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Focal epilepsies and focal disorders

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Abstract

Electroencephalographic (EEG) investigations are crucial in the diagnosis and management of patients with focal epilepsies.

EEG may reveal different interictal epileptiform discharges (IED: spikes, sharp waves). The EEG visibility of spike depends on the surface area of cortex involved (>10cm$^2$) and the brain localisation of cortical generators. Regions generating IED (defining the “irritative zone”) are not necessarily equivalent to the seizure onset zone. Focal seizures are dynamic processes originating from one or several brain regions (generating fast oscillations and called “epileptogenic zone”) before to spread to other structures (generating lower frequency oscillations and called “propagation zone”). Several factors limit the expression of seizures on scalp EEG, such as area involved, degree of synchronization and depth of the cortical generators. Different scalp EEG seizure onset patterns may be observed: fast discharge, background flattening, rhythmic spikes, sinusoidal discharge, or sharp activity but to a large extent EEG changes are linked to seizure propagation.

Finally, in the context of presurgical evaluation, the combination of interictal and ictal EEG features is crucial to provide optimal hypothesis about the epileptogenic zone.

Keywords: Epilepsy, EEG, Video-EEG, SEEG, Spike, Seizure, Network, HFO, Epileptogenic Zone
1. Introduction

Electroencephalographic (EEG) recordings have an important place in the diagnosis and management of patients with focal (partial) epilepsies. These investigations provide functional information related to the disorder and important clues to the diagnosis, and are thus complementary to neuroimaging (Gilliam et al., 1997). Interpretation of the EEG must, however, always be considered within the clinical context of a given patient (Cascino, 2002).

Several types of recordings may be carried out depending on the expected objectives. Standard EEG recordings using 10/20 montage are systematically proposed for the initial diagnosis. The standard EEG can be completed by a sleep recording (daytime nap or night) that allows recording over a longer period, which is often associated with activation of focal spikes. In detail, non-rhythmic eye movement (NREM) sleep is associated with higher rate of spikes (increasing with the deepness of the sleep) but more often bilateral, whereas in some rare patients rhythmic eye movement (REM) sleep revealed more localized spikes (Asano et al. 2007; Bazil 2003; Halász 2013; Malow et al. 1998; Malow et al. 1999; Okanari et al. 2015; Sammaritano et al. 1991;). Moreover, the localizing value of ictal discharge on scalp-EEG may also be improved during sleep (Buechler et al., 2008). Moreover, in some cases longer recording is mandatory, because some patients have low spike rates (e.g. in one study, 7.3% of the first IEDs were present within 20 min, 9.7% within 30 min, 74.5% within 24 h, 87.9% within 48 h and 96.4% within 72 h) (Werhahn et al., 2015). Furthermore, longer recording allows better detection of
contralateral spikes (for example, in temporal lobe epilepsy (TLE) the mean latency for detect contralateral IED is 5h)(Ergene et al., 2000).

Video-EEG recordings provide an additional visual record of the seizure allowing clarification of diagnosis and classification and is required for pre-surgical evaluation of focal epilepsies. Video-EEG consists of both scalp EEG and video monitoring of the patient’s activity, and is carried out in specialized video-telemetry units. In this case, the scalp electrodes are typically placed according to the 10/20 system with additional temporal-basal electrodes (FT9, TP9, FT10, TP10) (Foldvary, 2001).

It is useful to analyse the scalp EEG over different types of montages (longitudinal, transverse, average reference) because the “visibility” of abnormalities in some region could depend on the montage used (e.g. temporal seizure are sometimes more visible using transversal montage).

Finally, more sophisticated techniques (high resolution EEG, MEG) can be used in the context of epilepsy surgery to estimate the source of the interictal activities (see specific chapters).

2. **Interictal recording in focal epilepsies**

EEG may reveal different types of interictal epileptiform discharge (IED) in patients with focal epilepsies. Some are non-specific and/or depend on the aetiology (e.g. localized slow waves or altered background activity). More specific features include spikes (predominantly negative and
transient with a characteristic steeply ascending and descending slope, and a duration of 20–70 ms) or sharp waves (differing mainly from spikes in their longer duration of 70–200 ms).

Notably, an increase in IEDs rate can occur after seizures but with a more extensive spatial distribution (Gotman & Koffler 1989; Gotman 1991). Moreover, IEDs can be falsely localized in some patients and have often a wider projection on scalp than the epileptogenic zone (Dworetzky and Reinsberger, 2011).

