Extracranial Interictal and Ictal EEG in sEEG Planning

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KEYWORDS

• Scalp EEG • Intracranial EEG • Epilepsy surgery • Hypothesis

KEY POINTS

- Systematic interpretation of scalp EEG findings is key to developing an epilepsy network hypothesis that guides a subsequent sEEG implant plan.
- Slowing and spiking on interictal EEG provide localizing information on core regions of the epilepsy network; advanced waveform analysis provides additional information on source location, orientation, and dynamics.
- The ictal EEG provides localizing evidence by concordance; specific waveform characteristics are described in brain subregions that may help diagnose particular electroclinical syndromes.
- Scalp EEG remains indispensable to the multimodality evaluation of refractory focal epilepsy; a preimplant hypothesis that yields a subsequently successful sEEG evaluation is built on the analysis of individual details and their synthesis.

INTRODUCTION

Hans Berger's description of the human scalp electroencephalogram (EEG)[1] was soon followed by the realization that the EEG could detect and classify seizure disorders. The first EEG abnormalities in epilepsy were described in the 1930s, and EEG-guided epilepsy surgery followed shortly afterward at the Montreal Neurologic Institute.[2] Today, scalp EEG remains indispensable in the diagnosis and classification of epilepsy. To convince oneself of this it is only necessary to consider two simple situations: a patient with an MRI-negative epilepsy, where there are no other objective clues to epilepsy other than an epileptiform EEG; and the converse, where a patient with an imaging lesion whose nonepileptic paroxysmal spells are diagnosed by a normal EEG. Analysis of abnormal waveforms remains important in outpatient practice to distinguish generalized from focal from undetermined epilepsy syndromes, which in turn inform prognosis and management options. However, scalp EEG is put to its most detailed clinical use in surgical epileptology, to identify the hypothesized epileptic network. In patients who need stereoelectroencephalogram (sEEG) evaluation, this hypothesized network is key to everything that follows: the sEEG implantation scheme, interpretation of the ensuing intracranial EEG data, and even the final therapeutic surgical strategy proposed.

INTERICTAL ELECTROENCEPHALOGRAM

Often neglected, the interictal EEG rewards the clinical neurophysiologist with an abundance of information about the underlying epilepsy syndrome. Positive (abnormal) findings are clearly of interest; yet, a negative (normal) interictal EEG in a patient with unequivocal evidence of focal epilepsy is the clue to a deep or small-volume source. Common abnormalities on interictal scalp EEG relevant to sEEG planning in surgical focal epilepsy are discussed next.

Slowing

Continuous slowing of the background EEG over a brain region is highly sensitive but not specific for

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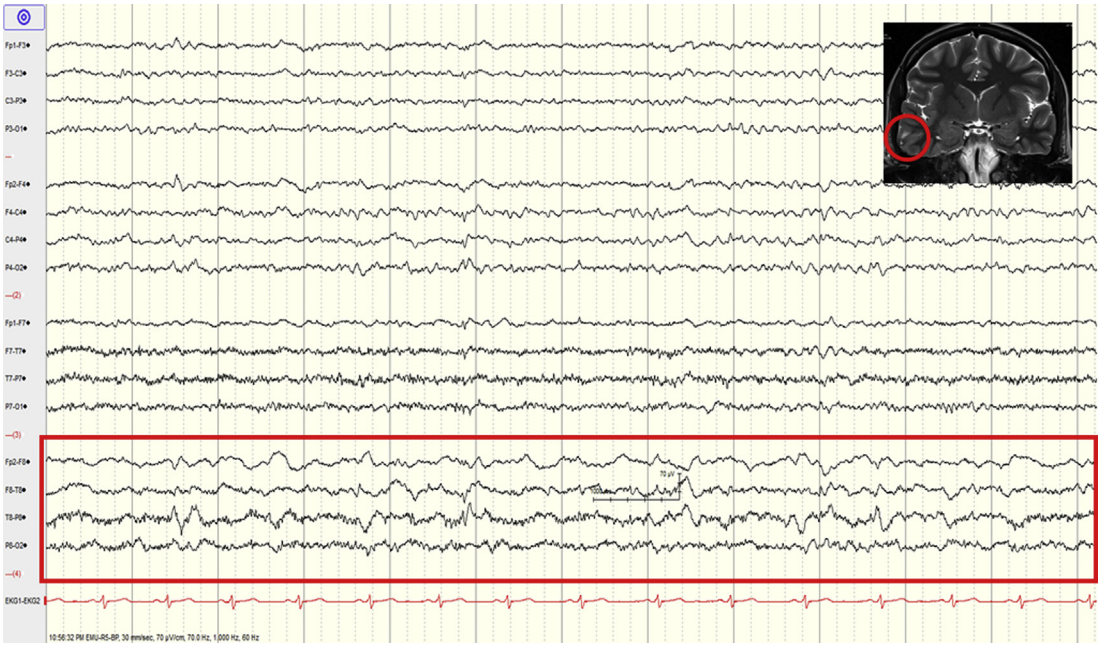

Fig. 1. Bipolar longitudinal montage, 10-second EEG page, 1–70 Hz passband, gain 7 μV/mm. Continuous polymorphic slowing in the delta range is seen over the right temporal lobe (*red box*) in patient with a right lateral temporal brain lesion (*red circle*) radiologically consistent with dysembryoplastic neuroepithelial tumor.

epilepsy; most brain pathologies, whether epileptogenic or not, feature EEG slowing. In the setting of a suggestive history and/or more specifically epileptiform EEG features (discussed later) slowing is highly localizing and indicates a fixed, lesional portion of the epileptogenic network (Fig. 1). Lesion-associated slowing is usually polymorphic, although occasionally slowing may exhibit a rhythmic character (intermittent rhythmic slowing) that is more specific for epilepsy.

Focal Spikes

Focal spikes are unmistakable when typical: large, sharp transients that stand out from the background EEG and are immediately followed by a slow wave (Fig. 2A). It is the electroencephalographer's job to distinguish such epileptiform spikes from myriad other benign variants and contaminants, subtleties not further discussed here (Fig. 2B illustrates a single such example). Making an accurate EEG diagnosis of focal epileptiform spike is, however, just the beginning of a longer analytical process. The notion of "focal spikes equal focal epilepsy," sufficient for outpatient practice, is inadequate in the surgical candidate, when additional features, such as spike field distributions, spike polarity, spike population types, and spike propagation, may be highly informative. We consider each of these in turn.

The Ebersole type I and type II spikes are classical examples[3] of differing field distributions in the setting of temporal lobe epilepsy (Fig. 3). The type I spike indicates a mesial spike focus with a dipole that is vertically (superoinferiorly) oriented; the type II spikes characterizes a neocortical (lateral) process with a dipole that points horizontally. A type I spike therefore may influence the treating team to explore a mesial temporal lobe epilepsy (MTLE) hypothesis targeting just the amygdalohippocampal structures through a lateral approach or an occipitotemporal approach that does not sample lateral temporal cortex at all. A type II spike, however, would mandate a lateral approach with multiple electrodes aiming to delineate lateral resection margins, and in the dominant hemisphere, serving to map language. Because MTLE is such a common disorder, it is worth emphasizing the singular character of spikes arising from the hippocampus. Spikes strictly restricted to the hippocampus are not detected on the scalp at all, the closed field geometry of the hippocampus creating large potential gradients within it, but essentially none outside (Fig. 4). The reason why hippocampal spikes are seen on scalp EEG is because of recruitment of lateral temporal cortex. Nevertheless, source localization methods applied to such spikes may yield source maxima within the hippocampus, thus confirming the hippocampal origin of a spike

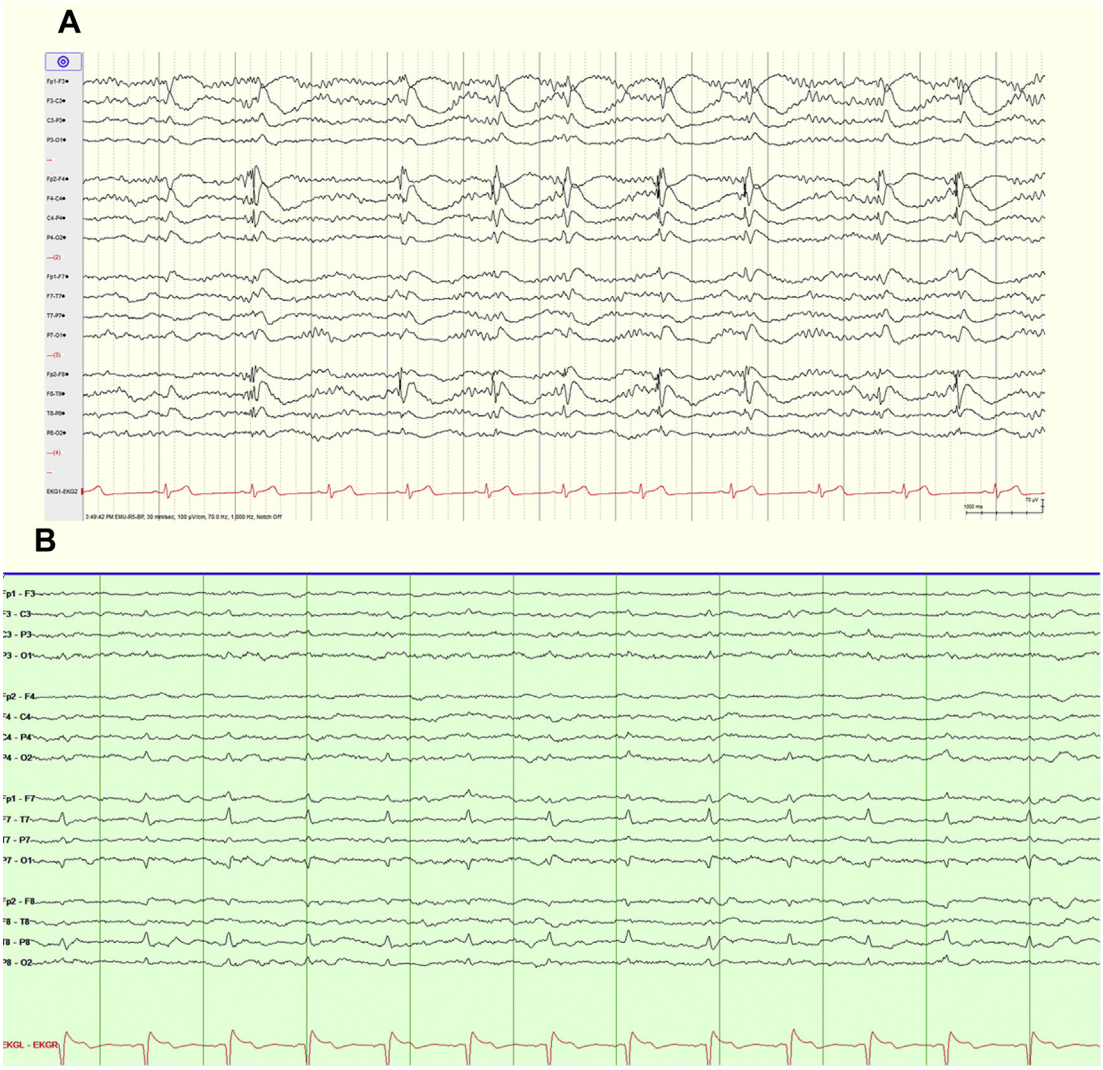

Fig. 2. Bipolar longitudinal montage, 10-second EEG page, 1–70 Hz passband, gain 7–10 μV/mm. (*A*) Repetitive right frontal spikes (large amplitude discharges standing out from the background, each discharge followed by a slow wave) in a sleeping patient with a history of refractory convulsive seizures. The concurrent electrocardiogram is clearly unrelated to the spike pattern. (*B*) Electrocardiogram-synchronous spike-like artifact (diffusely distributed repetitive sharp transients with bitemporal maxima of opposite polarity) in a comatose patient.

that essentially occupies the entire cross-section of the temporal lobe (Fig. 5). Apart from the gross features that identify an epileptiform spike as such, attention to the polarity of the sharp component is informative. An interictal spike is a surface negative phenomenon (ie, the paroxysmal shift in the extracellular field potential is depolarizing in nature) and is conventionally represented by an upgoing deflection on EEG. Such upward deflection is so often the case that one may take it for granted. However, in the setting of recurrent seizures following a temporal lobectomy (for example), spikes may instead show a downgoing (positive) deflection. This is the clue for the generator being deep (possibly embedded in the depths of the resection cavity) with the positive end of its dipole pointing up to the surface. A surface negative spike (whose positive dipolar end would point into the brain) would contrarily indicate a superficial source, and suggest a generator along the intact cortical surface. Different spike types (morphology and distribution), however, are virtually the norm in refractory focal epilepsy, and become important for sEEG planning when the differing spike types also involve disparate regions of the brain. A common example again is temporal lobe epilepsy, when bilateral interictal spikes are commonplace (Fig. 6). How is the

