horizontally along the extended axis of the intraparietal sulcus into P1 (superior) and P2 (inferior). The occipital lobe is divided along the extended axis of the lateral occipital sulcus into O1 (superior) and O2 (inferior). Distal target labels include A—amygdala, C—cingulate gyrus, H—hippocampus, I—insula, OF—orbitofrontal cortex, OT—Occipitotemporal gyrus, and PH—parahippocampal gyrus.

Several technical advances have helped promote the greater adoption of SEEG and its evolution to include more complex nonorthogonal trajectories, including electrode hardware miniaturization and the development of efficient and flexible robotic-assisted techniques, allowing for increased coverage without significantly extending anesthesia time.[25] Nonorthogonal SEEG electrodes can reach a given target through an almost limitless number of trajectories; hence, multiple electrode trajectories reaching the same target can cover vastly different territories. Increasingly, complex electrode implantation schemes must be designed and interpreted in three dimensions, and identification of electrodes must take these complexities into account. For example, an electrode targeting the head of the hippocampus can commonly do so by entering orthogonally from a temporal gyrus or parasagittally from an occipital entry. Most SEEG centers have used locally developed simple sequential labels for planned or implanted SEEG electrodes that may be inconsistent, not provide much or any anatomical information, and not be reliably reproducible.

Uniquely naming each electrode in a reproducible and useable manner that accurately indicates recorded structures and relationships between electrodes, without creating confusion, is not a trivial matter. By analogy, in the 1940s, multiple EEG naming schemes were creating intolerable confusion. For example, the Gibbs, Schwab and Abbot, and Montreal Neurological Institute systems were variably used in different centers. In the late 1940s, Jasper[26] was tasked by the First International Congress of EEG to develop an international standard EEG electrode placement nomenclature and ultimately created the now universally adopted 10 to 20 system. The 10 to 20 system enabled generalizable training and collaboration across centers by creating a common language for EEG electrode placement.[27] Currently, there is no generally accepted and standardized nomenclature for SEEG electrodes that is anatomically and spatially informative, trajectory specific, reproducible, and concise. Here, we describe a simple rule-based system for naming SEEG electrodes based on their fundamental characteristics that efficiently provides a succinct, reproducible, and distinct method for specifying the anatomical trajectory, target(s), and relative position of each SEEG electrode in each patient. Furthermore, we propose that broad adoption of this nomenclature could greatly facilitate sharing of information in both the clinical and research settings within and between institutions.

METHODS

We have designed a novel nomenclature system for SEEG electrodes that we refer to as the Standardized Electrode Nomenclature for SEEG Applications or "SENSA". In the field of psychology, the word "sensa" is synonymous with "sense data", which refers to fundamental objects of perception. In keeping with this concept of perception and the fact SEEG electrodes harbor important relationships both to the brain anatomy they sample and the electrodes that surround them, the SENSA system (SS) is a mixture of absolute and relative attributes of SEEG electrodes: electrode names relate both to their location in the brain and to their location relative to other electrodes.

