



# Clinical implications of scalp ictal EEG pattern in patients with temporal lobe epilepsy <sup>☆</sup>



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## HIGHLIGHTS

- Scalp ictal EEG is important for seizure localization in patients with temporal lobe epilepsy (TLE).
- Both scalp theta/alpha and delta ictal onsets are commonly found in patients with mesial TLE (MTLE).
- Scalp delta ictal onset is not a unique EEG pattern for lateral TLE (LTLE) as commonly believed.

## ABSTRACT

**Objective:** To determine the clinical implications of scalp ictal EEG pattern in patients with temporal lobe epilepsy (TLE).

**Methods:** Scalp EEG ictal patterns were retrospectively determined in 27 consecutive patients with medically refractory temporal lobe epilepsy who underwent phase-1 scalp video-EEG and phase-2 simultaneous scalp and intracranial video-EEG recordings for pre-surgical evaluation.

**Results:** Of the 192 temporal lobe seizures recorded during phase-1 and phase-2 scalp video-EEG studies, 124 (65%) seizures were associated with theta/alpha (5–9 Hz) ictal onset pattern, and 68 (35%) seizures were associated with delta (2–5 Hz) ictal onset pattern. Fourteen (52%) patients had exclusively theta/alpha ictal onset, 3 (11%) patients had exclusively delta ictal onset, and 10 (37%) patients had mixed theta/alpha and delta ictal onsets. MTLE was observed in 26 patients who had 124 seizures with theta/alpha ictal onset and 59 seizures with delta ictal onset. LTLE was observed in one patient who had 9 seizures with delta ictal onset. Scalp ictal EEG pattern was not significantly correlated with postsurgical seizure outcomes.

**Conclusions:** Both scalp delta and theta/alpha ictal onset patterns can be commonly found in patients with MTLE.

**Significance:** Scalp delta ictal onset is not a unique EEG pattern for LTLE as commonly believed.

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## 1. Introduction

Temporal lobe epilepsy (TLE) is one of the most common focal epilepsies and has the tendency to become medically resistant. It

**Abbreviations:** EEG, electroencephalography; MTLE, mesial temporal lobe epilepsy; LTLE, lateral temporal lobe epilepsy; LITT, laser interstitial thermal therapy; ALT, anterior temporal lobectomy; MTS, mesial temporal sclerosis; AHC, amygdalohippocampal complex; RNS, responsive neurostimulation; LVHF, low voltage high frequency.

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is commonly classified into two subtypes: Mesial TLE (MTLE) and lateral TLE (LTLE). MTLE occurs in about two-thirds of patients with TLE and is often associated with the following features: hippocampal atrophy and hyperintensity on MRI, theta/alpha scalp ictal onset on scalp EEG, low-voltage, high frequency (LVHF) intracranial ictal discharges or repetitive low frequency spiking activities mostly restricted to hippocampus (Tao et al., 2018, Vossler et al., 1998). Meanwhile, LTLE occurs in about one-third of TLE patients and is often associated with no hippocampal atrophy on MRI, greater neocortical gliosis, scalp delta-frequency ictal onset and diffuse neocortical high voltage low frequency (HVLF) ictal onset (Ebersole and Pacia, 1996, Pacia and Ebersole, 1997, Tao et al., 2007b). The scalp ictal EEG onset pattern has been used as an important EEG marker for differentiating MTLE from LTLE.

Scalp electroencephalography (EEG) is an essential component of epilepsy presurgical evaluation. When congruent with other non-invasive data, such as ictal semiology, anatomic and functional neuroimaging studies, scalp EEG data can guide the surgical resection of an epileptic focus. (Davidson and Falconer, 1975, Mariottini et al., 2001, Zumsteg and Wieser, 2000) In patients with TLE, the distinction between mesial and lateral TLE is clinically important. Patients with MTLE can be often be treated with selective amygdalohippocampectomy or minimally invasive stereotactic MRI-guided laser interstitial thermal therapy (LITT),(Gross et al., 2018, Josephson et al., 2013, Kang et al., 2016, Tao et al., 2018) minimizing cognitive impairment associated with traditional anterior temporal lobectomy (ATL),(Helmstaedter et al., 2008, Morino et al., 2006, Paglioli et al., 2006, Wendling et al., 2013) However, patients with LTLE may require an invasive EEG study to delineate the seizure onset zone and identify eloquent cortex in order to tailor an anterior temporal lobectomy (Josephson et al., 2013, Zumsteg and Wieser, 2000).