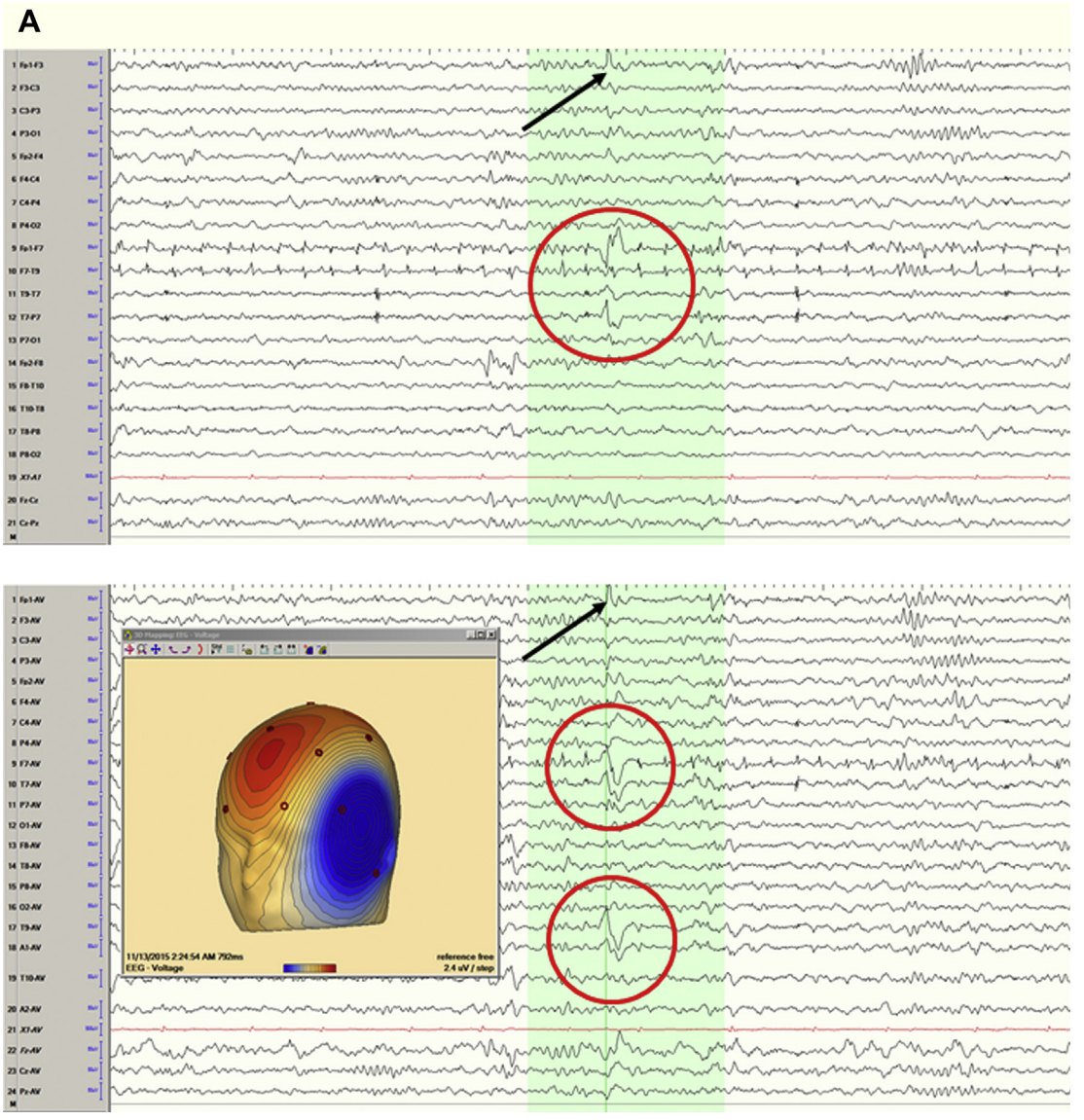

Fig. 3. Bipolar and referential longitudinal montages, 10-second EEG pages, 3–70 Hz passband, gain 7–10 μV/mm. (*A*) Ebersole type I spike in a patient with mesial temporal lobe epilepsy. *Top*, a single spike with a broad anterior and midtemporal maximum (*red circle*) features a positive phase reversal at F3 (*arrow*). *Bottom*, in referential montage the spike appears in the mid- and anterior temporal and subtemporal channels. The *green vertical marker* marking the spike maximum coincides with downward deflections in the frontocentral channels, with a voltage topography map (*inset*) confirming a spike-coincident positivity (*red contours*). The *blue contours* over the temporal region mark the negative primary spike field. (*B*) Ebersole type II spike in a patient with neocortical temporal lobe epilepsy. *Top*, a single spike with broad anterior and midtemporal maxima (*circles*) seen in an extended bipolar montage. *Bottom*, in referential montage the spike appears in the mid- and anterior temporal and subtemporal channels. The *green vertical marker* marking the spike maximum coincides with small upward deflections (*arrow*) in the frontocentral channels, with a voltage topography map (*inset*) confirming broad frontotemporal negativity of the primary spike field over the anterior right hemisphere (*blue contours*).

determination of the more epileptic temporal lobe then made? In the absence of a lateralizing brain lesion and concordant ictal data, this is a difficult problem and is often the reason for proceeding to sEEG with bilateral placements (see Case 2).

Finally, there is the issue of spike propagation. It is natural, but incorrect, to think of a recurring stereotypic interictal spike as fixed disturbance that implicates a single brain location of origin. The duration of an epileptiform spike is defined as

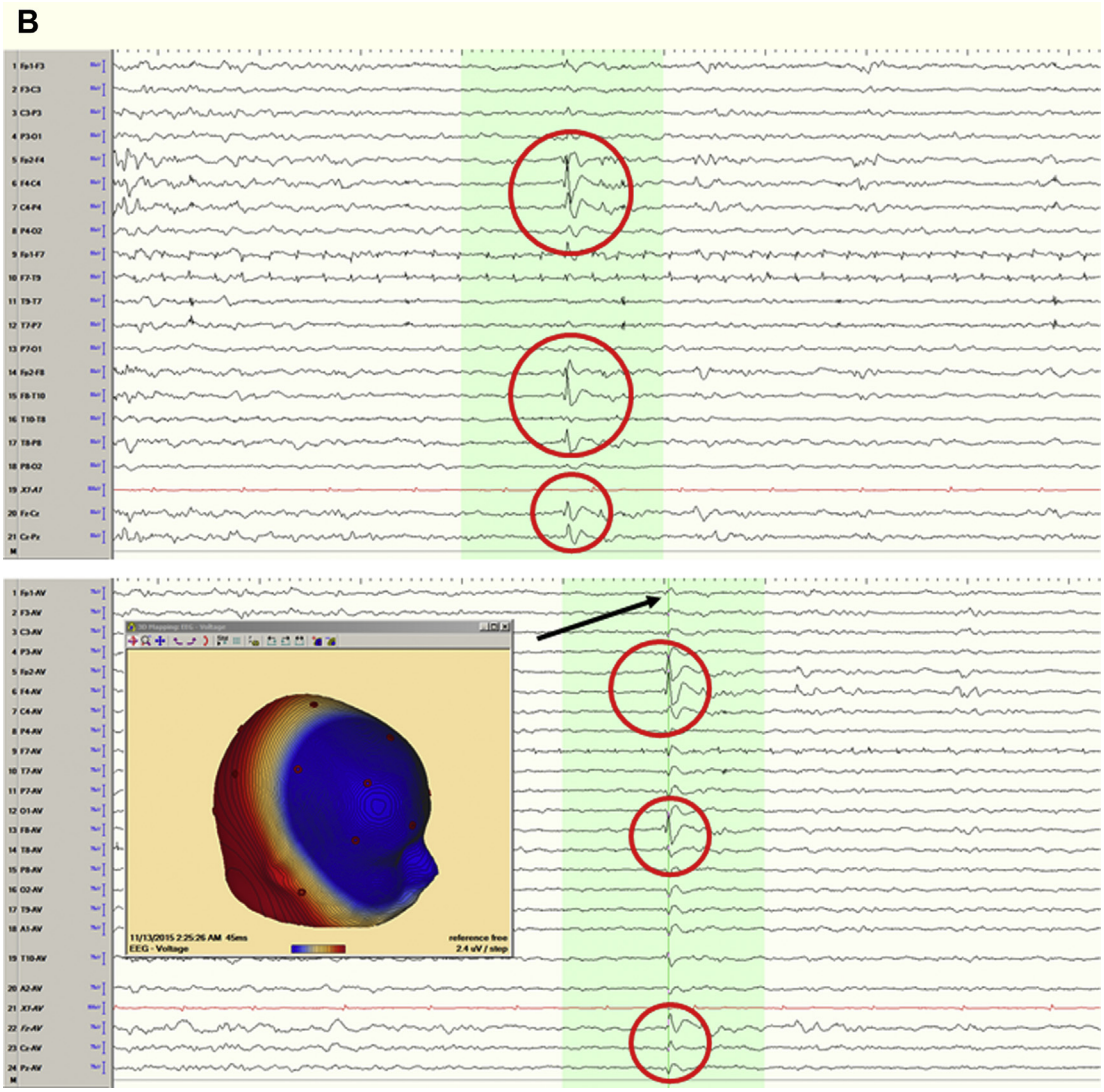

Fig. 3. (*continued*)

less than 80 milliseconds, a period sufficient for neural signals to propagate along the entire rostrocaudal dimension of the brain. The common practice of ascribing spike maxima to a fixed brain region, although technically correct, implicitly assumes that the maximum so identified in within the immediate neighborhood of an important node in the epileptic network. This assumption is often valid in practice, but a more careful analysis provides information about the wider epileptogenic network that can influence sEEG implant strategy (Fig. 7).

Generalized Spikes

Interictal epileptiform activity that seems generalized does not negate the diagnosis of focal lobe epilepsy; equally, generalized epilepsies may exhibit focal EEG features. Clearly, sEEG is only contemplated when the diagnosis of focal epilepsy has been made beyond reasonable doubt in the setting of generalized-looking interictal epileptiform activity. In particular, the spikes of frontopolar epilepsies, naturally maximal in the Fp1/Fp2 derivations, may be confused with the spikes of generalized epilepsy. The distinction is clarified by closer examination that reveals the more limited caudal spatial extent of frontopolar discharges with steeper gradients away from the maxima (Fig. 8). The phenomenon of paradoxic lateralization may confound the picture further in polar and mesial frontal epilepsies. Essentially, a spike dipole situated in the medial wall of one hemisphere may project across the midline to mimic a

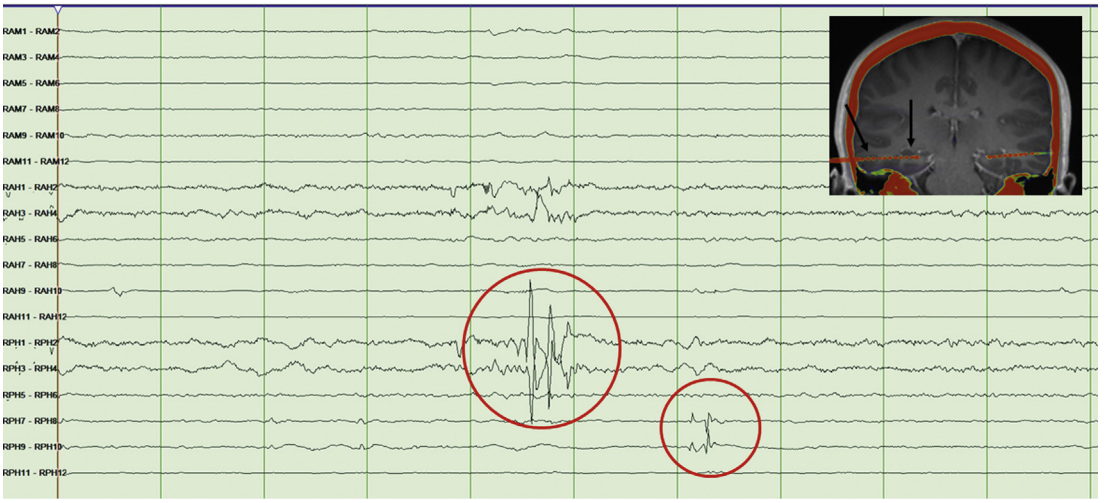

Fig. 4. Closed-field nature of hippocampal spikes. A 10-second intracranial EEG page of a patient undergoing sEEG to confirm suspected right temporal lobe epilepsy, showing right amygdalar, anterior hippocampal, and posterior hippocampal activity in sparse bipolar montage (passband 3–200 Hz, gain 50 μV/mm). Small numbers (eg, RAH1, RAH2) refer to deep contacts and larger numbers (eg, RAH 9, RAH 10) to superficial contacts. *Inset* shows the position of bilateral posterior hippocampal electrodes derived from a coregistered post-implant computed tomography within the MRI volume. The high amplitude posterior hippocampal discharge (RMH1-RMH2, RMH3-RMH4; *large red circle*; *vertical arrow* in inset) has no detectable presence in the lateral channels. Independent neocortical spiking (RPH7-RPH8, RPH9-RPH10; *small red circle*; *oblique arrow* in inset) is seen.

contralateral process (Fig. 9). Careful analysis of spike polarities, in addition to the ancillary clinical information, should make the distinction clear. It is evident how significantly the plan of an sEEG implant could change dependent on these analyses. Medial frontal epilepsies are another mimic of generalized epilepsy because of the phenomenon of secondary bilateral synchrony: essentially the rapid spread of an interictal discharge across the narrow gap between the hemispheres along fast-conducting callosal fibers. In a nonlesional patient without convincing lateralizing seizure semiology, the distinction between a left and right hemispheric epilepsy is difficult to make, leading to bilateral implants that sample medial frontal areas (Fig. 10).

ICTAL ELECTROENCEPHALOGRAM

The spatiotemporally dynamic nature of the ictal EEG renders it less valuable for precise delineation of the core epileptic network. For example, the seizure of mesial temporal epilepsy may emerge from the hippocampus to involve the temporal neocortex, and then evolve further to a generalized convulsion. Such a sequence does not imply the temporal neocortex, much less the whole brain, should be considered part of the epileptic network. Yet, as in this example, a concordant ictal EEG remains all-important in securing the electroclinical hypothesis for a subsequent (if needed) sEEG implant. In temporal lobe epilepsy, it is useful to bear in mind well-established empirical rules regarding specific concordances. Because of the previously referenced closed-field nature of the hippocampus, seizures of hippocampal origin may not be seen on the surface at seizure onset. The Risinger criteria[4] allow for a delay of up to 30 seconds between the clinical onset of a seizure (eg, aura reported by the patient) and the appearance of a surface EEG ictal rhythm, for that seizure to still be classified as a mesial temporal lobe seizure. Once visible on the surface, a sharply defined theta (4–7 Hz) is highly correlated with the mesial temporal origin of that seizure (Fig. 11A). Slower ictal rhythms in the delta (<4 Hz) range (Fig. 11B), or higher than theta (>7 Hz) are more likely to be of neocortical temporal onset.[5] An implantation scheme in the temporal lobe significantly depends on whether the hypothesis is a medial or lateral one. Frontal lobe ictal EEG depends on the source and propagation pattern of the seizure. Lateral frontal lobe patterns are easily understood if they accompany versive semiology characteristic of seizures involving this brain area. Low-voltage fast discharges generally indicate superficial,

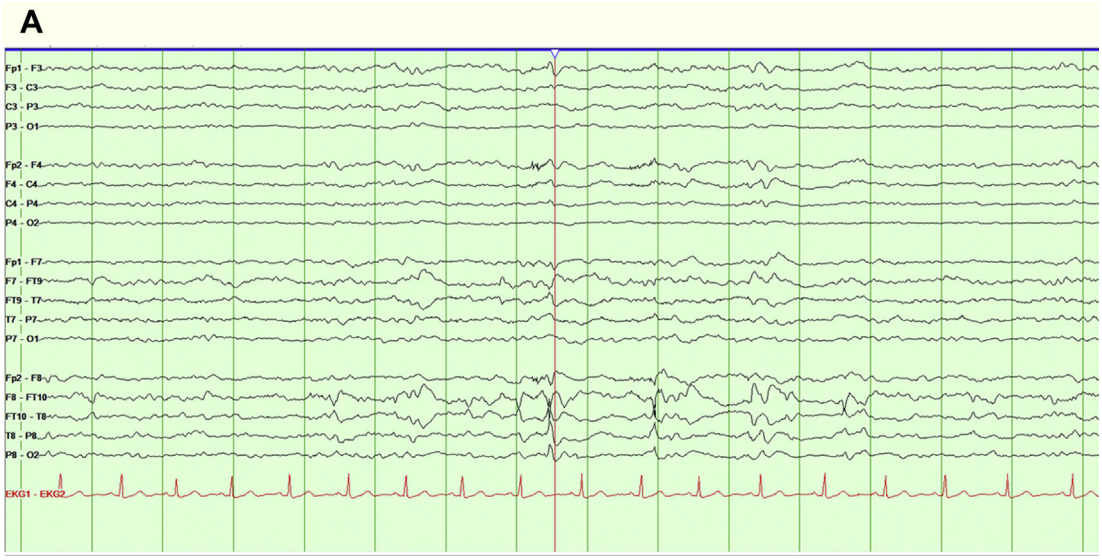

Fig. 5. (*A*) A 10-second EEG page, bipolar longitudinal montage, 1–70 Hz passband, gain 7 μV/mm. Repetitive spikes, maximum FT10 (right anterior temporal) in a patient with a history suggestive of seizures of mesial temporal origin. Scalp EEG spikes of this type necessarily imply neocortical involvement (see text). (*B*) Source localization nevertheless positions the single equivalent current dipole solution (*red ball and stick* projected on the lateral cortical surface (*top*) and within the MRI volume (*bottom*) in the right hippocampus with Ebersole type I dipole orientation.

delimited sources[6] that an implant should explore. Polar, orbitofrontal, and medial frontal ictal EEG is more variable and essentially depends on the network propagation pattern. Orbitofrontal seizures with temporal lobe spread may well mimic a temporal lobe ictal EEG, whereas propagation along the medial frontal surface may be nonlocalizing. Premotor medial frontal seizures may be accompanied by diffuse electrodecrement. sEEG exploration of the frontal lobe remains challenging in a patient without a relevant structural lesion; an implant scheme, perhaps more than in any other case, needs to be based on the gestalt of the patient presentation and not lean too heavily on any one modality. Because of the rich feedforward connections of the brain's visual areas, the ictal EEG of posterior cortex epilepsies may be more prominent in spread pattern than in onset patterns. Indeed, prominent engagement of anterior brain areas may swamp posterior onsets, and a high index of suspicion for posterior quadrant epilepsy is not out of place in frontal or temporal lobe syndromes with suggestive features (see Case 3). A final group of epilepsies to consider is that associated with subcortical heterotopias. The era of sEEG increasingly discovers the complex network patterns of epilepsy associated with heterotopias, ranging from seizure networks firmly originating in the heterotopias, to those more involving the overlying cortex, to hybrid situations between the previous two, and to networks seemingly remote to the heterotopias.[7,8] The latter situation includes our observations (Kalamangalam, unpublished data, 2020) of profusely heterotopic temporal lobes with clinical features of temporal lobe epilepsy, that when explored with sEEG exhibit seizure onsets that barely involve the heterotopias but instead arise from their structurally normal hippocampi. A rule of thumb strategy in epilepsy associated with heterotopias is probably to sample as many of the discrete heterotopic nodules as possible, the overlying cortex in every case, and any other brain areas clinically suspected to involve the network.