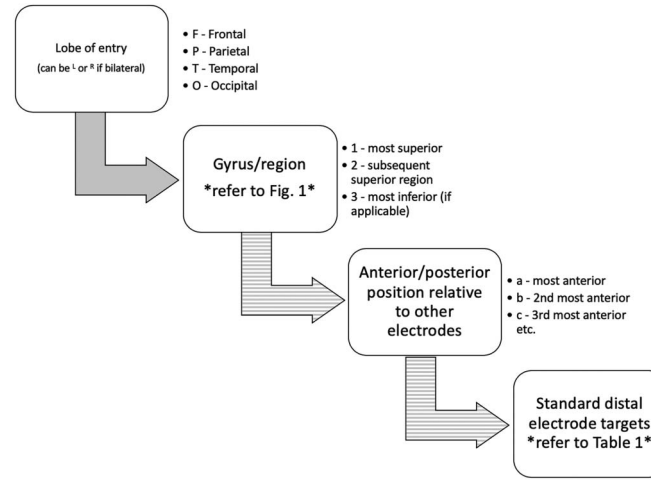

FIG. 2. Standardized Electrode Nomenclature for Stereoelectroencephalography Application system in a flowchart format, describing the sequential rule-based system for creating standardized electrode names. Each electrode name is comprised a minimum of two characters, with more added as dictated by the individual trajectory and its relationship to other electrodes, and begins by assigning an uppercase letter and number to indicate the proximal entry point into the cerebral cortex. Solid filled arrow indicates a required step in the naming process; striped arrows indicate steps used as required.

The framework of this nomenclature requires each electrode name be comprised a minimum of two characters, with more added as dictated by the individual trajectory and its relationship to other electrodes, and begins by assigning an uppercase letter and number to indicate the proximal entry point into the cerebral cortex (Table 1, Figs. 1 and 2).

The first character is a single uppercase letter denoting the lobe of entry: F—frontal, P—parietal, T—temporal, and O—occipital. The second character is a digit, representing the major gyrus/lobule through which the electrode enters. The most superior gyrus/lobule is indicated by "1" (e.g., F1 indicates an entry point into the superior frontal gyrus) and progressively more inferior gyri/lobules are indicated by increasing numbers as depicted in Fig. 1 (e.g., P2 indicates an entry point into the inferior parietal lobule).

A third character is a lowercase letter used when multiple electrodes enter the same gyrus/lobule, in which case they are differentiated based on their relative location in the anterior-posterior (A-P) plane. For example: F1a is the most anterior electrode in the superior frontal gyrus, followed by F1b, and then F1c, etc.

Subsequent characters represent standard distal electrode targets as required, ordered from proximal to distal along the electrode trajectory, each followed with lowercase letters to identify their relative location in the A-P plane when more than one electrode records from the same distal target. One or two capital letters signify standard distal targets and include the following: A—amygdala, C—cingulate, H—hippocampus,