Scalp ictal EEG pattern has been used as an EEG benchmark in the distinction between MTLE and LTLE. In the hallmark studies by Pacia and Ebersole, scalp theta/alpha (5–9 Hz) ictal onset pattern (type-1 seizure) was highly correlated with MTLE, whereas delta (2–5 Hz) ictal onset pattern (type-2 seizure) was highly correlated with LTLE (Ebersole and Pacia, 1996, Pacia and Ebersole, 1997). However, Malter et al. later showed that both scalp theta/alpha (5–9 Hz) ictal onset and delta (2–5 Hz) ictal onset were commonly observed in patients with unilateral MTLE plus mesial temporal sclerosis (MTS). Neither scalp theta/alpha nor delta ictal EEG patterns predicted the surgical outcomes in patients who underwent direct selective amygdalohippocampectomy (Malter et al., 2016). These observations challenged the view that scalp delta ictal EEG onset is a reliable EEG marker for LTLE. In light of these conflicting data, we reviewed simultaneous scalp and intracranial EEG recordings in patients with temporal lobe epilepsy during per-surgical evaluation to reassess the role of scalp ictal EEG patterns in distinguishing mesial from lateral TLE.

## 2. Methods

### 2.1. Patient selection

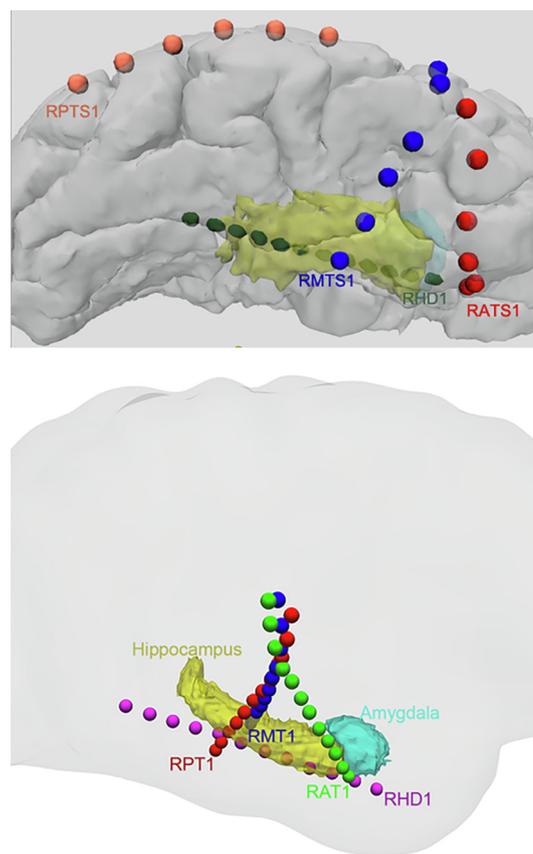
Data were collected from 27 consecutive patients with TLE who underwent invasive pre-surgical evaluation at the University of Chicago adult epilepsy center between January 2014 and July 2018. Scalp and intracranial EEG recordings were reviewed by three investigators (XL, SW and JXT) with differences resolved by consensus. Patients who met the following criteria were included: (1) diagnosis of medically refractory TLE; (2) underwent both phase-1 and phase-2 EEG studies and during the phase-2 study there were simultaneous scalp and intracranial video-EEG recordings; (3) at least one depth electrode implanted along the longitudinal axis of hippocampus. Data from a subject were excluded if: (1) the patient had significant a structural abnormality such as a tumor, vascular malformation or encephalomalacia from stroke; (2) EEG recordings were significantly compromised by muscle or electrode artifacts; (3) the quality of scalp EEG recording was compromised by a craniotomy for implantation of subdural electrodes. The study was approved by the Institutional Review Board.

### 2.2. Scalp and intracranial EEG recordings

Scalp video-EEG was recorded according to the international 10–20 system with 6 additional sub-temporal electrodes (F9, T9, M1, F10, T10 and M2) using the Xltek EEG system (Natus Medical Incorporated, Pleasanton, CA, USA) during phase-1. Simultaneous

scalp and intracranial EEG was recorded during phase-2. In our standard intracranial implantation, one depth electrode was implanted through an occipital approach along the longitudinal axis of amygdalohippocampal complex (AHC) to sample the AHC ipsilateral to the side of seizure onset. Bilateral hippocampal depth electrodes were placed in patients with suspected bilateral temporal ictal onsets. Three lateral temporal depth or strip electrodes were implanted to sample the anterior, mid and posterior temporal neocortex and paleocortex (entorhinal and parahippocampal cortices) (Fig. 1). Additional frontal, orbitofrontal and posterior temporal strips or depth electrodes were placed as clinically indicated if temporal-plus focus was a concern (Barba et al., 2016, Ryvlin and Kahane, 2005).

The depth electrodes contained 6–12 cylindrical 2.3 mm long platinum contacts separated by 5 mm between centers of adjacent contacts. The subdural strip arrays contained 4–8 disc contacts with a diameter of 4 mm separated by 10 mm between centers of adjacent contacts (Integra LifeSciences Corporation, Plainsboro, NJ). The locations of intracranial electrodes were determined by intraoperative computed tomography (CT) and were co-registered to the patient's non-deformed pre-surgical 3D brain MRI images using a geometry-based technique. (Brang et al., 2016) Scalp and intracranial EEG were sampled at the rate of 1024 samples per second and typically bandpass filtered for viewing between 1 and 70 Hz. Additional digital filtering was used for scalp EEG data when necessary to improve the signal-to-noise ratio. All data were recorded in a referential montage relative to scalp electrode CPz and reviewed in common average montage.