COMBINING THE INTERICTAL AND ICTAL SCALP ELECTROENCEPHALOGRAM FOR STEREOELECTROENCEPHALOGRAM

The goal of individual analyses of the interictal and ictal EEG, detailed as they may be, is to synthesize the findings into a unified hypothesis. When there is spatial concordance between the interictal and ictal EEG, such synthesis is unambiguous in implicating a single brain region or well-defined network. Indeed, a formal Bayesian approach shows that concordance of this type (ie, colocalization of the interictal and ictal EEG to the same brain lobe) is

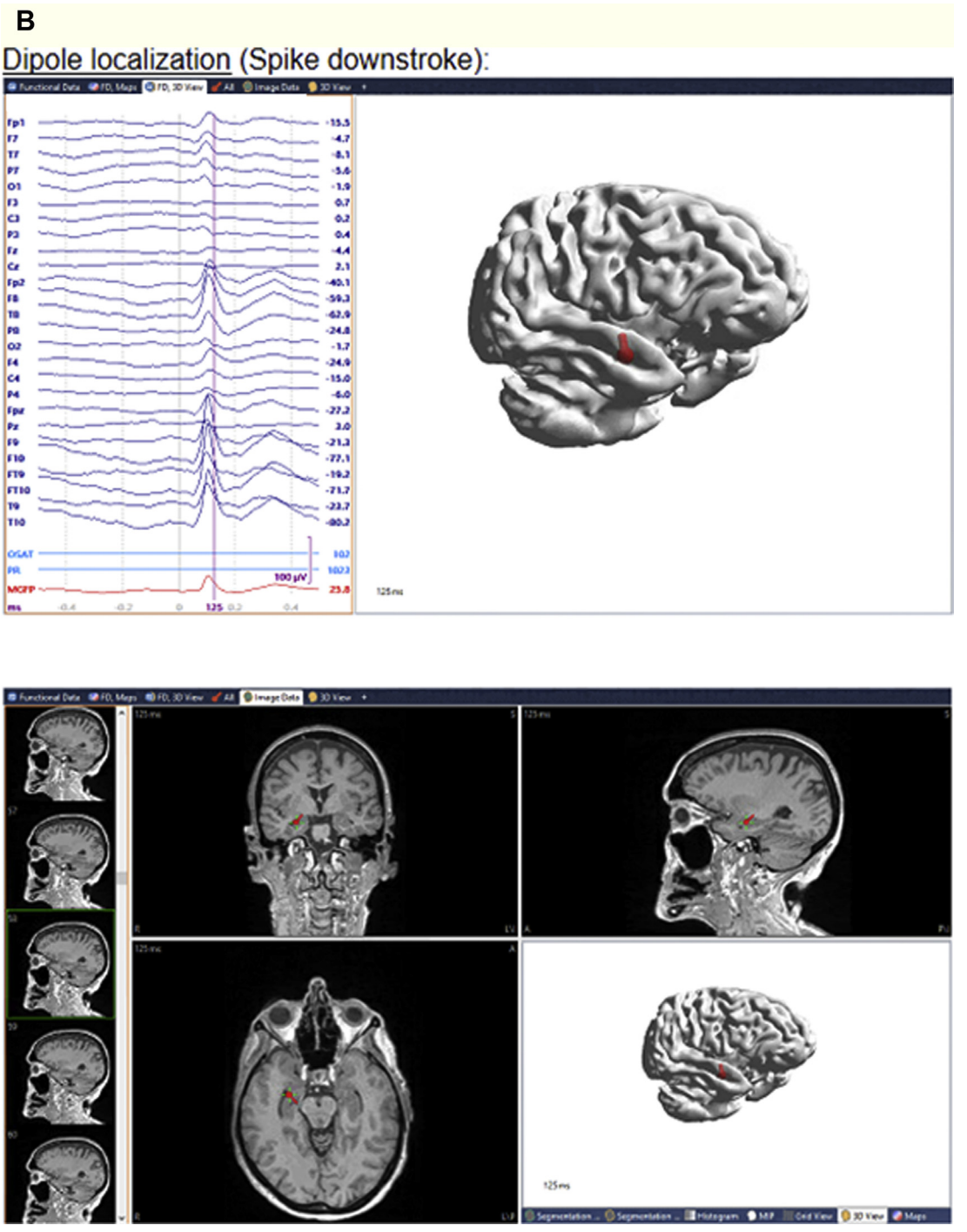

Fig. 5. (*continued*)

highly predictive of a successful subsequent intracranial exploration.[9,10] Yet, much of the challenge of sEEG, and often the indication for sEEG, is because of discordant or uninformative individual data points. The following case scenarios particularly illustrate the role of the extracranial interictal and ictal EEG in building an electroclinical network hypothesis for sEEG implantation.

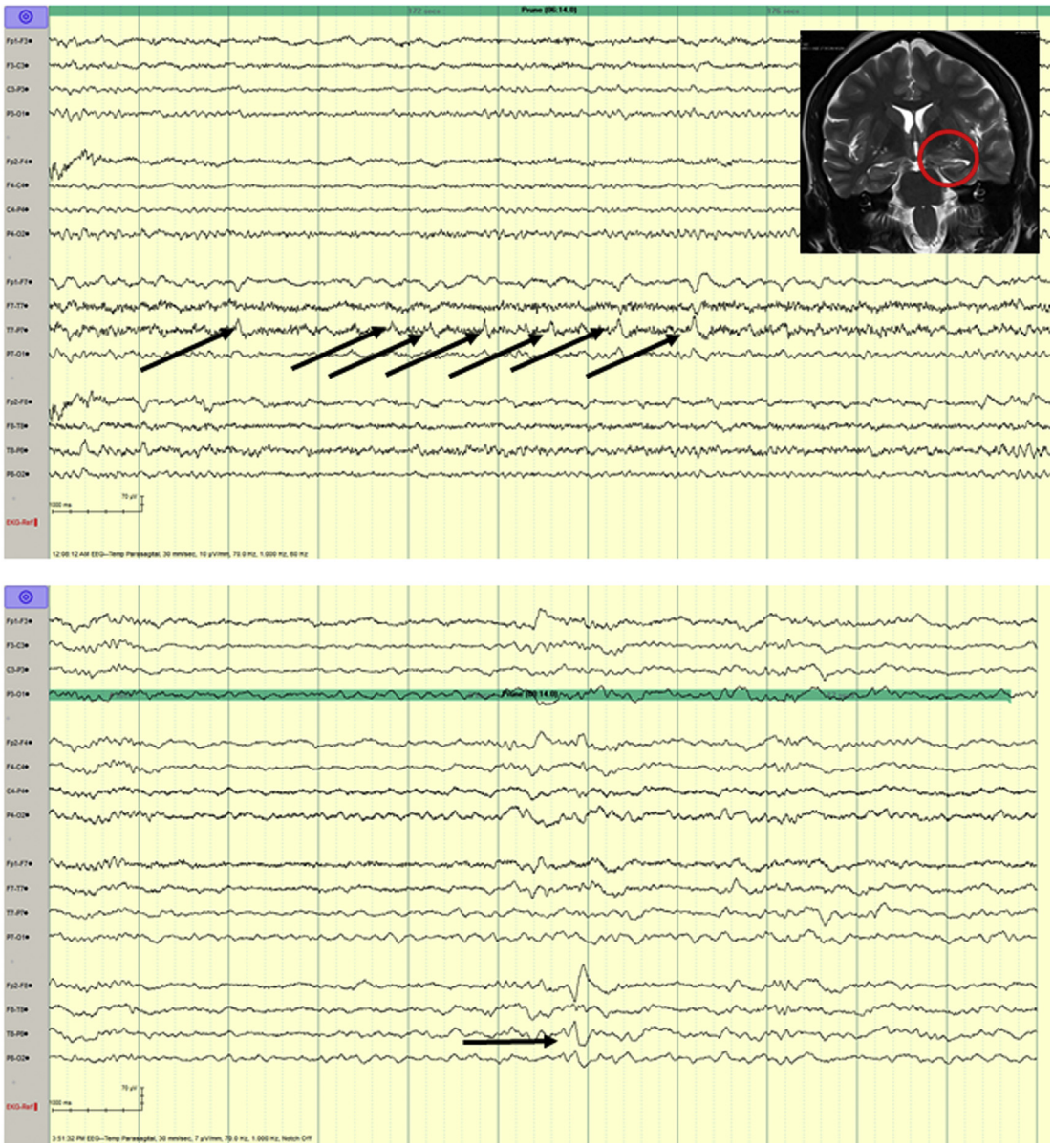

Fig. 6. A 10-second EEG page, bipolar longitudinal montage, bandpass 1–70 Hz, gain 7 μV/mm. *Top*, repetitive spikes (*oblique arrows*) in the left temporal lobe, maximum midtemporal, in a patient with mesial temporal lobe epilepsy associated with left hippocampal sclerosis (*inset*). *Bottom*, right temporal spike (*horizontal arrow*) in the same patient.

CASE 1

Data

A 47-year-old right-handed woman was evaluated for a 30-year seizure history. Seizures started with a feeling of panic and an urge to overbreathe, progressing to loss of speech and comprehension lasting a few minutes. Occasionally she experienced generalized convulsive seizures. Interictal EEG was normal. Ictal EEG showed either no definite change, or a left temporal rhythmic theta (not shown) occurring within 30 seconds of clinical push-button onset. MRI brain showed left hippocampal sclerosis.

Analysis

Despite the imaging findings, seizure semiology, with its strong autonomic and affective features,

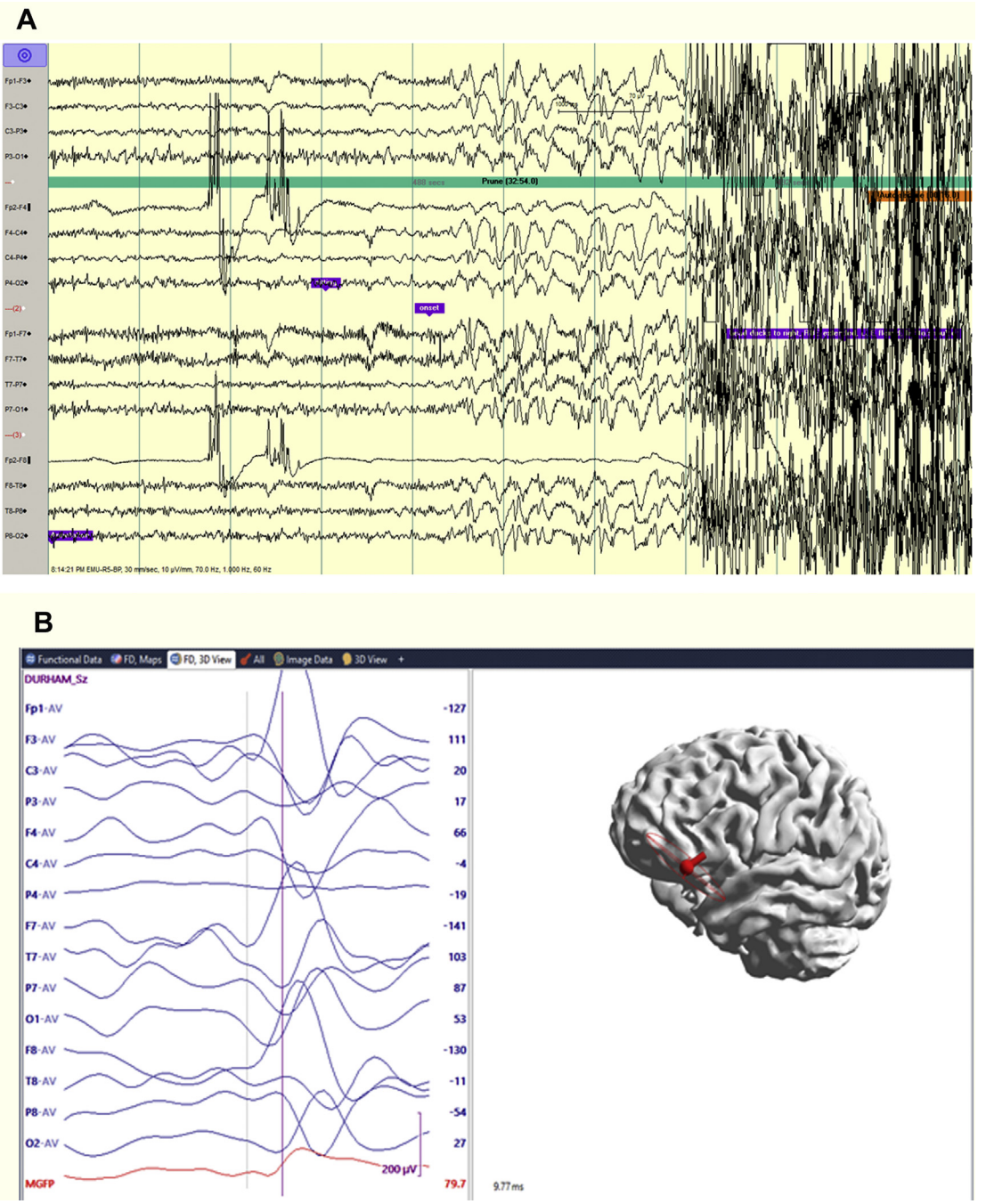

Fig. 7. (*A*) A 10-second scalp EEG page, longitudinal bipolar montage, 1–70 Hz bandpass, 10 μV/mm gain. A broadly distributed spike burst, subtly asymmetric and higher over the left hemisphere, seen in a patient with refractory tonic seizures suggesting premotor focal epilepsy. (*B*) The first of a sequence of dynamic spike localizations by an equivalent current dipole model. The *vertical red line* indicates the time point considered at the upstroke of a single discharge within the burst. The source is localized to the anterior inferior left frontal lobe of the patient's reconstructed MRI surface (*red ball and stick* indicates maximum; the surrounding ellipse is retained to indicate error margins). (*C*) Forward progress along the discharge by a single time step (5 ms, equal to the EEG sampling frequency) moves the dipole more anteriorly and superiorly; the error ellipse shrinks to indicate a highly localized source at this instant. (*D*) A further time step forward locates the dipole in the left medial frontal region. The error ellipse expands again but stays within the medial frontal wall. The spike propagation pattern overall confirms a left anterior frontal epilepsy and suggests a lateral-to-medial network pathway, explaining the scalp EEG spike activity indicating a superficial source, and the seizure semiology implicating medial premotor frontal cortex.