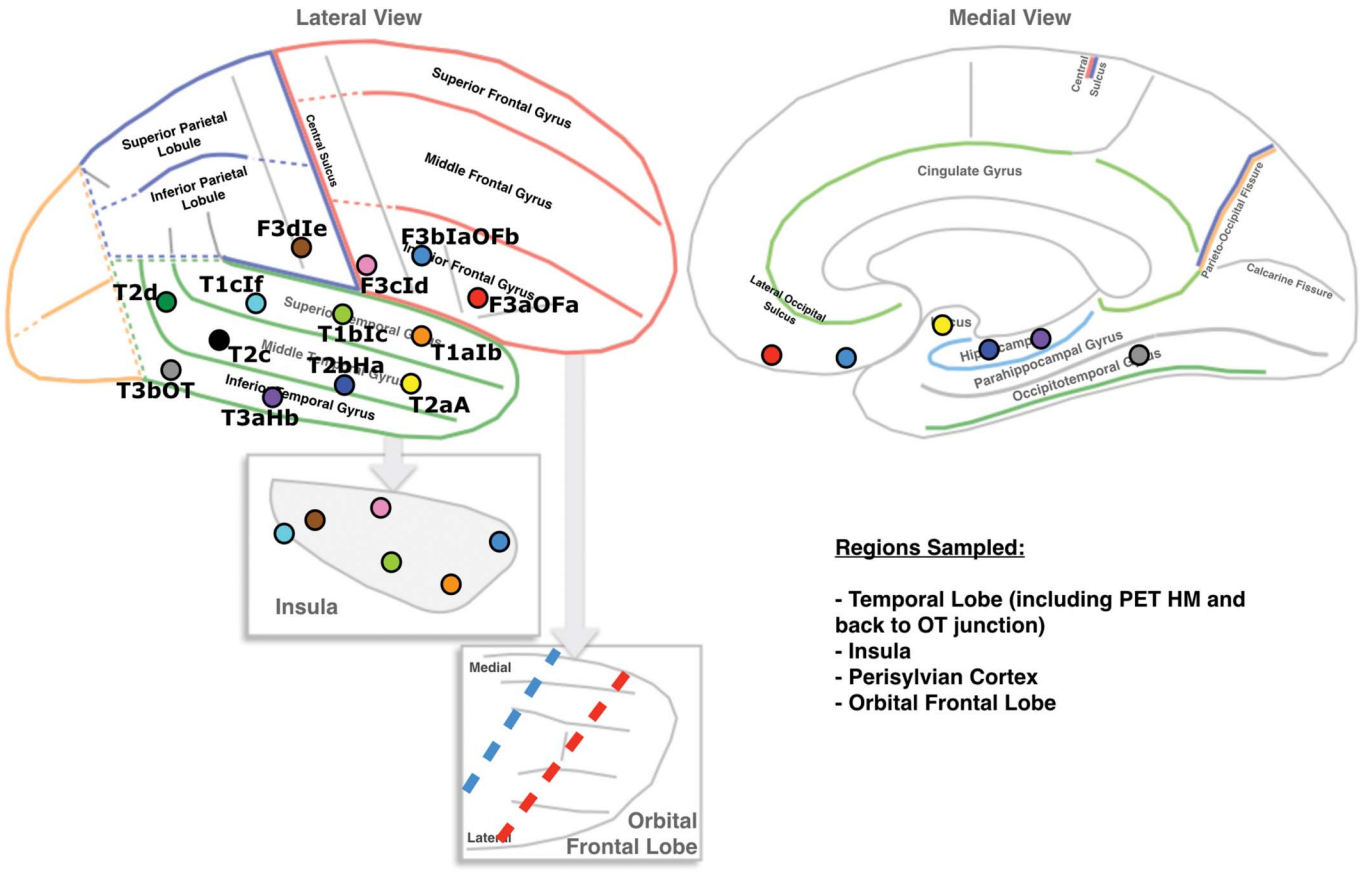

FIG. 3. Sample stereoelectroencephalography implantation plan showing the Standardized Electrode Nomenclature for Stereoelectroencephalography Application system applied to 13 unilateral right electrodes, with lateral surface entry points (left image) and where applicable distal targets in the insula (inset box), orbitofrontal cortex (inset box), or mesial surfaces (right image) indicated by electrode-specific colored dots or broken lines. For instance, the electrode F3bIaOFb entry point is depicted as a blue dot on the left image, distal position in the insula is indicated by a blue dot on the inset box, and distal course and terminus in the orbitofrontal cortex is depicted as a blue broken line and dot on the inset box and right images, respectively.

I—insula, OF—orbitofrontal cortex, OT—occipitotemporal gyrus, and PH—parahippocampal gyrus. For example, T2aA would be the most anterior electrode entering the middle temporal gyrus that terminates in the amygdala (Figs. 3 and 4). F3aOFa would be the most anterior electrode entering the inferior frontal gyrus which terminates as the most anterior orbitofrontal cortex electrode (Figs. 3 and 4). The relative location of electrodes in distal targets is determined by each electrode's most anterior contact in the A-P plane. For example, F3bIaOFb is the second most anterior electrode entering the inferior frontal gyrus that is then the most anterior insular electrode and finally terminates as the second most anterior electrode in the orbitofrontal cortex (Figs. 3 and 4). Although the complete name for each implanted electrode has the potential to include several characters, a maximum of 3 characters is all that is needed to provide a unique name for each electrode (e.g., there can only be one F1a electrode, regardless of where it terminates). A preceding superscript ^{L} or ^{R} can denote side if bilateral electrode implantation is planned (Fig. 5). Patient specific features, such as lesions or vascular structures, can be depicted on brain diagrams (Fig. 5). Worksheets for clinical use are provided as **Supplemental Digital Content 1** (see **Figures** 1–3 http://links.lww.com/JCNP/A74, http://links.lww.com/JCNP/A75, http://links.lww.com/JCNP/A76).