**Fig. 1.** 3D reconstructed intracranial electrodes. Top panel: standard placement of hippocampal depth electrode and lateral temporal subdural strip electrodes. Low panel: standard placement of hippocampal and lateral temporal depth electrodes. RHD: right hippocampal depth electrode; RATS: right anterior temporal strip; RMTS: right medial temporal strip; RPTS: right posterior temporal strip; RAT: right anterior temporal; RMT: right mid temporal; RPT: right posterior temporal.

### 2.3. Intracranial ictal onsets correlating with scalp ictal EEG patterns

Scalp ictal EEG patterns were determined based on the first clearly recognizable and progressive ictal rhythm that was distinct from background. Scalp ictal onset patterns were categorized into three different groups according to onset frequency: (1) theta/alpha bands (5–9 Hz) ictal onset, (2) delta (2–5 Hz) ictal onset, and (3) mixed seizure onset if individual patients had some seizures with theta/alpha onset and other seizures with delta ictal onset. Intracranial EEG ictal onset patterns were categorized into following patterns: (1) High frequency low amplitude gamma/beta rhythmic activity (>13 Hz); (2) low-frequency (1–4 Hz) high-amplitude rhythmic activity; (3) periodic spike-and-wave complex; (4) traditional rhythmic alpha (8–12 Hz) or theta (4–7 Hz) (Spanedda et al., 1997, Vossler et al., 2017).

### 2.4. Surgical techniques and postictal follow-up

MRI-guided stereotactic laser interstitial thermal therapy (LITT) was performed to ablate AHC in patients with MTLE as previously described (Tao et al., 2018).

Patient with LTLE underwent standard anterior temporal lobectomy with resection of both mesial and lateral temporal cortices. Patients with bilateral temporal lobe onsets underwent response neurostimulation (RNS).

### 2.5. Statistical analysis

Fisher's exact test was performed to compare scalp theta/alpha ictal onset to delta ictal onset between patients with class I outcome and those with class II, III and IV outcomes. To be consistent with the previous study, patients with mixed theta/alpha and delta ictal onsets were counted in the delta ictal onset group (Malter et al., 2016). Statistical significance was defined as  $P < 0.05$ .

## 3. Results

### 3.1. Patient data

Data from 27 patients were included in this study. The mean age was  $40 \pm 13$  years. Seventeen patients were female and 10 patients were male. The mean duration of epilepsy was  $20 \pm 15$  years. Twelve patients had mesial temporal sclerosis (MTS) and 15 patients had a normal brain MRI. Based on intracranial recordings, 9 patients had left temporal ictal onset, 12 patients had right temporal ictal onset, and 6 patients had bitemporal ictal onset. Twenty-two patients with mesial temporal ictal onset underwent minimally invasive LITT, including two patients who had bilateral mesial temporal onsets with >90% seizures lateralized to one side. One patient with temporal neocortical ictal onset underwent anterior temporal lobectomy. Four patients with bilateral temporal lobe seizure onset were treated with responsive neurostimulation (RNS). The average duration of post-surgical follow-up was  $22 \pm 11$  months. Patient demographics and seizure characteristics are summarized in Table 1.

### 3.2. Scalp ictal EEG patterns during phase-1 and-2 video-EEG recordings

During phase-1 scalp video-EEG recording, 121 temporal lobe seizures were recorded in the 27 patients. The mean ictal onset frequency was  $4.6 \pm 1.2$  Hz. Delta (2–5 Hz) ictal onset was observed in 50 (43%) seizures, while theta/alpha (5–9 Hz) ictal onset pattern was observed in 71 (57%) seizures. At the individual patient level, 15 (56%) patients had exclusively theta/alpha ictal onset pattern, 8 (30%) patients had exclusively delta ictal onset pattern, and 4 (15%) patients had mixed delta and theta/alpha ictal onset patterns.

During phase-2 video-EEG recording, 71 scalp temporal lobe seizures were recorded in the 27 patients. The mean scalp ictal frequency was  $5.6 \pm 1.5$  Hz, which was approximately 1 Hz faster