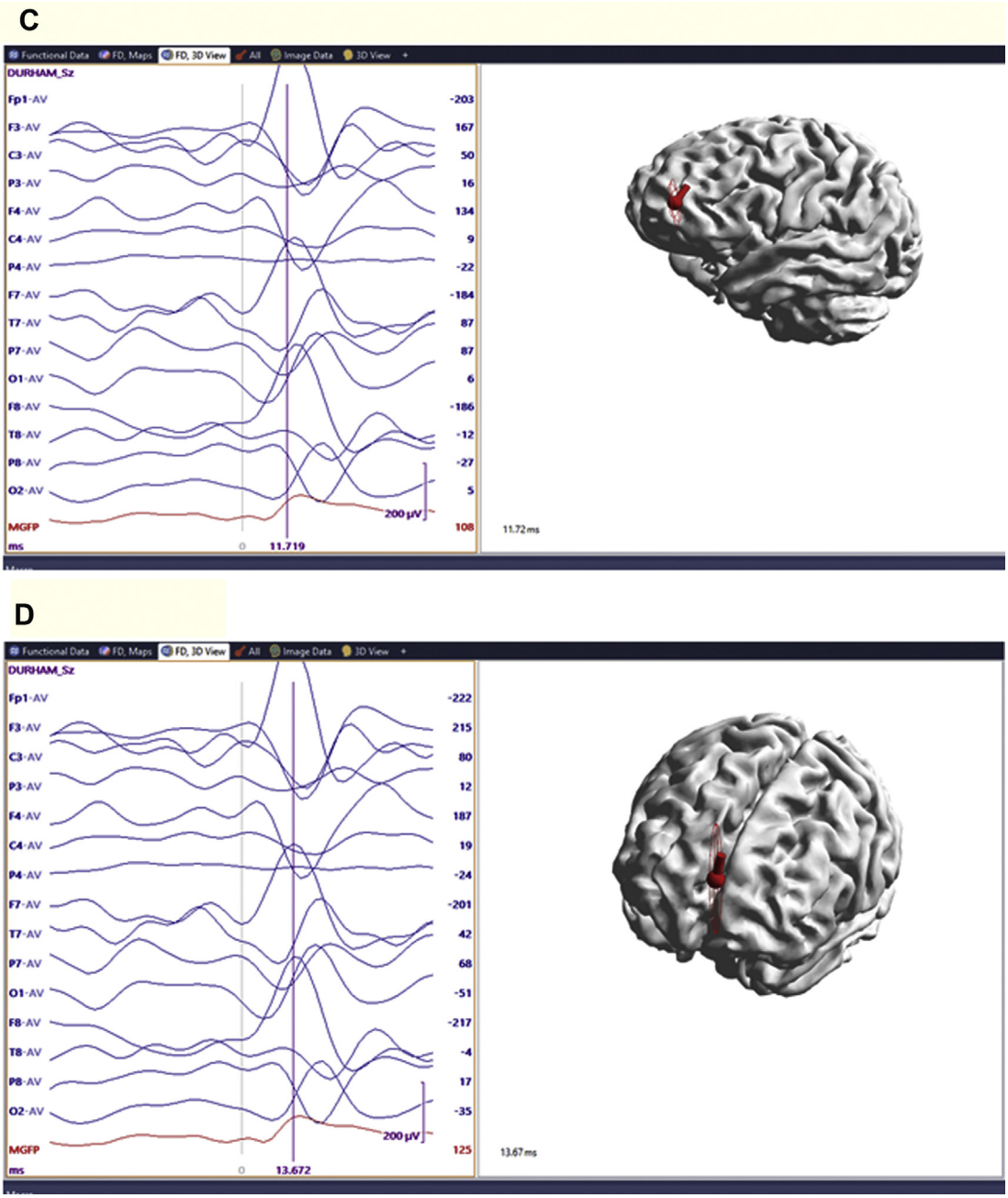

Fig. 7. (*continued*)

was considered atypical for MTLE. The complete lack of interictal EEG abnormalities and the equivocal ictal EEG during some seizures raised the possibility of a network involving deep limbic regions in addition to the amygdalohippocampal complex (the cingulum and septal-posterior orbitofrontal region) and the insula.

Implant

The left temporal lobe was sampled orthogonally to target the amygdala and hippocampus, with a more posterior electrode to sample the parahippocampal gyrus (**Fig. 12**A). Extratemporal contacts were introduced into the anterior insula, anterior

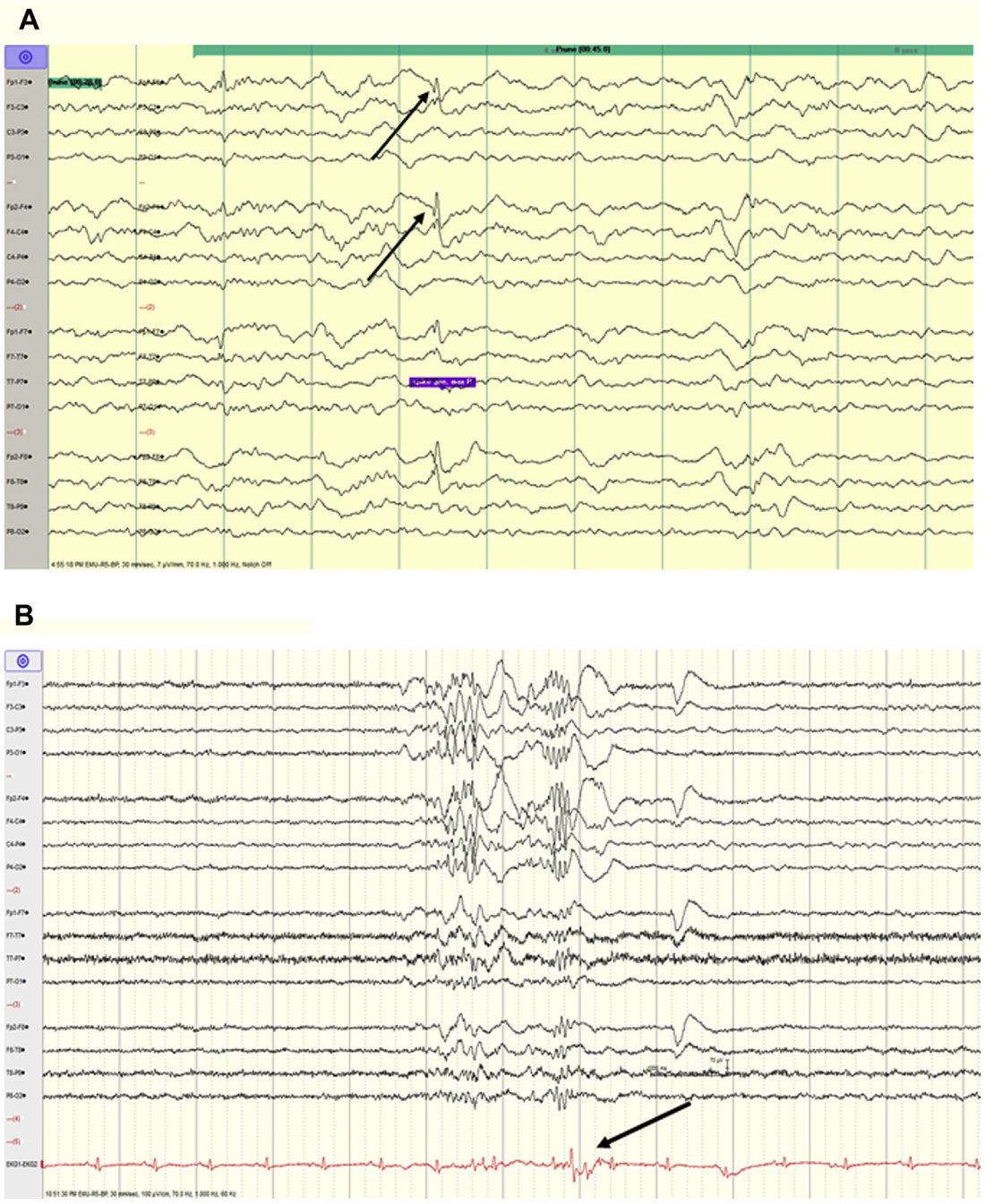

Fig. 8. A 10-second scalp EEG page, longitudinal bipolar montage, 1–70 Hz bandpass, 7 μV/mm gain. (*A*) Bifrontal spikes in a patient with a frontopolar epilepsy, mimicking a generalized epileptiform discharge. Focal epilepsy is suggested despite the bilateral appearance of the spike from its sharp anteroposterior gradient (the posterior channels are uninvolved). Closer examination of the polarity of the spike (*arrows*) suggests an initial positivity, implying a deep source (the basal medial frontal area in this case). (*B*) Two successive generalized polyspike discharges in a patient with juvenile myoclonic epilepsy. There is no appreciable asymmetry; the spikes involve every channel. Electrocardiogram artifact (*arrow*) is evidence of sudden body movement (myoclonus) time-locked to the discharge, typical of juvenile myoclonic epilepsy.

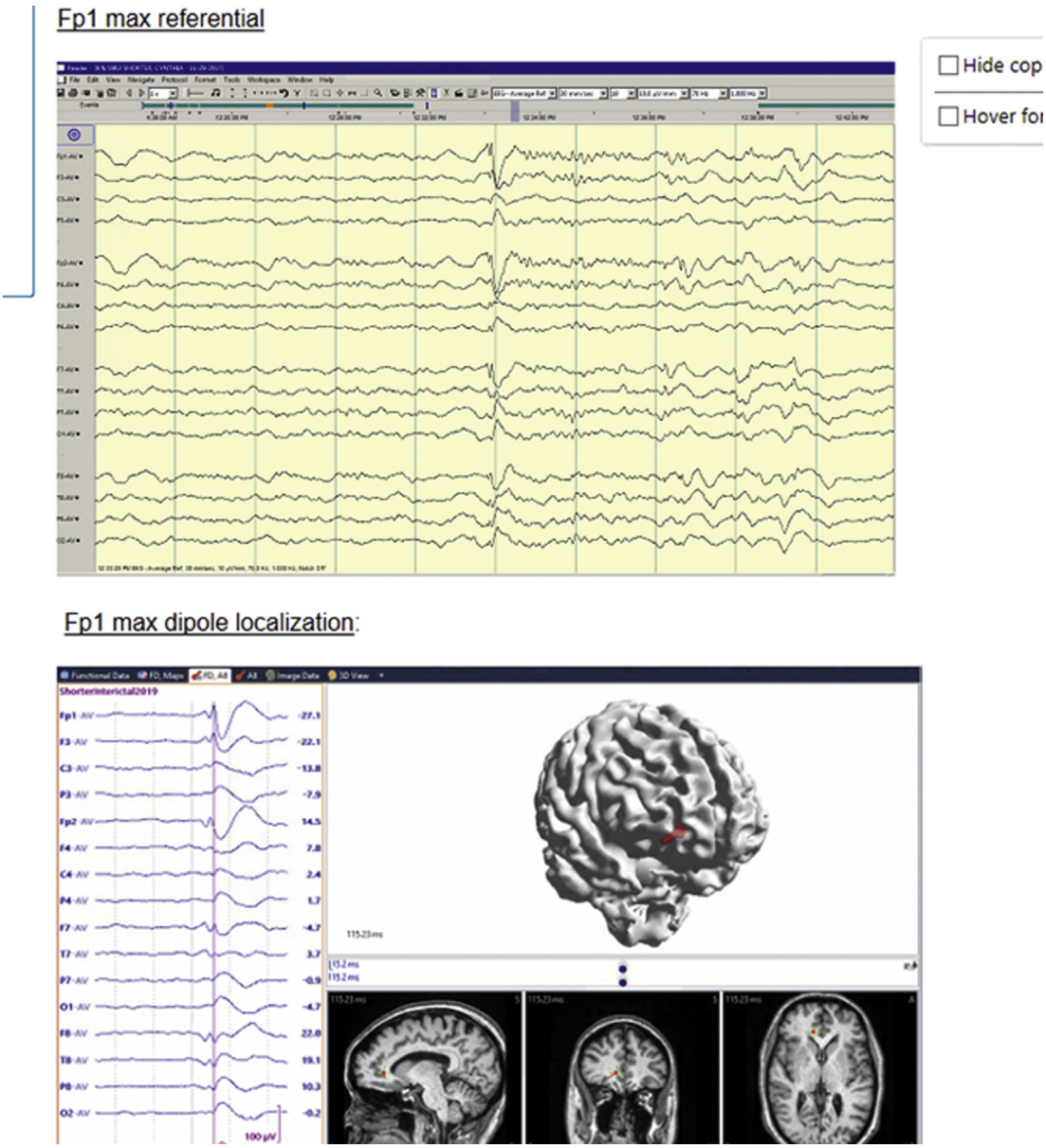

Fig. 9. Paradoxic lateralization in a patient with frontal pole epilepsy (same patient as in Fig. 8A). (*Top*) A 10-second EEG page, longitudinal referential montage, passband 1–70 Hz, 10 μV/mm gain. Bifrontal spike discharge in sleep, apparently higher over the left hemisphere. (*Bottom*) Source localization positions an equivalent current dipole in the hemisphere, but oriented with negativity pointing across the interhemispheric fissure. A broad negative deflection maximal over the frontal pole (Fp1) is therefore picked up over the left hemisphere, falsely lateralizing the right-sided spike source.

cingulate, the rostral cingulate/septal region, and the orbitofrontal cortex.

Outcome

Spikes arose exclusively from the hippocampus, and all seizures were of exquisite focal onset within the hippocampus (Fig. 12B). The patient underwent a thermal ablation of the left hippocampus and has done well since.