2.1. Intracerebral organization of interictal spikes

It is important to recall some of the principles of EEG interictal spike genesis in focal epilepsies in order to understand how surface electrodes can detect these spikes. Animal models have demonstrated that focal spikes are caused by large, synchronous bursts of depolarization of the cortical neurons within the experimentally induced ‘focus’ (Prince and Futamachi, 1968). The slow wave that may follow the spikes corresponds to local hyperpolarization that follows the paroxysmal depolarization shift. In the limbic epilepsy model (Barbarosie & Avoli 1997; Bertram 2003), it has been shown that spikes may also ‘travel’ through synaptic connections and be recorded through a network of hyper-excitable structures rather than from an unique structure.

Intracerebral recordings in patients with pharmacoresistant epilepsies have revealed that intracerebrally recorded spikes are produced in some brain regions that are also involved in seizure generation (called the ‘primary irritative zone’) (Badier and Chauvel, 1995). A good
spatial superimposition of interictal and ictal activities is particularly encountered in epilepsies related to focal cortical dysplasias (Gambarrella et al., 1996).

On the other hand, the fact that interictal discharges can also be seen in areas other than the seizure onset zone and in tissue distant from the lesional site has long been described (Penfield & Jasper 1954; Jasper et al. 1961). In this case, the irritative zone is larger than the seizure onset zone (Talairach and Bancaud, 1966) and may form a distinct network independent from the seizure onset zone (Bourien et al., 2005). These regions represent the ‘secondary irritative zone’ and are generally regions affected by seizure propagation (Badier & Chauvel 1995; Badier et al. 2014; Bettus et al. 2010). Finally, even in intracranial EEG, concordance between the areas generating interictal spikes and those generating seizures is good for only about 60 % of patients (75% with focal cortical dysplasia) (Bartolomei et al., 2016). For this reason, interictal EEG is insufficient to define the epileptogenic zone.

2.2. **Correspondence between intracranial and scalp-EEG inter-ictal recordings**

Recent simulation studies (Cosandier-Rimélé et al., 2008) have revealed that a cortical source of 10 cm² area is required in order to observe scalp activity with a good signal to noise ratio (Cosandier-rime et al., 2010). For example, the cortical discharges that corresponded to scalp EEG recorded spikes involved 8-21 contacts of SEEG electrodes for temporal and 15-10 contacts of SEEG electrodes for extra-temporal sources (Merlet and Gotman, 1999). Interestingly, in this
study no scalp EEG spikes were observed that corresponded exclusively to focal activity limited to mesial temporal structures. It is noteworthy that, despite repeated standard EEG, some patients, particularly those with medial temporal lobe epilepsy, do not exhibit interictal spikes. This may be due to the spike generator characteristics. Therefore, it has been shown that the location of the cortical generator relative to the recording electrodes strongly influences EEG signal properties, thus underlining the importance of source geometry in this context (Ramantani, Maillard and Koessler, 2016). For example, the curved, inwardly rolled shape of the hippocampus, combined with its relations with surrounding structures such as the para-hippocampal gyrus, tend to create a closed electric field, cancelling out the effects on the external field (Niedermeyer and Silva, 2004). The activity of more lateral temporal neocortex, in addition to the mesial temporal structures, is therefore required for the generation of scalp-visible EEG spikes (Merlet and Gotman, 1999).

Moreover, different locations of the intracerebral spike generators can lead to relatively similar distribution of electrical potentials on scalp EEG (Cosandier-Rimélé et al., 2008). As a consequence, the IED observed at a given electrode does not necessarily represent the interictal activity of the directly underlying brain region.

2.3. **Interictal scalp-EEG recordings in focal epilepsies**

2.3.1. **Interictal scalp EEG in temporal lobe epilepsy**
A number of studies, some of them validated by intracerebral recordings, have indicated that surface interictal spikes are not seen when interictal activity is limited to medial structures and always indicate interictal activity in widespread lateral structures (Gavaret et al. 2004; Merlet et al. 1998). In this scenario, the absence or paucity of interictal spikes in the scalp EEG in TLE could then be suggestive of medial TLE if the seizure semiology is compatible. On the other hand, IEDs on scalp EEG with maximal amplitude on anterior temporal and anterior temporo-basal channels are evocative of a temporo-polar origin, whereas IEDs with maximal amplitude within mid-temporal region evokes lateral temporal origin.

Moreover, amplitude mapping of interictal spikes is a way to improve non-invasive EEG localization (Asadi-Pooya et al., 2016). In this context, two different populations of IED have been identified in TLE: type 1 = dipolar with inferior temporal negativity and vertex positivity; type 2 = non-dipolar with a lateral temporal maximum. The intracranial EEG correlates of these IEDs show that Type 1 is associated with mesial temporal sources, and Type 2 with temporal or frontal neocortical sources (Ebersole and Wade, 1990).