**Table 1**  
Demographics and characteristics of scalp ictal patterns.

Patient	Age (y)	Sex	Epilepsy Duration (y)	# of scalp seizures (P1)	Scalp ictal pattern (Hz) (P1)	# of scalp seizures (P2)	Scalp ictal pattern (Hz) (P2)	MTS	Hippo ictal onset	Engel's outcome
1	20	M	17	4	Delta (3 Hz)	1	Delta (4 Hz)	no	yes	IV
2	53	F	3	4	Theta (4 Hz)	2	Theta (5 Hz)	no	yes	II
3	36	F	7	3	Theta (6 Hz)	1	Theta (6 Hz)	no	yes	III
4	25	M	15	6	Theta (5 Hz)	2	Theta (5 Hz)	yes	yes	I
5	20	M	5	8 (2D, 6 T)	Mixed (4–6)	3	Theta (6 Hz)	no	yes	III
6	50	F	6	3	Theta (6 Hz)	2	Theta (6 Hz)	no	yes	II
7	42	M	41	4 (3D, 1 T)	Mixed (3–5 Hz)	6	Theta (5–6 Hz)	yes	yes	II
8	46	F	30	3	Theta (5 Hz)	2	Theta (5 Hz)	yes	yes	I
9	41	F	4	4	Delta (4 Hz)	4	Theta (5–6 Hz)	no	yes	II
10	29	M	25	4	Theta (6 Hz)	2	Theta (6 Hz)	no	yes	III
11	58	F	11	2	Theta (6 Hz)	7	Theta (5–8 Hz)	yes	yes	II
12	41	F	33	4 (3D, 1 T)	Mixed (3–5 Hz)	2	Alpha (9 Hz)	no	yes	IV
13	32	M	23	2	Theta (5 Hz)	2	Alpha (8 Hz)	yes	yes	I
14	32	F	27	1	Theta (6 Hz)	1	Theta (5 Hz)	yes	yes	I
15	61	F	34	7	Delta (3 Hz)	1	Theta (7 Hz)	yes	yes	II
16	56	M	55	5	Delta (3 Hz)	6 (5D, 1 T)	Mixed (3–5 Hz)	no	yes	I
17	51	F	5	2	Delta (4 Hz)	5 (4D, 1 T)	Mixed (3–5 Hz)	no	yes	I
18	46	F	45	4	Theta (5 Hz)	2	Theta (6 Hz)	yes	yes	I
19	20	F	8	7	Theta (6 Hz)	2	Theta (6 Hz)	yes	yes	I
20	60	F	17	3 (2D, 1 T)	Mixed (3–5 Hz)	2	Theta (5 Hz)	yes	yes	I
21	21	F	5	2	Theta (6 Hz)	2	Theta (6 Hz)	no	yes	I
22	41	F	5	4	Delta (2 Hz)	5	Delta (2 Hz)	no	no	I
23	50	F	43	9	Delta (4 Hz)	1	Alpha (8 Hz)	no	yes	III
24	43	F	41	8	Theta (6 Hz)	2 (1D, 1 T)	Mixed (3–5 Hz)	no	yes	RNS
25	50	M	27	5	Delta (3 Hz)	2	Delta (3 Hz)	yes	yes	RNS
26	21	M	12	4	Theta (6 Hz)	3	Theta (6 Hz)	yes	yes	RNS
27	33	M	2	9	Theta (5–6 Hz)	1	Theta (6 Hz)	no	yes	RNS

Abbreviations: M: male; F: female; P1: Phase 1; P2: phase 2; D: delta; T: theta; Hippo: hippocampal; RNS: response neurostimulation.

than that of seizures recorded during phase-1 recording. Delta scalp ictal onset was observed in 18 (25 %) of 71 seizures, where theta/alpha scalp ictal onset was observed 53 (75%) of 71 seizures. At the individual patient level, 21 (78%) patients had exclusively theta/alpha scalp ictal onset, 3 (11%) patients had exclusively delta scalp ictal onset, and 3 (11%) patients had mixed delta and theta/alpha scalp ictal onset.

Overall, MTLE was observed in 26 patients who had 124 seizures with theta/alpha ictal onset and 59 seizures with delta ictal onset, whereas LTLE was observed in one patient who had 9 seizures with delta ictal onset during phase 1 and 2 video-EEG studies. The appearance of 5 Hz or faster rhythmic activity within 30 seconds of an initial delta ictal onset was observed in 47 (69%) of 68 seizures during phase 1 and 2 studies, with 42 of the 47 scalp patterns correlating with MTLE.

### 3.3. Intracranial EEG substrates of scalp EEG ictal onset patterns

Intracranial EEG substrates of scalp ictal onset patterns were determined during phase-2 recording. Seizures with scalp theta/alpha onset had hippocampal ictal onset in 56 seizures. The most common hippocampal pattern at seizure onset was low voltage, high frequency (LVHF) gamma/beta activity. These hippocampal LVHF ictal discharges can be sometimes recorded in the entorhinal and parahippocampal regions. They were occasionally preceded by 1–2 Hz repetitive hippocampal spiking and/or electrodecremental activity. At this stage, mesial temporal ictal discharges were not typically visible on scalp EEG. They gradually and sequentially propagated to ipsilateral basolateral and anterior temporal cortices before being visible on the scalp EEG (Tao et al., 2007a, Tao et al., 2005). The frequency of these ictal discharges commonly slowed into the theta band and occasionally alpha band, which were con-