Comment

It is rare to encounter long-standing temporal lobe epilepsy without spikes on scalp EEG. Yet, on first principles, hippocampal spikes do not have the

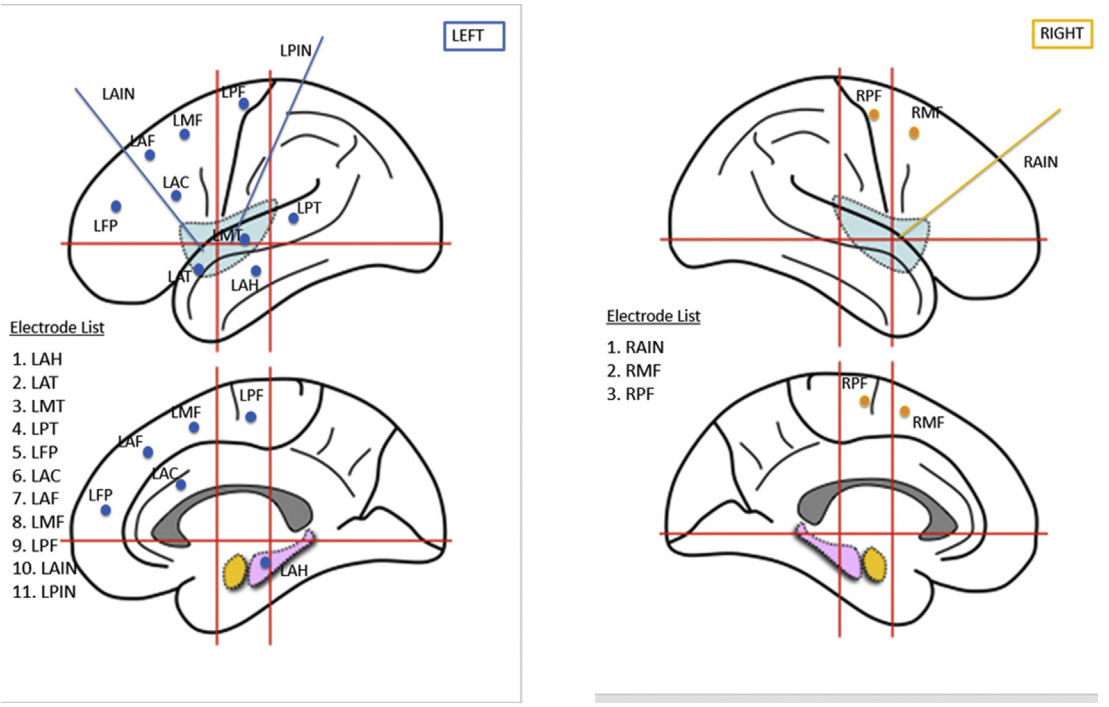

Fig. 10. Illustration of the sEEG implant plan for a patient with suspected medial frontal symptomatogenic seizure semiology and diffuse, left-maximum interictal discharges (same patient as in Fig. 7). The left frontal lobe is sampled broadly with orthogonally placed electrodes (LFP, LAF, LMF, LPF, LAC). Temporal lobe involvement for a broader understanding of the network is studied with a single electrode targeting the left hippocampus (LAH). Additional neocortical temporal electrodes (LAT, LMT, LPT), normally extraneous in such a case, were placed because of concerns of possible subtle cortical thickening over the superior temporal surface. The left insula was sampled anteriorly and posteriorly (LAIN, LPIN). The right frontal lobe and insular regions were sampled sparsely (RMF, RPF, RAIN). AC, anterior cingulate; AF, anterior frontal; AH, anterior hippocampus; AIN, anterior insular; AT, anterior temporal; FP, frontopolar; L, left; MF, midfrontal; MT, midtemporal; PF, posterior frontal; PIN, posterior insular; PT, posterior temporal; R, right. (sEEG templates *Courtesy of* Dr Phillippe Kahane and Dr Philippe Ryvlin.)

field geometry for detection on the surface, and this was largely the reason the diagnosis of MTLE was in doubt in this patient. The exclusively hippocampal nature of her seizure onsets may also have been the reason for the uninformative ictal EEG in a few of her briefer scalp-recorded seizures.

CASE 2

Data

A 21-year-old right-handed man was evaluated for a 5-year history of seizures, comprising episodes of lightheadedness followed by blinking and unresponsiveness. Occasionally, he experienced seizures arising from sleep characterized by agitation and confusion. Interictal EEG showed right greater than left polyspike bursts over the temporal regions (Fig. 13A, B). Ictal onset of his nocturnal seizures was over the right hemisphere, in the posteroinferior derivations; several subclinical EEG seizures were recorded from the left temporal region as well (Fig. 13C, D). MRI revealed a region of pachygyric dysplasia in the right inferomesial temporal lobe (Fig. 13E).

Analysis

Despite the imaging lesion, the floridly bilateral EEG findings precluded proceeding to resection without an invasive evaluation. The hoped-for answer was that the network was largely right-sided, and that left-sided seizures was secondary to right-sided onsets that were not visible on the scalp. In such a case, a right-sided surgical resection is possible; however, truly independent left-sided seizure onsets preclude such a resection.

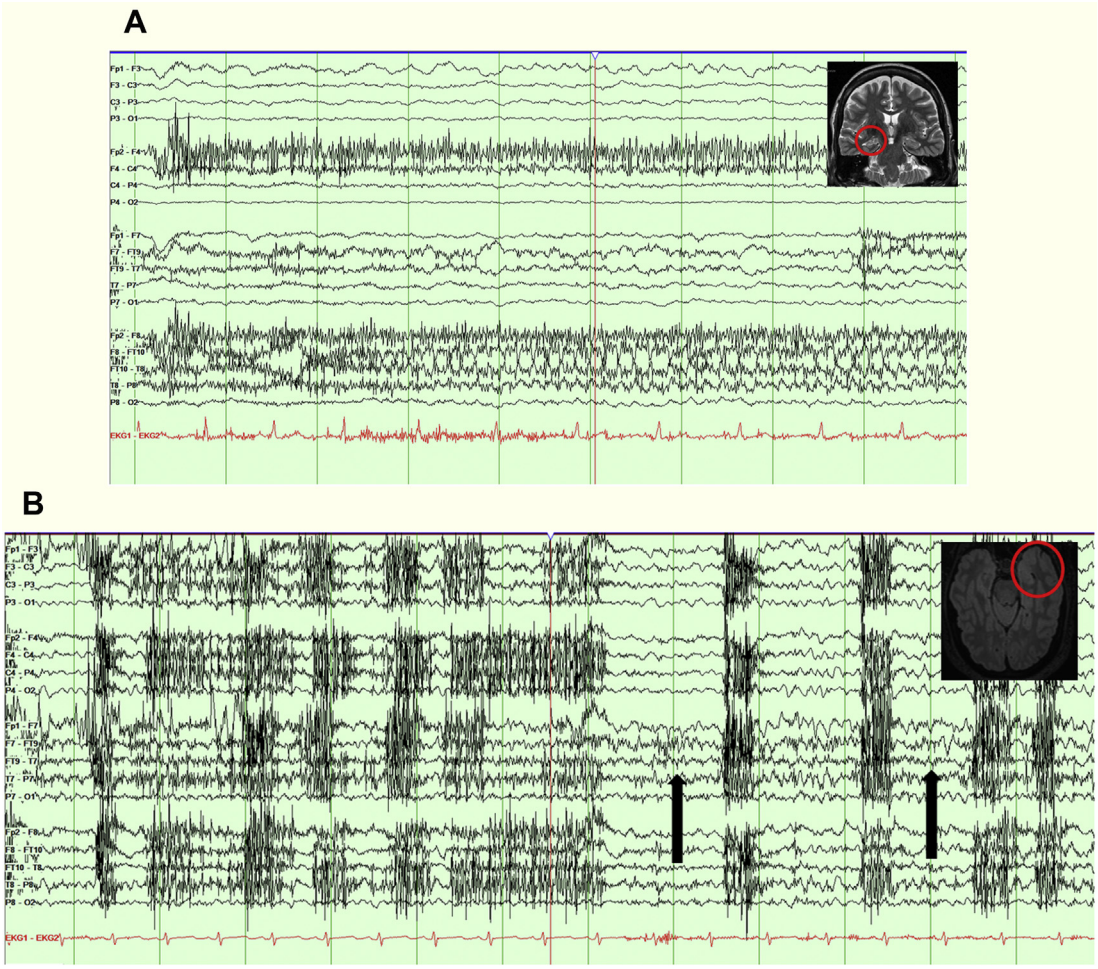

Fig. 11. (*A*) A 5- to 6-Hz rhythmic pattern in the right temporal derivations, typical of seizures in mesial temporal lobe epilepsy in a patient with a concordant history and right hippocampal sclerosis (*inset*). (*B*) Partial seizure characterized by confusion and speech difficulties in a patient with neocortical temporal lobe epilepsy because of left temporal pole cortical dysplasia (*inset*). The ictal rhythm over the left temporal derivation is ~4 Hz and more diffusely distributed.

Implant

The right temporal lobe was sampled diagonally through the superior temporal gyrus to sample the dysplastic area anteriorly and posteriorly, in addition to orthogonal placements to sample the temporal neocortex from temporal pole to the temporo-occipital region, including one electrode each targeting the amygdala and hippocampus (Fig. 13F). The left temporal lobe placements were essentially a sparse mirror image of the right.

Outcome

Interictal spikes arose from the right hippocampus and from lateral and medial contacts of the neocortical electrodes that targeted the dysplasia (Fig. 13G). On the left, spikes were less profuse but in a similar distribution. Four seizures with typical clinical manifestations arose from the right side, with onsets multifocal over the hippocampal and neocortical contacts (Fig. 13H). There were 18 seizures recorded from the left of more restricted hippocampal-basal temporal origin (see Fig. 13H) either with no clinical signs or

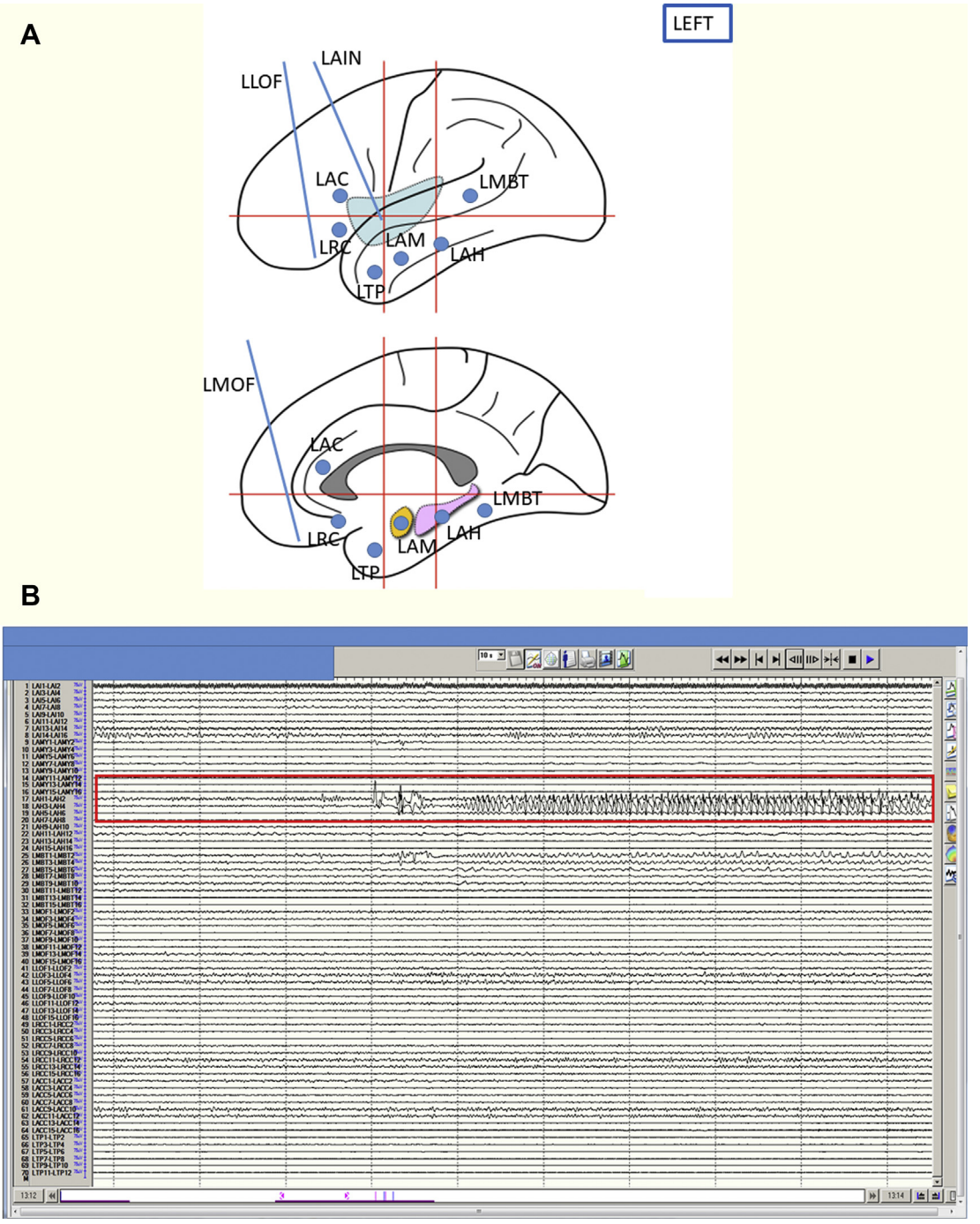

Fig. 12. (*A*) The left temporal lobe is sampled with orthogonally placed electrodes (LTP, LAM, LAH, LMBT). Additional electrodes sample deep limbic structures (LLOF, LLMF, LAC, LRC) in addition to the left anterior insula (LAIN). AC, anterior cingulate; AH, anterior hippocampus; AM, amygdala; L, left; LOF, lateral orbitofrontal; MBT, midbasal temporal; MOF, medial orbitofrontal; RC, rostral cingulate; TP, temporal pole (sEEG templates for this and following cases *Courtesy of* Dr Phillippe Kahane and Dr Philippe Ryvlin.) (*B*) A 10-second intracranial EEG page, showing all implanted channels in bipolar montage (passband 5–70 Hz, gain 50 μV/mm). Exquisitely focal ictal onset is demonstrated within the left hippocampus (LAH1-LAH2, LAH3-LAH4).