In mesial TLE (MTLE), the most prevalent (in about 90% of patients) IEDs are anterior temporal spikes or sharp waves with a maximum voltage in the anterior temporal regions (Tp and Fp electrodes; see Figure 2) (Williamson et al., 1993). IEDs may also be seen on mid-temporal electrodes (T3-T5-T4-T6) but if present should raise the question about a more widespread extra-mesial temporal generator (Tatum, 2012). In addition to spike and sharp waves, slow waves may also be observed. Temporal intermittent rhythmic delta activity (TIRDA), contrary to temporal polymorphic delta activity (TIPDA) or theta activity, could be evocative of TLE (Geyer
et al., 1999). Such delta activity can be bilateral, but has a high concordance with spikes (Gambardella et al., 1995). Notably, IEDs coming from the amygdalo-hippocampal complex are invisible on scalp EEG recording, because of the spike-generator characteristics, especially the spatially restricted source. Thus, IEDs recorded on scalp EEG reflect at least the propagation to basal temporal regions with synchronization of larger areas (i.e. entorhinal and fusiform cortices). Scalp EEG detects only a small proportion of the IEDs generated within mesial temporal areas (Fernández Torre et al., 1999). Therefore, some authors have suggested that the spike frequency could reflect a higher involvement of extra-hippocampal structures in patients with MTLE (Krendl, Lurger and Baumgartner, 2008). Another study suggests that high spike frequency is associated with longer epilepsy duration (Jozsef Janszky et al., 2005). Complementarily, patients with low spike rates have classically less severe epilepsy (later age at seizure onset, as well as less frequent and less severe seizures) (Rosati et al., 2003). Finally, patients with hippocampal sclerosis tend to have more restricted IEDs than patients with mesial temporal tumours (Hamer et al., 1999).

At least one-third of patients have bilateral temporal IEDs (Tatum, 2012), which become more apparent with longer EEG monitoring (Ergene et al., 2000). Nevertheless, in such patients explored by intracranial EEG, more than 75% had unilateral seizure onset zone (So, Gloor, et al., 1989). There is no clear difference concerning epilepsy aetiology between patients with unilateral versus bilateral IEDs (Lim et al., 1991). Although the association between bitemporal IEDs and post-surgical prognosis remains debated, it is noteworthy that many patients with bitemporal IEDs but unilateral seizure onset will benefit from a unilateral temporal resection (Holmes et al. 1996; Hufnagel et al. 1994; Janszky et al. 2005; Krendl et al. 2008; So et al. 1989).
It is therefore more important to consider the degree of lateralization of IEDs rather than merely the existence of independent bilateral IED in patients with independent bitemporal abnormalities (Chung et al., 1991). Thus, patients with bitemporal IEDs should not be precluded from surgery because of the bilaterality of interictal abnormalities.

In lateral TLE, while some patients show IEDs over anterior temporal electrodes (about one third), the majority of them have been noted to predominate over the lateral temporal electrodes (T3-T5-T4-T6; see Figure 3)(Kennedy & Schuele 2012; Pfänder et al. 2002). Moreover, in neocortical TLE, contralateral IEDs are less frequent than in MTLE (only 10% to 20%)(Kennedy & Schuele 2012; Pfänder et al. 2002). Finally, neocortical TLE have more frequent IEDs (including lateralized slow waves)(Kennedy & Schuele 2012; O’Brien et al. 1996).

Patients with temporal “plus” epilepsies more frequently have pre-central IEDs (F4-C4; F3-C3) (Barba et al., 2007).

2.3.2. Interictal scalp EEG in frontal lobe epilepsy

In frontal lobe epilepsy (FLE), interictal spikes on scalp EEG (Figure 4) may be non- or mis-localizing, and are often widespread and bilateral (Harner and Riggio, 1992). Indeed, a high proportion of patients with FLE have IED discordant with their seizure onset zone (about 45%) (Vadlamudi et al., 2004). Widespread surface interictal spikes in FLE can be explained by the fast and remote propagation of interictal activities due to the extensive intra- and inter-lobar
connections that characterize the frontal lobe. Widespread surface interictal spikes can also be explained by electric fields that have a diffuse projection on surface EEG (Sutherling et al., 1991). Moreover in children with FLE, IEDs may be bilateral synchronous, multifocal or even localized to temporal lobe (Lawson et al., 2002). On the other hand, up to 20% of patients with FLE seizures do not have IED (Salanova et al., 1993; Bautista, Spencer and Spencer, 1998; Vadlamudi et al., 2004). Electrical activities arising from lateral, medial and basal regions of the frontal lobe are projected differently on scalp EEG and thus pose different detection problems.