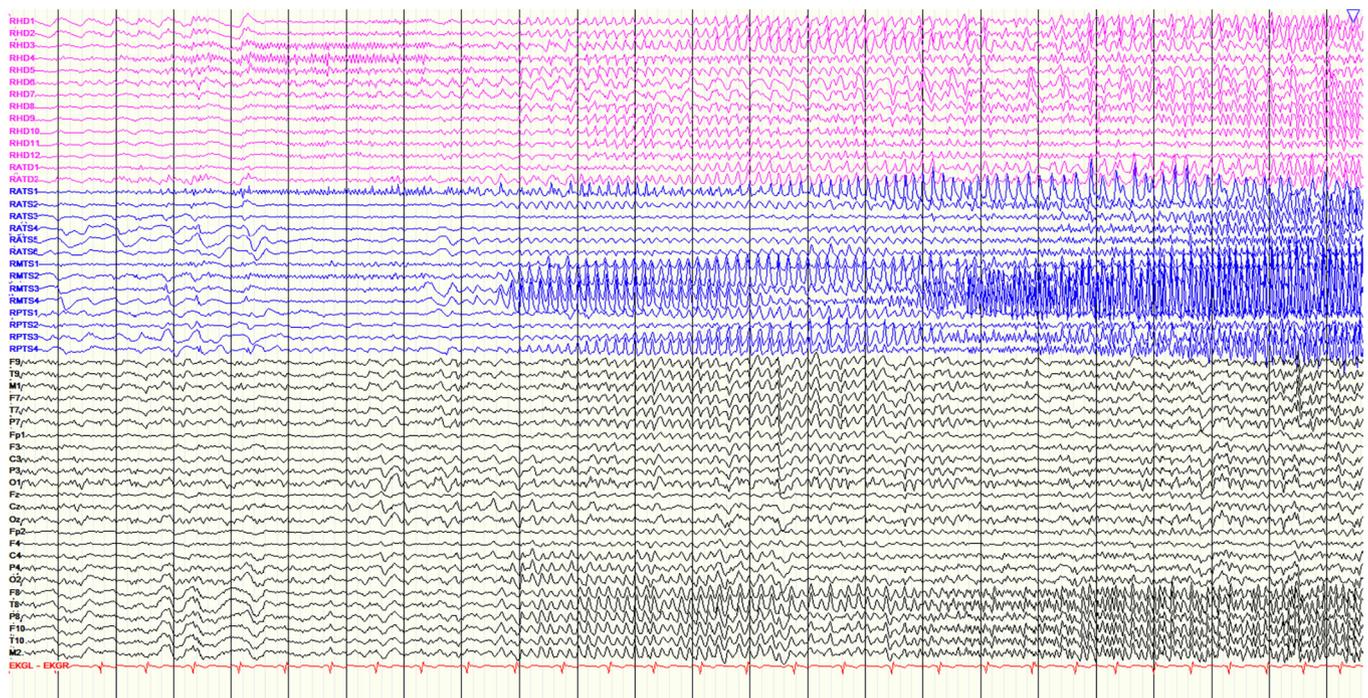
currently recorded as rhythmic theta/alpha ictal discharges on scalp EEG (Fig. 2).

In 13 of 18 seizures (5 of 6 patients) with scalp delta onset, seizures began in the hippocampus with LVHF gamma/beta activity. Ictal activity then propagated to basolateral temporal cortical areas, commonly slowed abruptly to the delta frequency range, and was then observed on multiple depth and subdural electrodes as well as on the scalp EEG (Fig. 3). In 5 of 18 seizures (one of 6 patients) with scalp delta onset, seizures began in temporal neocortex as HVLf delta-frequency activity. These seizures had a regional ictal onset, and were visible on multiple subdural and depth electrodes covering basolateral and anterior temporal cortical areas (Tao et al., 2007b). These HVLf ictal discharges were visible on the scalp EEG as rhythmic or semi-rhythmic delta activity without temporal lag between intracranial and scalp EEG recordings (Fig. 4).