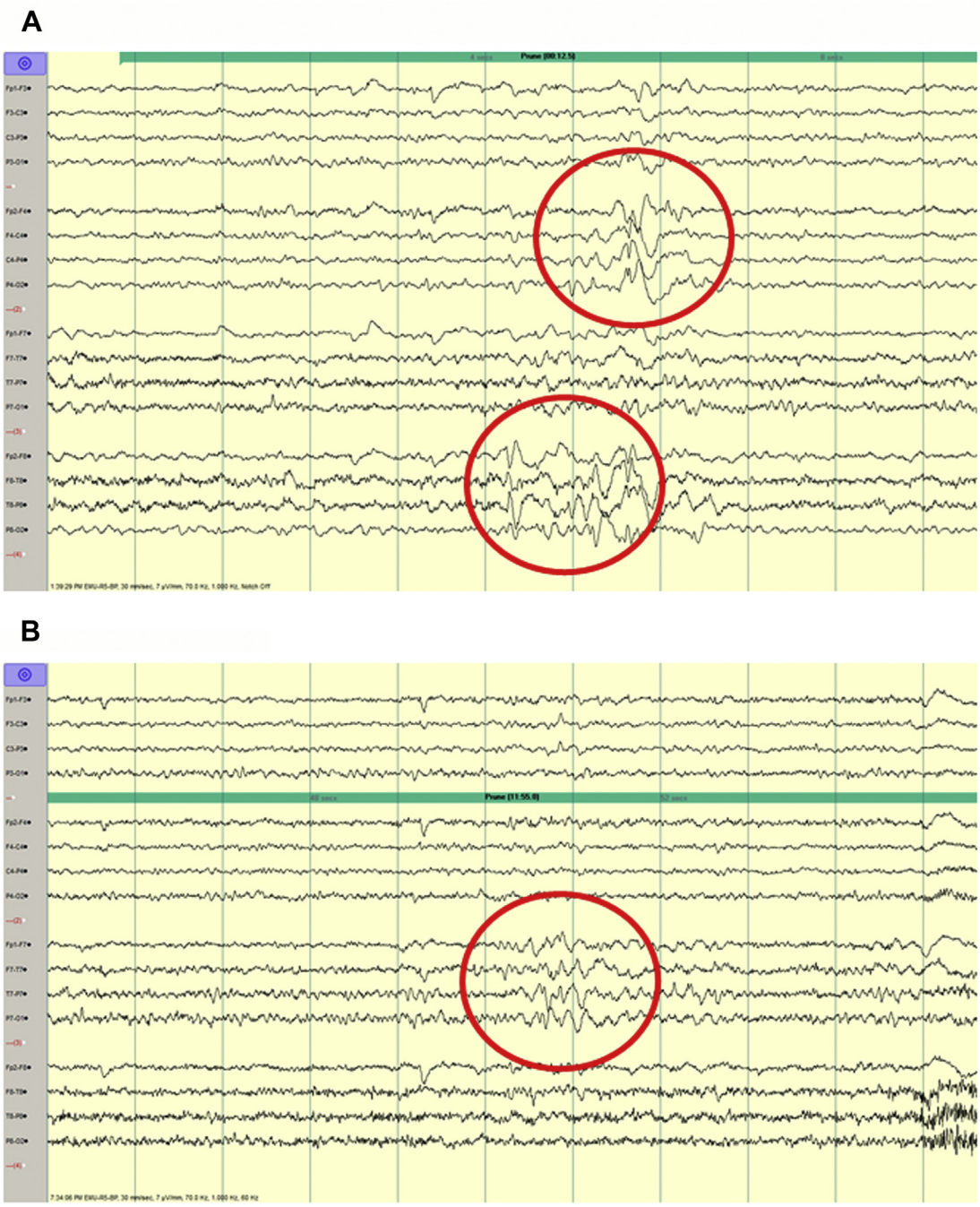

Fig. 13. A 10-second EEG page, longitudinal bipolar montage, passband 1–70 Hz, 7 μV/mm gain. (*A*) Broadly distributed, temporal maximum spike-polyspike burst (*circled*) over the right hemisphere. (*B*) More spatially restricted but independent left temporal spike-polyspike burst (*circled*). (*C*) Right-sided ictal onset arising from sleep, with beta frequency evolving discharge, maximum posterior temporal (*arrows*). (*D*) Rhythmic theta frequency EEG seizure (*boxed*) over the left temporal lobe. (*E*) T2-weighted coronal view through the midhippocampal region showing pachygyric dysplasia of the right inferomedial temporal lobe (circle). (*F*) The right temporal lobe including the lesional area is sampled with orthogonally placed electrodes (RTP, RAM, RAH, RABT, RPBT). Sampling is carried posteriorly with electrodes in the lingula, retrosplenium, and the occipital lobe. Implant on the left side is a sparse version of the right. ABT, anterior basal temporal; LIN, lingula; O, occipital; PBT, posterior basal temporal; RS, retrosplenium. (*G*) A 10-second intracranial EEG page, showing right-sided (*top*) and left-sided (*bottom*) implanted channels in bipolar montage (passband 5–70 Hz, gain 50 μV/mm). Spike bursts within the right amygdalohippocampus and throughout the length of the anterior basal temporal electrode; a prolonged polymorphic spike-polyspike burst is seen over the superficial contacts of the left posterior basal temporal electrode (*box*). (*H*) Ictal onsets over the right-sided electrodes in a multifocal manner (*arrows, top*); focal ictal onset within the left hippocampus (*arrow, bottom*).

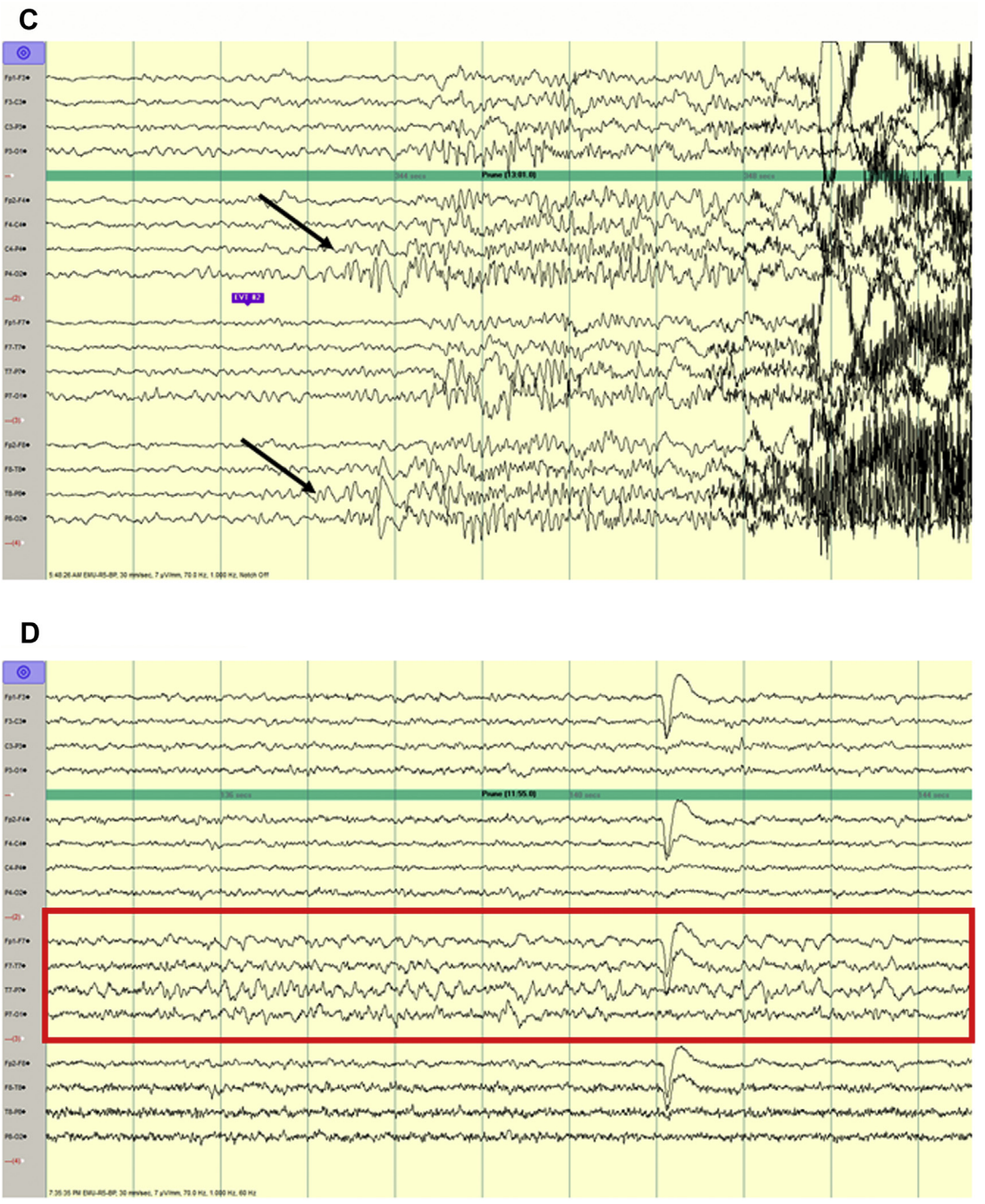

Fig. 13. (*continued*)

with subtle subjective feelings that were not well described. Following discussion, the patient accepted neuromodulatory treatment with responsive neurostimulation of both temporal lobes. If over the longer term, because of neuromodulatory changes or otherwise, his seizures develop a significant right greater than left asymmetry, surgical resection of the right temporal lobe to include the dysplastic area remains a possibility.[11]

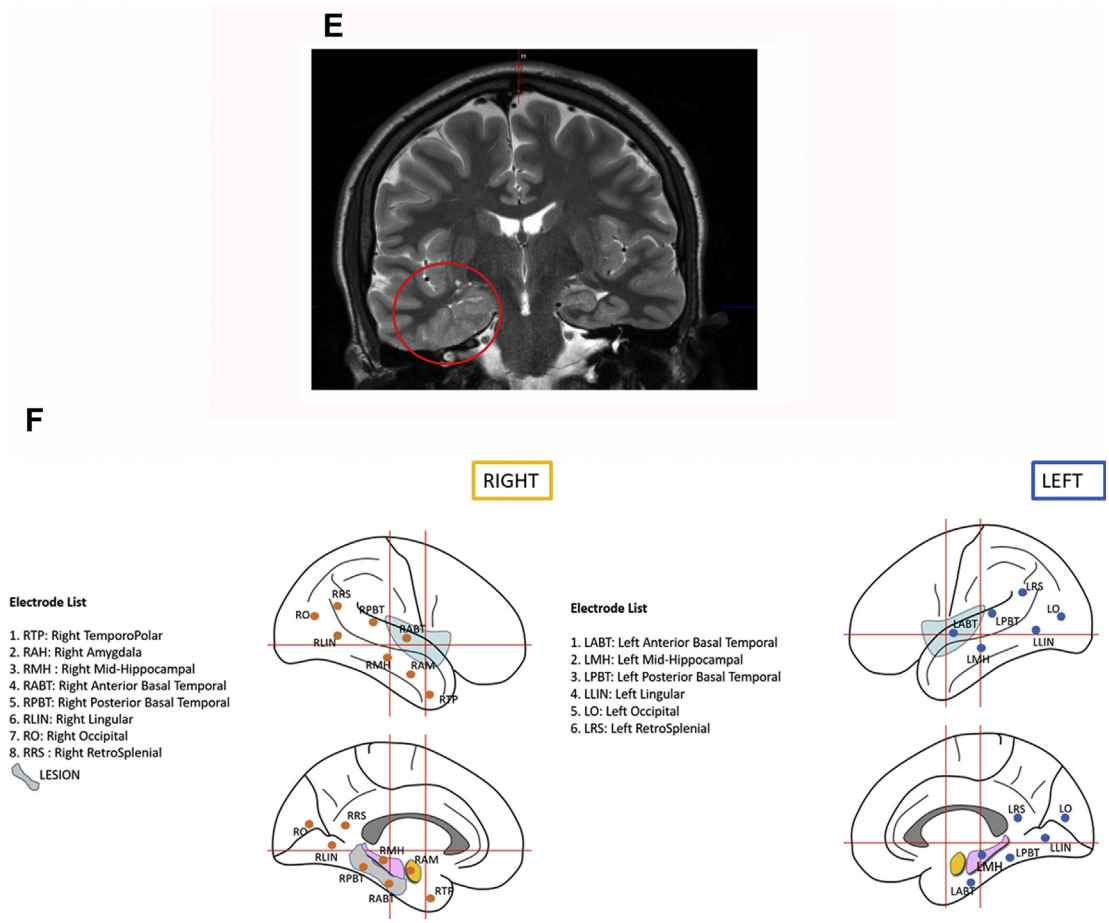

Fig. 13. (*continued*)

Comment

Although bilateral spikes are virtually universal in otherwise unilateral temporal lobe epilepsy, this patient's bilaterality hinted at independent right-left epileptogenic processes at the outset. Contralateral interictal spikes in unilateral temporal lobe epilepsy tend to have a monomorphic character, and when source localized, yield a hippocampal maximum (see Fig. 5B). This patient's left-sided spikes had a polyspike character, more in keeping with a superficial source. Ictal involvement of the left side always appeared exclusive of any preceding right-sided changes, and had a markedly different character to his clinically manifesting right-sided seizures. This feature pointed to two distinct propagation pathways from the same right-sided source, or two separate right-sided sources, if indeed his left-sided seizures were consequent to right-sided onsets that were invisible on scalp recordings. The alternative interpretation was that there was an independent left-sided epileptogenic process, which sEEG confirmed to be the case.

CASE 3

Data

A 50-year-old man was evaluated for a 40-year seizure history. Seizures were characterized by a sense of his right eye pulling outward and difficulty perceiving objects in the right hemifield; these feelings either passed off spontaneously or progressed to longer episodes with staring, loss of contact, and amnesia. Convulsive seizures also occurred, but were rare. Interictal EEG showed left greater than right spikes over the temporal lobe (Fig. 14A, B). During monitoring, several pushbutton events of his visual aura occurred

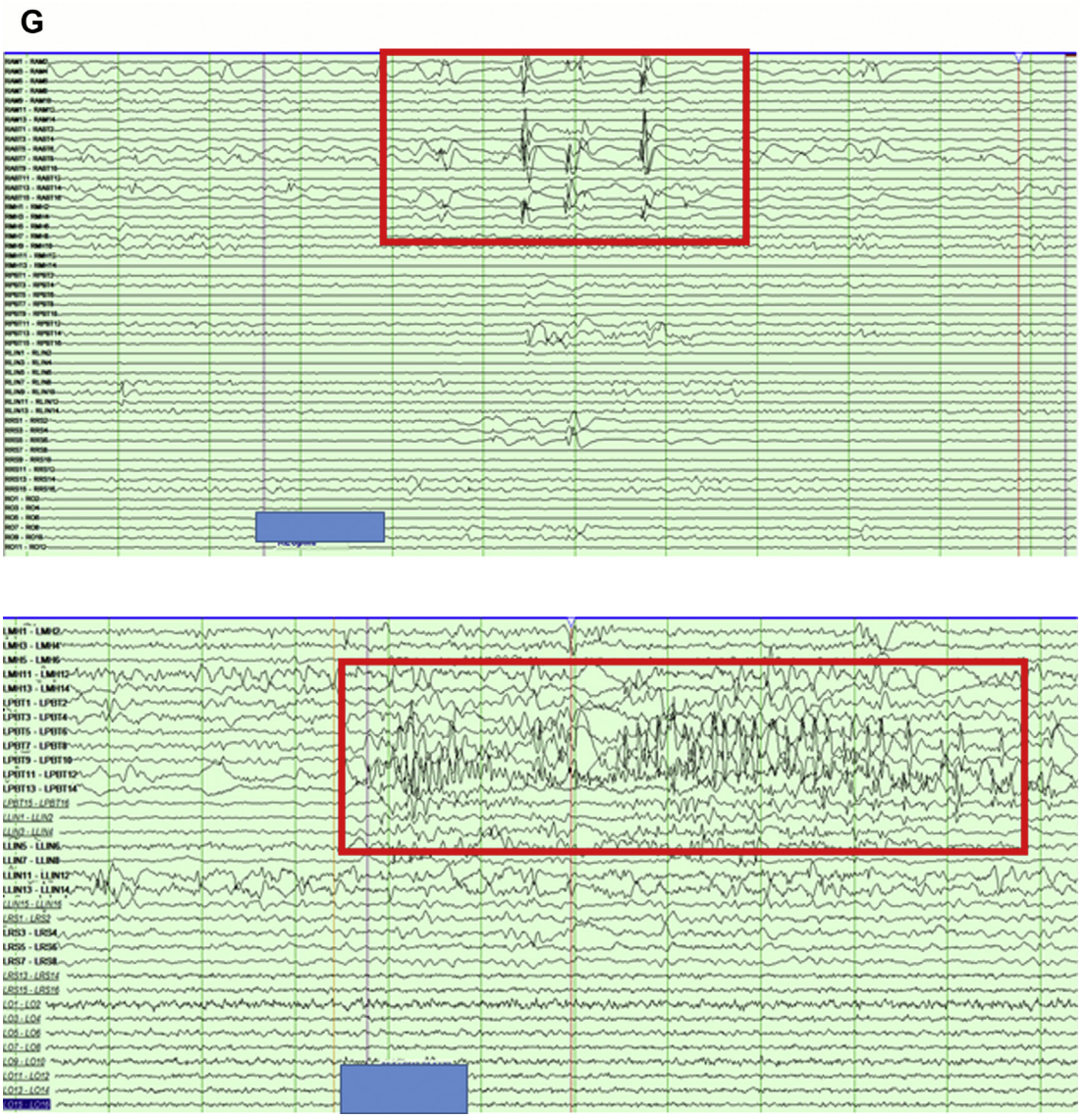

Fig. 13. (*continued*)

with no EEG change; EEG during other seizures with clinical manifestations showed either right or left rhythmic change (Fig. 14C, D). MRI showed a small region of FLAIR/T2 high signal in the left occipital pole (Fig. 14E).