The feasibility of implementing the SS into clinical workflows was assessed by exclusively using this system in 40 consecutive SEEG cases managed by the Boston Children's Hospital Epilepsy Surgery Center, including by the neurosurgical, neurology, and neurophysiology teams. To measure inter-rater agreement, electrode names were removed from a random sample of 10 previous cases with 136 electrode names having been assigned by the neurosurgeon lead author and developer of the SS. Additional blinded raters, including another neurosurgeon (J.M.), two epilepsy neurologists (P.P. and J.B.), and a neurosurgery fellow (V.S.) provided with a description of the SS, then named the electrodes, and the percent agreement was calculated by determining whether all character elements and their order of usage were identical or not.

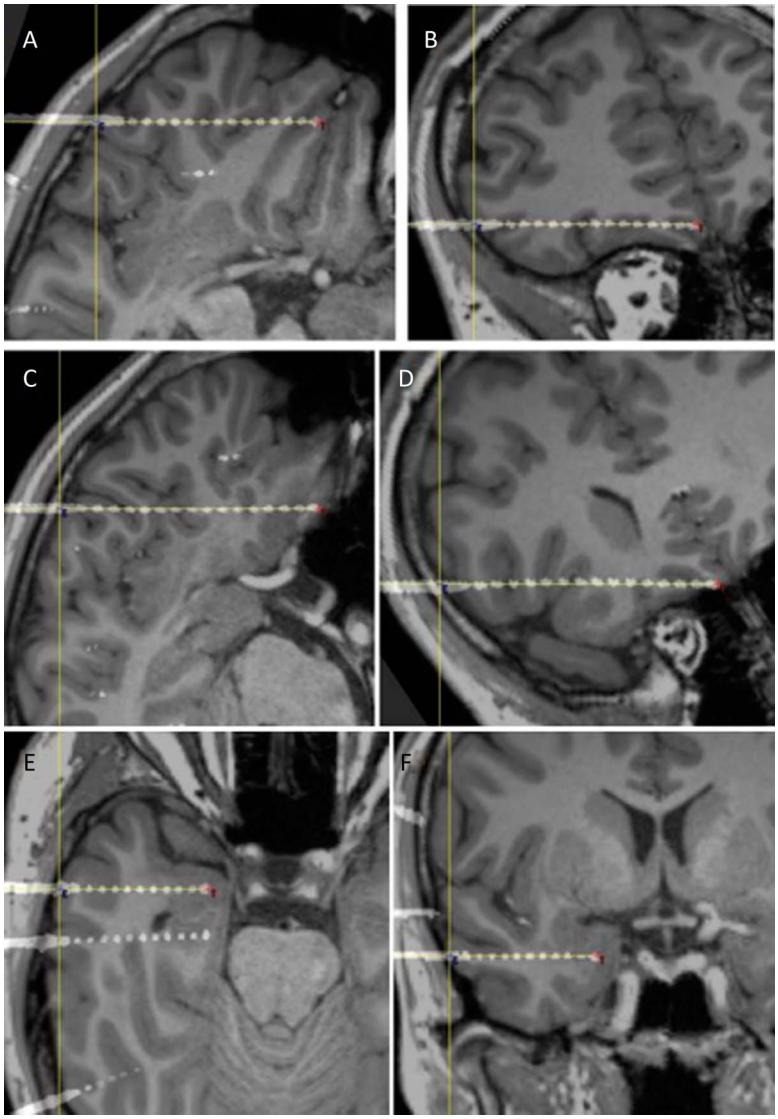

FIG. 4. Preoperative magnetic resonance and postimplantation computed tomography image overlays of implanted electrodes from the case depicted in Figure 3. **A** and **B** show in-plane trajectory views of electrode F3aOFa, which enters most anteriorly into the inferior frontal gyrus and terminates most anteriorly in the medial orbitofrontal cortex. **C** and **D** show in-plane trajectory views of electrode F3bIaOFb, which enters the inferior frontal gyrus more posteriorly, grazes the insular cortex most anteriorly, and terminates most posteriorly in the orbitofrontal cortex. **E** and **F** show in-plane trajectory views of electrode T2aA as it enters the middle temporal gyrus most anteriorly and terminates in the amygdala. Also visible in (**E**) is electrode T2bHa, which enter enters the middle temporal gyrus more posteriorly and terminates at the most anterior aspect of the hippocampus.

RESULTS