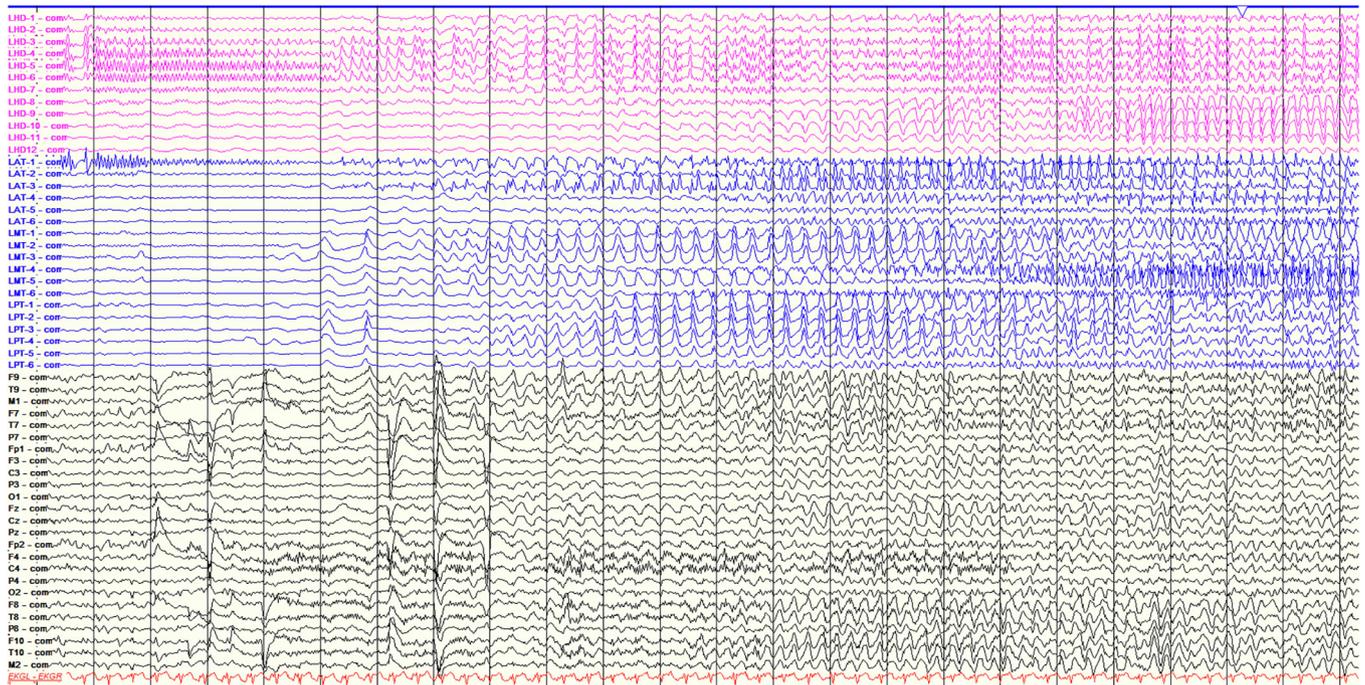
### 3.4. Surgical outcomes

Seizure outcomes were assessed during post-surgical follow up visits at 3, 6, and 12 months and yearly thereafter; in addition, the status of seizure freedom at the time of most recent follow-up was reported. Pre-operative anti-epileptic drugs (AEDs) were maintained at least for 6 months after surgery and in some cases were reduced thereafter if patients remained seizure free. Seizure outcomes were determined according to Engel's classification and categorized as either seizure free (Engel I) or not seizure free (Engel II–IV) groups. Twenty-two patients with MTLE underwent stereotactic LITT, and one patient with LTLE underwent standard anterior temporal lobectomy. The remaining 4 patients with bilateral temporal onset were treated with RNS.

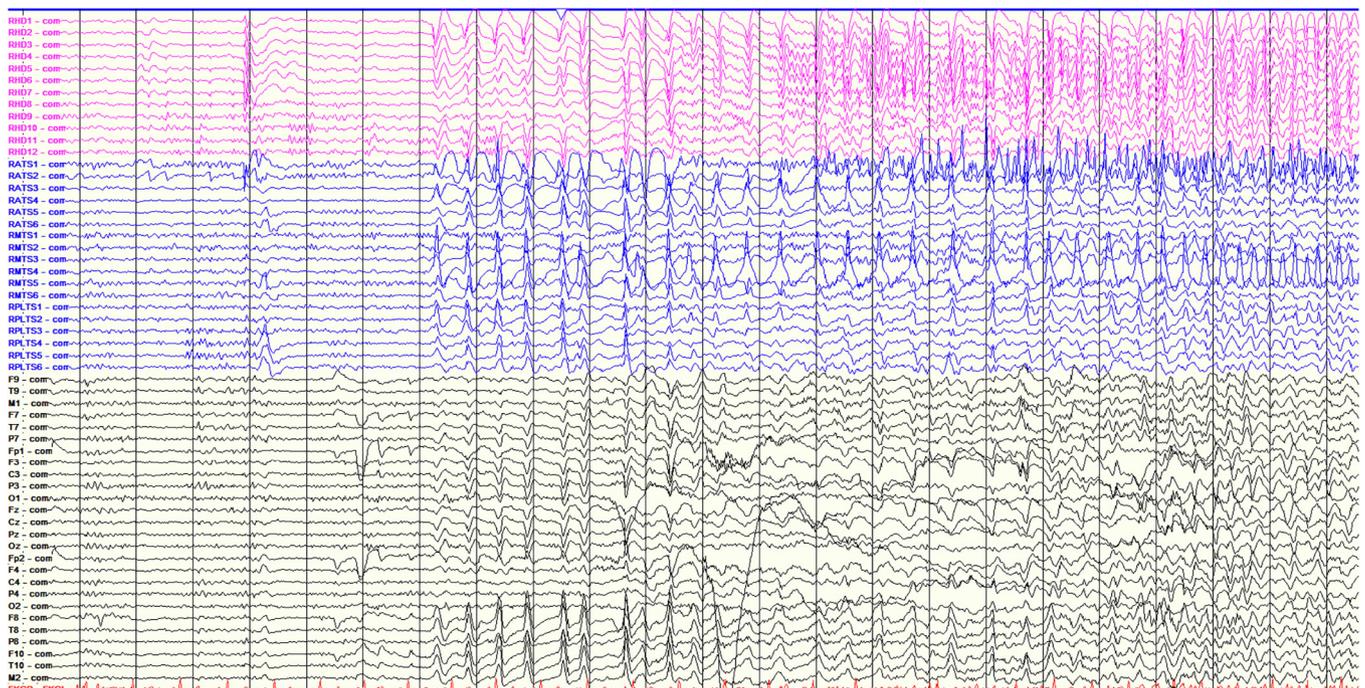
The mean duration of postsurgical follow-up was  $23 \pm 10$  months, ranging from 7 to 48 months. Overall, 23 patients