Analysis

The visual auras, notwithstanding accurately interpreting a complaint described as pulling of the right eye outward, suggested a left posterior quadrant seizure onset area, the location indeed of the brain lesion. The absence of spikes and ictal EEG findings with his auras were entirely consistent with the small, medially disposed lesion. The temporal lobe spikes, and the seizure recorded of temporal lobe semiology, indicated a wider network of anterior propagation into either hippocampus. The only question was of the independent epileptogenicity of the hippocampi (ie, the degree of lesion-dependence of the posterior cortex-temporal lobe network).

Implant

The lesion was sampled with three encircling electrodes, with hypothesized anterior

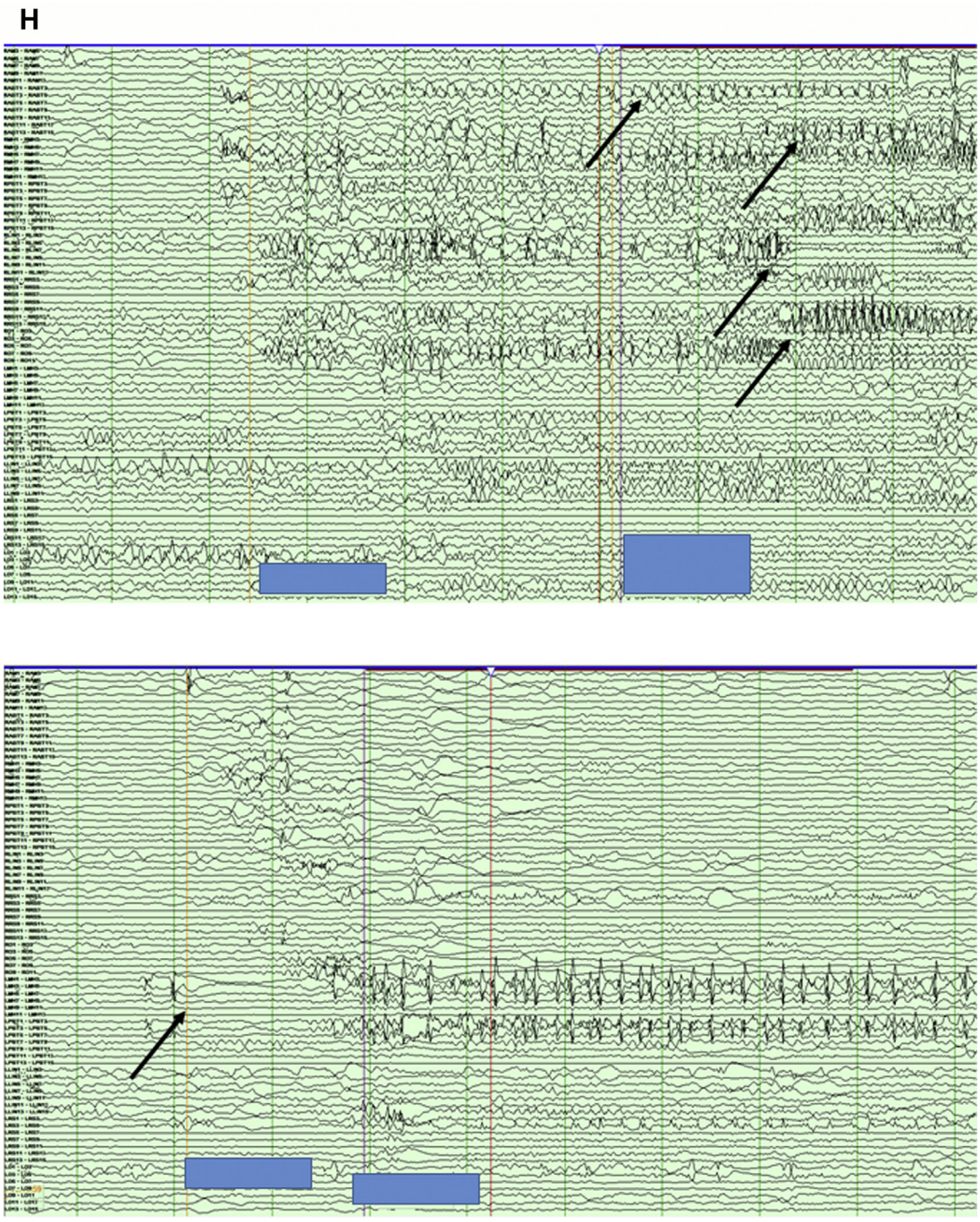

Fig. 13. (*continued*)

propagation pathway into the ipsilateral hippocampus explored with a sequence of orthogonally placed anteriorly placed contacts, the most anterior sampling the amygdala (Fig. 14F). On the right side, the sequence was essentially similar without the necessity for occipital placements.

Outcome

Profuse hippocampal spiking was observed bilaterally and independently (Fig. 14G); spikes

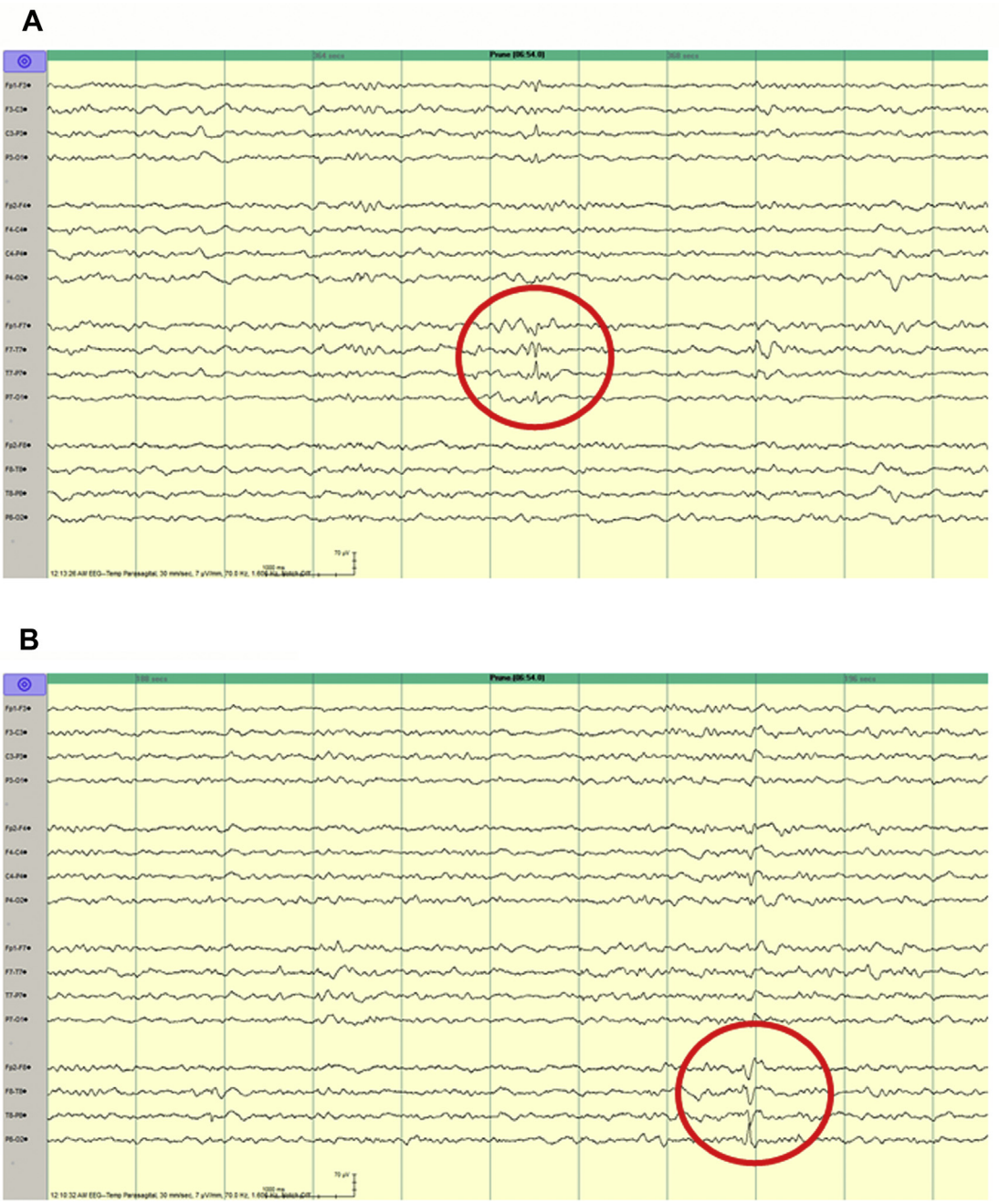

Fig. 14. A 10-second EEG page, longitudinal bipolar montage, passband 1–70 Hz, 7 μV/mm gain. (*A*) Left temporal spike burst (*circle*). (*B*) Independent right temporal spike (*circle*). (*C*) Left-sided ictal onset arising from sleep, with a beta frequency evolving discharge over the left hemisphere, maximum temporal (*arrow*). (*D*) Rhythmic slow theta frequency EEG seizure (*box*) over the right temporal lobe. (*E*) FLAIR axial view through the midtemporal region showing focal high signal (*circle*) in the left occipital pole (*left*). Coronal T2-weighted view (*right*). (*F*) The left hemisphere is sampled to include one intralesional (LO) and three perilesional contacts (LSO, LMO, LIO) and sampling is carried anteriorly into the ipsilateral temporal lobe. Implant on the right side reproduces the left temporal lobe coverage. IO, inferior; MO, midoccipital; SO, superior occipital. (*G*) A 10-second intracranial EEG page, showing all implanted channels in sparse bipolar montage (passband 5–70 Hz, gain 50 μV/mm). Spike bursts are seen over the right and left amygdalohippocampal contacts (*arrows*); small amplitude spikes are seen the lesional contacts LO13-LO14 and LO31-LO32 (electrode nomenclature was changed inadvertently during sEEG montage preparation: the electrodes LO, LSO, LMO, and LIO were named LO1, LO2, LO3, and LO4, respectively). (*H*) Ictal onsets of evolving gamma over the perilesional electrodes (*arrow, top*) corresponding to visual auras; some auras progressed to confusion and loss of contact that corresponded to propagation into the right hippocampus (*box, bottom*) and the left neocortical temporal lobe and left hippocampus.

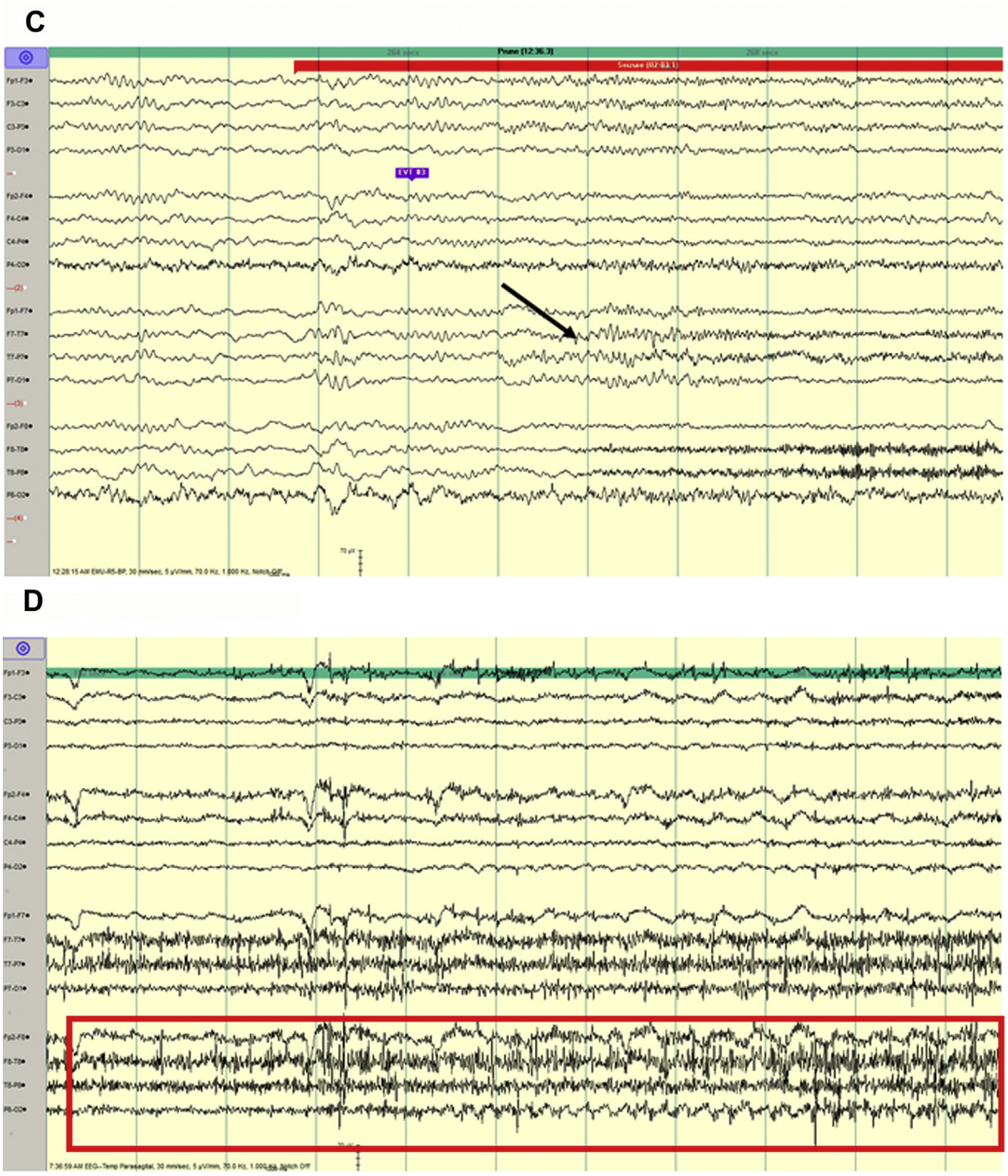

Fig. 14. (*continued*)

were of smaller amplitude but of greater frequency in the perilesional zone. Multiple visual auras were captured accompanied by a fast discharge in the perilesional electrodes (Fig. 14H). Dyscognitive seizures were accompanied by perilesional fast discharge, progressing to contralateral hippocampal involvement and further progressing to ipsilateral hippocampus (see Fig. 14H). Independent seizure onsets were also seen from the right