We have prospectively implemented this nomenclature in approximately 40 consecutive patients undergoing SEEG monitoring at our institution, constituting over 500 electrodes (e.g., Figs. 3–5). The SS generated unique names in all cases and was universally and exclusively used by the neurosurgical, neurology, and electrophysiology teams. Eliminating competing alternative electrode names from the workflow across the board permitted fluid transfer of information and interpretation within and between involved groups in the planning, recording, and therapeutic phases of care. Recording was performed using the NATUS Quantum system (Natus, Inc) in all cases and the CortiQ system (G.TEC Medical Engineering, Inc) was also used in select cases, both of which posed no trouble with using this naming system.

In a random sample of 10 previous cases with electrode names assigned by the lead neurosurgeon author and developer of the SS, there was 97.5% agreement with electrode names assigned by four additional blinded raters familiar with the naming system. Disagreements included errors in the order of naming distal targets along an electrode trajectory and in assigning relative positions in the A-P plane for certain electrodes. For example, disagreement arose for an inferior frontal gyrus entry electrode, second most anterior, that traversed the insula anterior to other insular electrodes and terminated as the sole orbitofrontal cortex electrode. The corresponding SS name is therefore F3bIaOF. Although all three anatomical regions and the electrode's relative position to other electrodes sampling those regions were identically indicated by both raters, the order of the distal targets (insula and orbitofrontal cortex) were reversed (incorrectly generating F3bOFIa). On collective review, both raters agreed that F3bIaOF was unambiguously appropriate. Disagreements also arose with 1 rater when assigning the relative position of electrodes in the A-P plane for certain electrodes. On collective review, all raters agreed to unambiguous relative