**Fig. 2.** Simultaneous scalp and intracranial EEG recording. High frequency and low amplitude gamma/beta ictal discharges arising from right hippocampal depth electrode RHD (pink color on contacts 3, 4, 5) subsequently propagated to anterior and basolateral cortices on electrodes RATS and RMTS (blue color), and gradually slowed down to 6 Hz theta ictal discharges. At this point, the cortical 6 Hz ictal discharges were recorded on the scalp EEG as 6 Hz theta ictal discharges over the right temporal lobe. RHD: right hippocampal depth electrode. RATS: right anterior temporal strip electrode. RMTS: right mid temporal strip electrode. RPTS: right posterior temporal electrodes. Sensitivity: Scalp EEG 15  $\mu$ V/mm; intracranial EEG: 100  $\mu$ V/mm. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



**Fig. 3.** Simultaneous scalp and intracranial EEG recording: High frequency and low amplitude gamma/beta ictal discharges arising from left hippocampal depth electrode LHD (pink color: contacts 3, 4, 5, 6, 7) subsequently propagated to anterior and basolateral cortices on subdural electrodes (blue color: LAT, LMT and LPT), and slowed down to 2–3 Hz discharges. At this point, the 2–3 Hz activity was recorded on the scalp EEG as 2–3 Hz delta activity over the left temporal lobe. The left temporal ictal discharges propagated to right temporal lobe 5 seconds later. LHD: left hippocampal depth electrode. LAT: left anterior temporal strip electrode. LMT: left mid temporal strip electrode. LPT: left posterior temporal electrode. Sensitivity: Scalp EEG 15 $\mu$ v/mm; intracranial EEG: 100  $\mu$ v/mm. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



**Fig. 4.** Simultaneous scalp and intracranial EEG recording: Low frequency and high amplitude 2 Hz delta ictal discharges arising diffusely from right anterior and basolateral cortices on electrodes RATS, RMTS and RPLTS (blue color), and were simultaneously recorded on the scalp EEG as 2 Hz ictal onset pattern. The ictal discharges quickly propagated to right hippocampus (pink color). RATS: right anterior temporal strip electrode. RMTS: right mid temporal strip electrode. RPLTS: right posterior lateral temporal electrodes. Sensitivity: Scalp EEG 15 $\mu$ v/mm; intracranial EEG: 100  $\mu$ v/mm. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

underwent resective surgery; 22 patients with MLTE had stereotactic LITT and one patient with LTLE had anterior temporal lobectomy. Eleven (48%) of 23 patients became seizure free (Engel I). The correlation of scalp ictal EEG pattern with post-surgical outcomes was determined in the subgroup of 22 patients with MTLE who underwent stereotactic LITT, while one patient who underwent standard anterior temporal lobectomy was excluded from this correlational analysis. Of the 12 patients with scalp theta/alpha onset, 7 (58%) patients became seizure free. Of the 10 patients with scalp delta ictal onset, 3 (30%) patients became seizure free. Scalp theta/alpha ictal onset was not significantly associated with seizure free outcome, as compared to the scalp delta ictal onset ( $P = 0.23$ ).

## 4. Discussion

### 4.1. Implication of scalp ictal pattern in distinction between MTLE and LTLE

In this retrospective study of 27 patients with TLE, MTLE was observed in 26 patients who had 124 seizures with theta/alpha ictal onset and 59 seizures with delta ictal onset whereas LTLE was observed in one patient who had 9 seizures with delta ictal onset. Scalp theta/alpha ictal onset was correlated with seizures that exclusively started in the hippocampus in all 26 patients with MTLE. Scalp delta ictal onset was observed with seizures that started either in the hippocampus (11 of 26 patients with hippocampal onset seizures had scalp delta onset) or in lateral temporal neocortex (all 9 seizures in one patient with LTLE had delta onset on scalp EEG). Because there was only one patient with LTLE in the study group, a negative predictive value of theta/alpha onset for LTLE could not be estimated. However, based on the phase-1 recordings from this group of 27 patients, delta-onset on scalp EEG had a positive predictive value for LTLE of only 8%. As such, scalp delta ictal onset was not a unique EEG ictal pattern for LTLE. Additionally, the appearance of 5 Hz or faster rhythmic activity within 30 seconds of an initial delta ictal onset was observed in 47 (69%) of 68 seizures during phase 1 and 2 studies, with 42 of the 47 scalp patterns correlating with MTLE, which appeared to have the similar localizing value as the initial 5 Hz or faster frequency (Risinger et al., 1989).