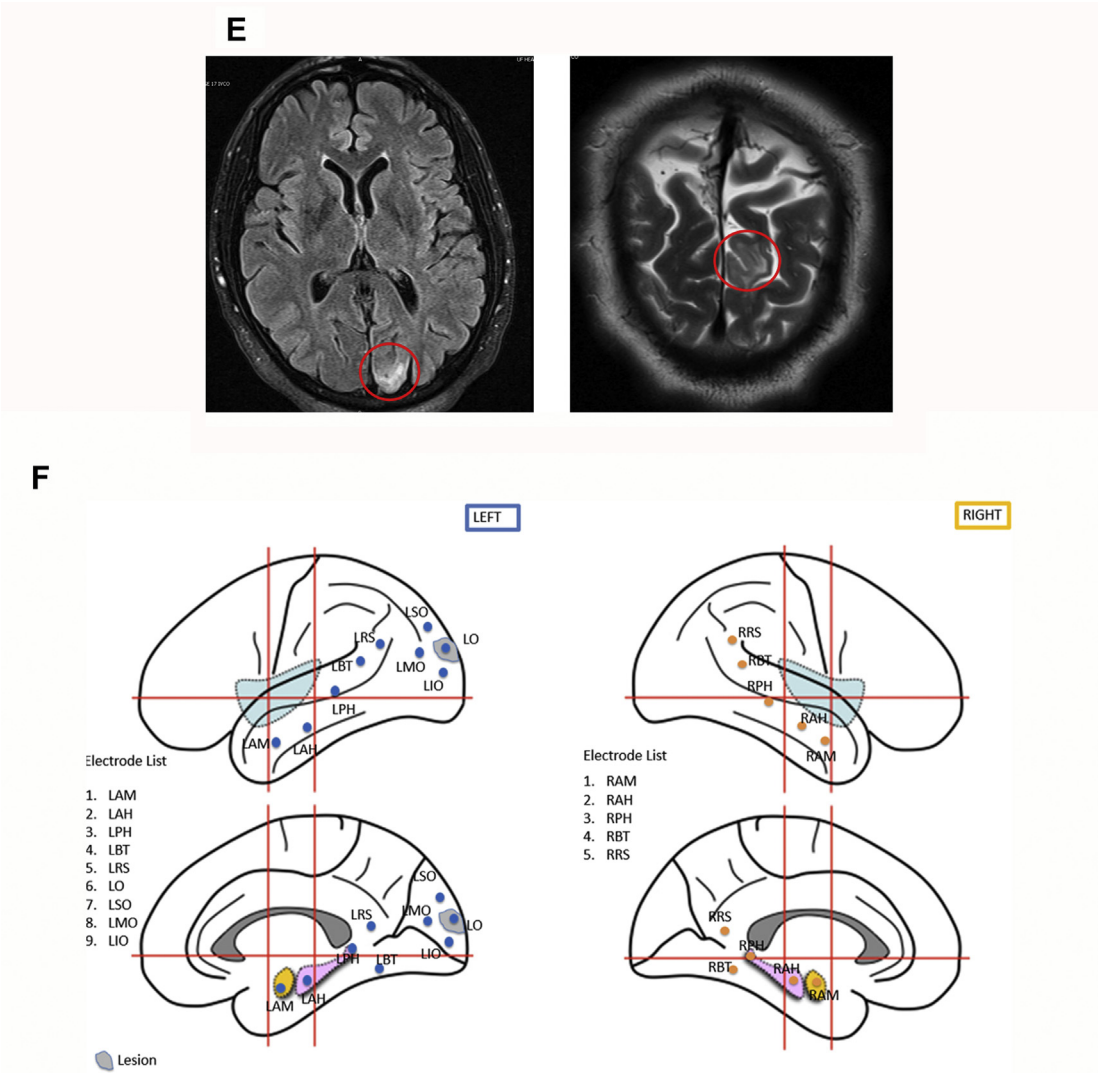

Fig. 14. (*continued*)

hippocampus (not shown). The patient underwent a posterior cortex lesionectomy, with worthwhile improvement at 6 months. The decision to ablate the right hippocampus or neuromodulate both hippocampi awaits further progress.

Comment

This was a classic case of so-called "temporal-plus" epilepsy involving a posterior cortex-hippocampus network. The frequent visual auras and the MRI lesion immediately suggested the diagnoses, despite the lack of lesion-associated ictal and interictal findings on scalp EEG. sEEG merely confirmed a confident preimplant hypothesis, with the details informing the surgical treatment choice eventually offered.

SUMMARY

Despite this article's focus on scalp EEG, it is clear that the epileptology of sEEG mandates a rigorous synthesis of the clinical (history and seizure

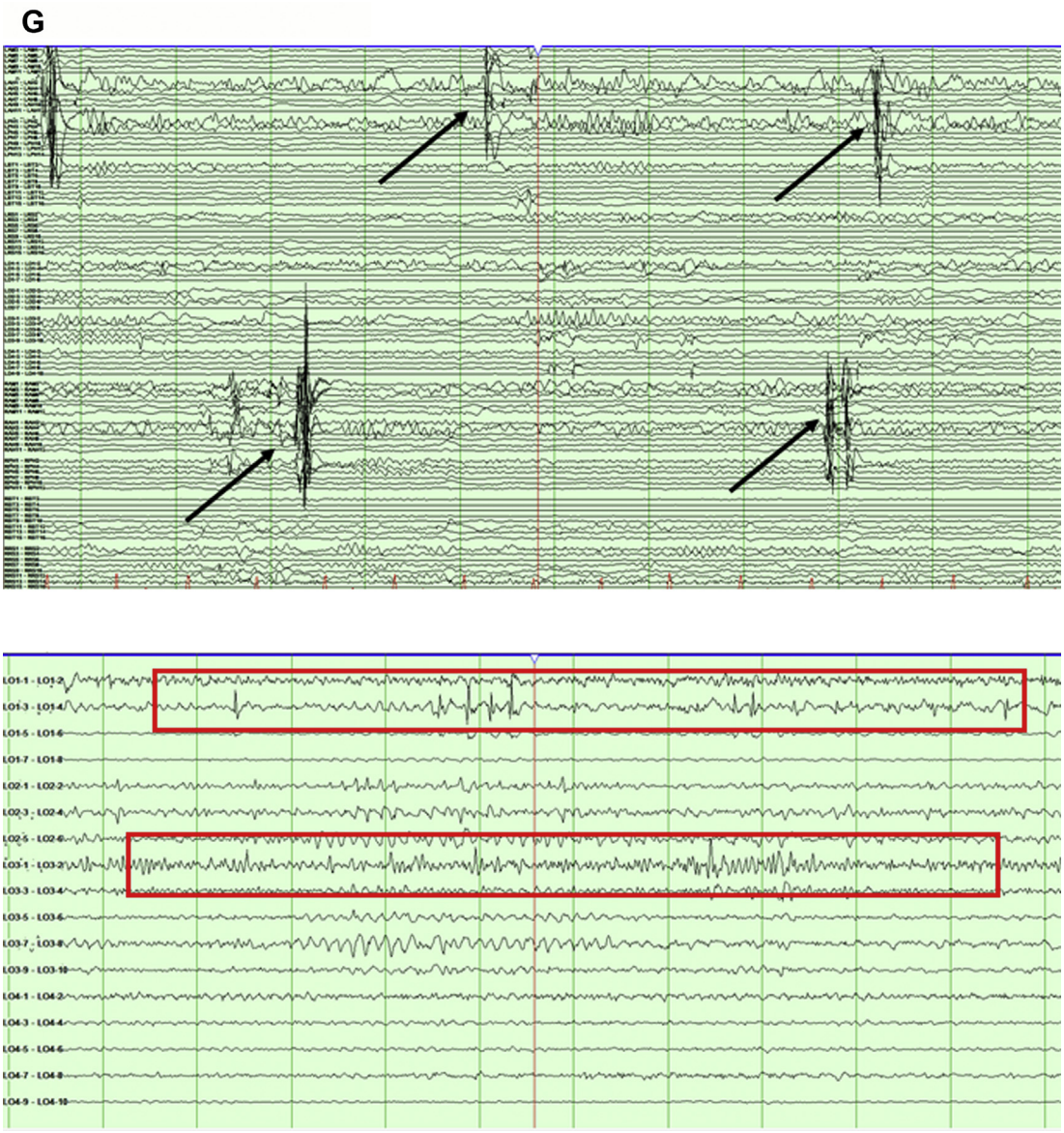

Fig. 14. (*continued*)

semiology), EEG, and imaging findings into a small set of unifying hypotheses. Regarding sEEG, we have seen the value of the presence and absence of interictal and ictal findings in formulating a network and implant hypothesis. Advanced waveform analysis is an advantage and highlights subtleties not evident on casual review. Occasionally, exhaustive analysis of the noninvasive data still does not suggest a single preimplant hypothesis. In this situation, the nontraumatic nature of sEEG makes it possible to explore more than one hypothesis and exclude alternatives.[12] The yield of surgical success following sEEG is therefore potentially high (higher than the subdural grid approach to invasive evaluation) as borne out by a recent large series.[13] A counterpoint to these advantages of sEEG is the level of attention to clinical data points demanded of the treating team in developing preimplant hypotheses. As sEEG emerges on to the world stage from its French-Italian-Canadian roots of 60 years ago,

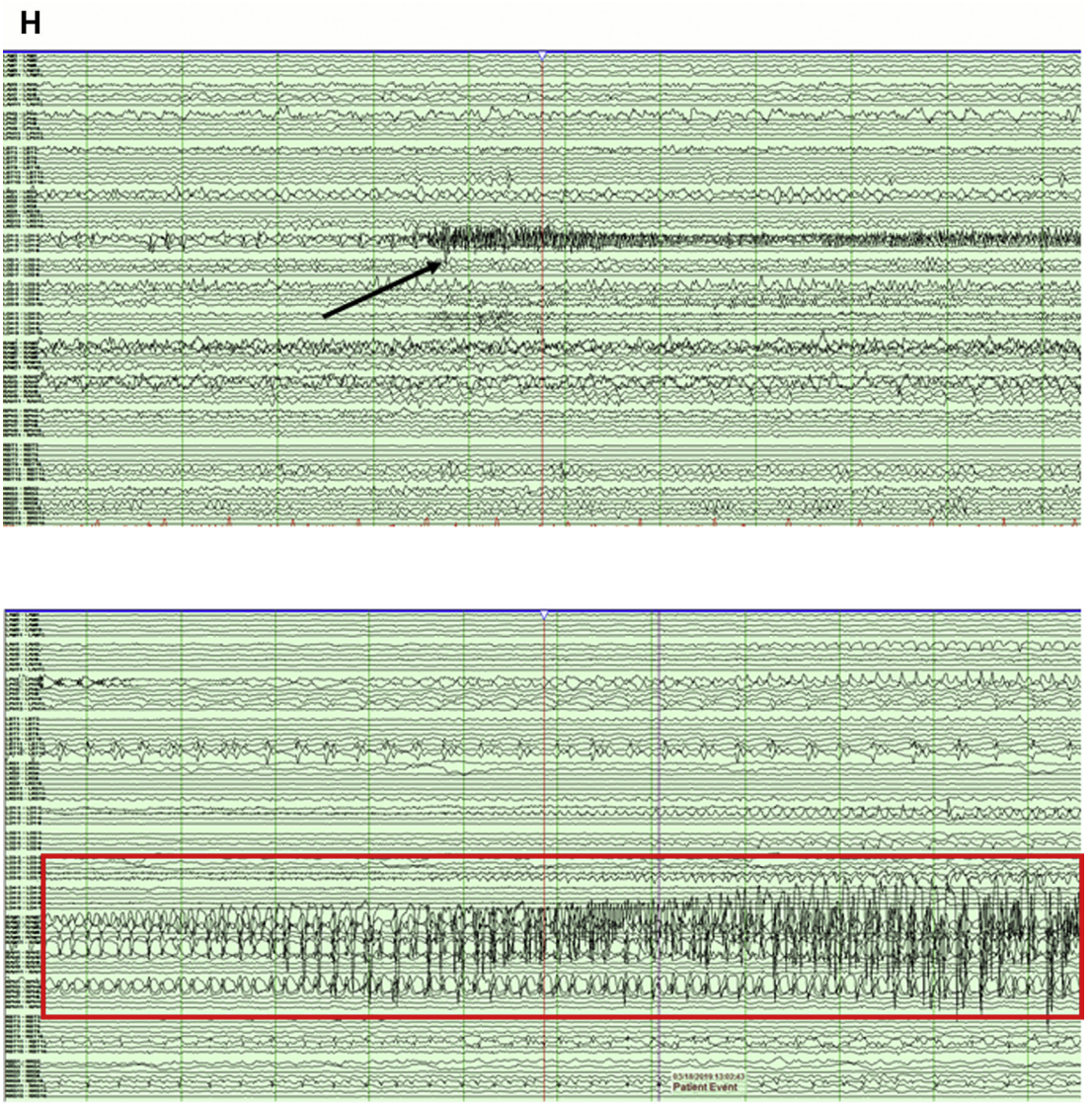

Fig. 14. (*continued*)

this is a lesson being relearnt by the current generation of practitioners.

DISCLOSURE

The author has nothing to disclose.

REFERENCES

1. Berger H. Uber das Elektrenkephalogramm des Menschen [On the electroencephalogram of man]. Arch Psych Nervenkrankheiten 1929;87:527–70.
2. Feindel W, Leblanc R, de Almeida AN. Epilepsy surgery: historical highlights 1909-2009. Epilepsia 2009;50(Suppl 3):131–51.
3. Ebersole JS, Wade PB. Spike voltage topography identifies two types of frontotemporal epileptic foci. Neurology 1991;41:1425–33.
4. Risinger MW, Engel J Jr, Van Ness PC, et al. Ictal localization of temporal lobe seizures with scalp/sphenoidal recordings. Neurology 1989;39:1288–93.
5. Ebersole JS, Pacia SV. Localization of temporal lobe foci by ictal EEG patterns. Epilepsia 1996;37:386–99.
6. Worrell GA, So EL, Kazemi J, et al. Focal ictal beta discharge on scalp EEG predicts excellent outcome of frontal lobe epilepsy surgery. Epilepsia 2002;43:277–82.

7. Aghakhani Y, Kinay D, Gotman J, et al. The role of periventricular nodular heterotopia in epileptogenesis. Brain 2005;128:641–51.
8. Khoo HM, von Ellenrieder N, Zazubovits N, et al. Internodular functional connectivity in heterotopia-related epilepsy. Ann Clin Transl Neurol 2019;6:1010–23.
9. Kalamangalam GP, Morris HH 3rd, Mani J, et al. Noninvasive correlates of subdural grid electrographic outcome. J Clin Neurophysiol 2009;26:333–41.
10. Kalamangalam GP, Pestana Knight EM, Visweswaran S, et al. Noninvasive predictors of subdural grid seizure localization in children with nonlesional focal epilepsy. J Clin Neurophysiol 2013;30:45–50.
11. Hirsch LJ, Mirro EA, Salanova V, et al. Mesial temporal resection following long-term ambulatory intracranial EEG monitoring with a direct brain-responsive neurostimulation system. Epilepsia 2020;61(3):408–20.
12. Kalamangalam GP, Tandon N. Stereo-EEG implantation strategy. J Clin Neurophysiol 2016;33:483–9.
13. Tandon N, Tong BA, Friedman ER, et al. Analysis of morbidity and outcomes associated with use of subdural grids vs stereoelectroencephalography in patients with intractable epilepsy. JAMA Neurol 2019;76(6):672–81.