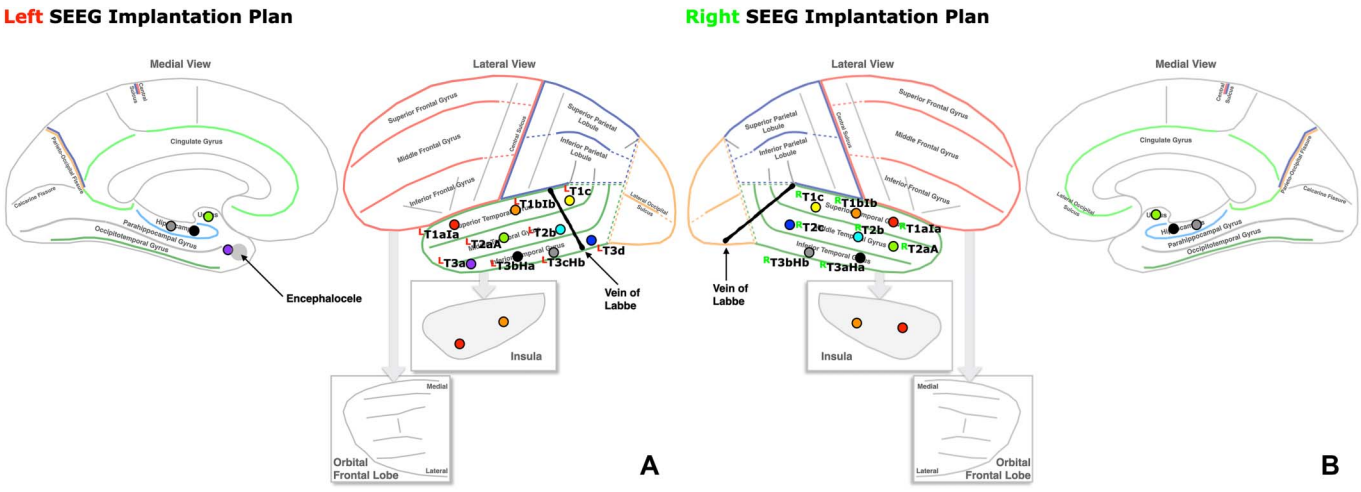

FIG. 5. Sample stereoelectroencephalography implantation plan showing eight right- (**A**) and nine left-sided (**B**) electrodes, with lateral surface entry points (left image in **A**, right image in **B**) and where applicable distal targets in the insula (inset boxes) or on the mesial surface (right image in **A**, left image in **B**) indicated by electrode-specific colored dots. For instance, the entry point of ^{L}T2aA is depicted in panel B as a green dot on the right image, and its distal terminus in the amygdala is depicted as a green dot on the left image. Note that initial superscript characters (^{L} or ^{R}) indicate laterality.

positions and noted that closely spaced electrodes require careful review to correctly determine their relative A-P position.

DISCUSSION

The proposed standardized nomenclature for SEEG electrodes described here has been successfully implemented at our institution, achieving full "buy-in" by all involved parties and transforming clinical workflow by providing simple, unambiguous, abbreviated, contextual, and anatomically informative electrode names. Once users adequately familiarize themselves with the SS, inter-rater reliability is excellent. In some circumstances, teams took advantage of the fact that a maximum of three characters is all that is needed to provide a unique name for each electrode. For example, the use of a shortened name was helpful when physically labeling electrodes and/or cables at surgery and when entering electrode names into EEG recording software that may have a character limit. In other situations, complete electrode names were advantageous by providing maximum contextual and anatomical information. For example, complete names were helpful during planning, interpretation, and therapeutic planning stages to assess the degree of sampling for given anatomical regions and determine surgical resection/disconnection boundaries. The adaptability and expandability of this nomenclature can also be advantageous, with more electrodes and targets easily added, as plans and implantations are modified. Although designed for the purposes of SEEG, the SS can also be applied to other clinical applications, involving brain trajectories, such as laser interstitial thermal therapy (which we have found particularly useful in cases with multiple trajectories), responsive neurostimulation, and deep brain stimulation.

An important limitation of this and any other SEEG electrode naming system is that it must be paired with high-resolution multiplanar anatomic imaging to truly appreciate detailed anatomic and interelectrode relationships. Rather than attempting to achieve those latter goals, the SS strives to standardize SEEG trajectory naming to facilitate workflow while balancing competing interests including simplicity, anatomic specificity, and interrater reliability. The anatomic regions defined by the SS were chosen both because of their clinical relevance to SEEG implantations and their ability to be fairly unambiguously defined anatomically. To further increase the anatomical detail afforded by a given electrode name, certain regions would require further subsegmentation (such as dividing the superior frontal gyrus into subregions along the A-P axis etc.). However, in the absence of anatomically conserved landmarks to define subregions, such as named sulci, our preliminary experience is that interrator reliability unacceptably suffers. An advanced solution to this in a future version could be to morph plans into a standardized 3D brain space with predefined subsegmented regions, potentially impairing its use for an individual patient but facilitating the combined analysis of a large number of cases.

This novel nomenclature has standardized planning and communication between neurosurgeons, neurologists, and electrophysiologists at our institution, and we believe that general adoption of this proposed SS could similarly enhance SEEG workflow at other centers and enable better transfer of information between institutions for both clinical and research collaboration.

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