Using simultaneous scalp and intracranial EEG recordings, our findings are consistent with the previous observations that scalp theta/alpha ictal onsets are present in ~two-thirds of patients with MTLE, and delta ictal onset is present in ~one-third of patients with MTLE. In the cohort study of 219 seizures in 63 patients with MTLE plus MTS, Malter et al showed that scalp theta/alpha ictal onset was observed in 124 seizures, and scalp delta ictal onset was observed in 95 (43%) seizures (Malter et al., 2016). In a similar study of 152 seizures in 48 patients with MTLE plus MTS, Sirin et al showed that theta/alpha ictal onset was observed in 82 (54%) seizures, delta ictal onset was observed in 49 (32%) seizures, and atypical ictal onset including repetitive spiking, attenuation of background activity and cessation of interictal epileptiform discharges was observed in 21 (14%) of 152 seizures (Sirin et al., 2013). Nevertheless, the diagnosis of MTLE in both previous studies was primarily based clinical history and the presence of MTS, and was not confirmed by invasive EEG recordings.

Our findings are inconsistent with those by Pacia and Ebersole. In their study with simultaneous scalp and intracranial EEG recordings, patients with MTLE had scalp theta ictal onset in 86% of seizures; however, delta scalp ictal onset was associated with LTLE in 84% of seizures (Pacia and Ebersole, 1997). The inconsistency in findings is likely due to the heterogeneous clinical features of patients enrolled in the two case series. For instance, lesional temporal lobe epilepsy in patients with benign tumors and vascular

malformations were excluded in this study, but were included in the study by Pacia and Ebersole. Additionally, depth electrode recording from hippocampus was not consistently performed in their studies (Ebersole and Pacia, 1996, Pacia and Ebersole, 1997); whereas depth electrode recording from hippocampus was performed in all patients in this study.

The rhythmic ictal delta discharges recorded in the neocortical temporal cortex was commonly the result of ictal propagation from the hippocampus, and was rarely *de novo* ictal onset rhythms in this study. Without depth electrode recording from hippocampus, the propagated delta ictal rhythm in temporal neocortex can be easily misinterpreted as neocortical ictal onset when recorded only with subdural electrodes over the basolateral and anterior temporal cortex (Fig. 3). As such, intracranial EEG sampling from both hippocampus and lateral temporal cortex is mandatory to differentiate MTLE from LTLE, which might explain the inconsistent findings in our similar studies. One puzzling finding in our study is that the mean scalp ictal onset frequency during phase 2 recording was approximately 1 Hz faster than that of ictal patterns recorded during phase 1. This might be related to the effects of skull defects generated by implantation in phase 2, and might be avoided by using foramen ovale electrodes that do not require trephination or a craniotomy (Alarcon et al., 2001).

### 4.2. Correlation of scalp ictal patterns and surgical outcomes

It has been controversial whether scalp ictal patterns are predictive of the surgical outcomes in patients with TLE. Assaf and Ebersole found that scalp ictal EEG recordings predict surgical outcome after anterior temporal lobectomy. Patients with theta rhythm as ictal onset had a significantly better postsurgical outcome than those with scalp delta ictal onset pattern (Assaf and Ebersole, 1999). A similar correlation was also observed by Sirin et al in a study of 48 patients with MTLE plus MTS who underwent selective amygdalohippocampectomy (Sirin et al., 2013). However, such correlation was not observed by Malter et al. In their study, scalp ictal onset pattern was not associated with the postsurgical outcomes at one year or at the last follow-up (Malter et al., 2016). In our study, scalp ictal EEG pattern was also not significantly correlated with postictal surgical outcomes. Heterogeneous patient populations enrolled in different studies are likely contributory to these inconsistent findings. Future large cohort studies are warranted to determine the value of scalp EEG ictal pattern for predicting the postsurgical outcomes.

### 4.3. Study limitations

Our study is limited by the inherent bias of patient selection in a retrospective study. The vast majority (26/27) of patients had MTLE and only one patient had LTLE in this study, albeit consecutive patients were enrolled. Compared to other study cohorts, the distribution of patients was skewed toward MTLE (Ebersole and Pacia, 1996, Pacia and Ebersole, 1997). Additionally, patients with lesional TLE (other than MTS) were not included in this study. Therefore, the findings in our study do not apply to patients with lesional TLE. There was a trend towards a better surgical outcome after LITT in patients with theta/alpha ictal onset pattern. But this study does not have sufficient power to assess the difference in outcome between patients with alpha/theta and those with delta EEG pattern.

## 5. Conclusion

Using simultaneous scalp and intracranial EEG recording, our study demonstrated that both scalp theta/alpha and delta ictal

EEG onset patterns are commonly found in patients with MTLE. As such, scalp delta ictal onset is not a unique EEG pattern for LTLE as commonly believed. Patients with MTLE and scalp delta ictal EEG onset may be treatable with less invasive surgical procedures such as open or stereotactic laser amygdalohippocampectomy, as scalp ictal EEG pattern may not be significantly correlated with the post-surgical outcomes.

### Declaration of Competing Interest

Authors have no funding or conflict of interest to be disclosed.

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