In dorsolateral FLE, there is generally good concordance between the IEDs and the seizure onset zone (about in 68% of patients) (Vadlamudi et al., 2004). Moreover, IEDs could be restricted to smaller irritative zones (see Figure 4).

On contrary, in mesial FLE only 33% of patients have good concordance between IEDs and seizure onset zone (Vadlamudi et al., 2004). Thus, patients with mesial FLE frequently have poorly localized or even absent IEDs (Unnwongse et al. 2012; Williamson et al. 1985). If visible, IEDs are mostly seen on frontal (F4, F3) or midline (Fz, Cz) electrodes. Notably, midline IEDs are particularly seen in patients with supplementary motor area seizures (figure 5) (Morris et al., 1988; Blume and Oliver, 1996). Furthermore, anterior medial spikes project to fronto-polar surface EEG electrodes, whereas posterior medial spikes project to central and centro-parietal surface EEG electrodes (Gavaret et al., 2006). On the other hand, bilateral frontal synchronous or multilobar IEDs are frequent in mesial FLE (Harvey et al., 1993). Interictal rhythmic midline theta (mean frequency of 6Hz and mean duration of 8 seconds, observed on Cz, Fz electrodes) during clear wakefulness, excluding periods of mental activation and drowsiness (differential
diagnosis with normal variants), is particularly evocative of FLE, especially mesial FLE, even in patients without IEDs (Beleza, Bilgin and Noachtar, 2009).

In orbital FLE, IEDs are mostly noted in frontal, fronto-polar, or fronto-temporal areas. In these epilepsies, bilateral synchrony is not uncommon, with maximum amplitude on fronto-polar or frontal electrodes; notably maximum IED presence in one anterior quadrant is possible (Chang et al. 1991; Kriegel et al. 2012; Ludwig et al. 1975; Rougier & Loiseau 1988; Smith et al. 2004;). IEDs often do not allow accurate localization of the irritative zone in the basal frontal lobe (Beleza and Pinho, 2011). IED are thought to appear widely distributed because of the large distance and intervening cortical area between the cortical generator and the scalp EEG electrodes. Moreover, false localization to anterior temporal region is possible in patients with basal frontal epilepsies (Shihabuddin et al., 2001).

2.3.3. Interictal scalp EEG in other lobes epilepsies

In parietal lobe epilepsy, IEDs may be recorded on several regions: parietal, fronto-central, temporal posterior, occipital, even entire hemisphere (Figure 6) (Salanova et al. 1995; Salanova et al. 2012). Secondary bilateral synchrony is also frequent (about in 31% of patients) (Salanova et al. 1995; Salanova et al. 2012).

In occipital lobe epilepsies, the IEDs could be seen on occipital (O1-O2; see Figure 7) but are more frequently seen on temporal posterior electrodes (T5-T6)(Salanova et al. 1992;
Williamson et al. 1992). In some patients, IEDs could be contralateral at the seizure onset zone, bilateral and independent, or even with bilateral synchrony (Salanova et al. 1992; P. Williamson et al. 1992).

In insular epilepsies, due to deep location, specific gyral organization and limited cortical surface, interictal epileptiform discharges (IEDs) limited to insula/operculo-insula can be invisible on scalp EEG (Luders, 2008). When visible, IEDs mostly reflect peri-sylvian propagation and are observed on temporal (T3/T5/T4/T6) and/or frontal (Fp1/Fp2/F7/F8/C4/C3) electrodes, even multifocal or falsely lateralized (Isnard et al., 2000, 2008; Nguyen et al., 2009; Kriegel, Roberts and Jobst, 2012; Dylgjeri et al., 2014; Laoprasert, Ojemann and Handler, 2017; Levy et al., 2017).

2.4. High frequency oscillations:

Recently, technological advances have allowed the recording of a new IED type: high frequency oscillations (HFOs; 80–500 Hz) in intracranial EEG. If HFOs were initially recorded from intracranial micro-electrodes in humans and rat models of epilepsy (Bragin et al., 1999), it can be recorded with conventional invasive EEG electrodes using high sampling rates ( > 2000 Hz). These interictal HFOs can be seen in both physiologic and pathologic situations. The HFO rates also vary according the cerebral area (Guragain et al., 2018). In pathologic situations, HFO are related to the seizure
onset zone in interictal periods and have been identified in a large variety of clinical
scenarios (e.g. different seizure onset zone topography, MRI negative epilepsies,
etc. ) (Andrade-Valença et al. 2012; Crépon et al. 2010; Jacobs et al. 2008;
Urrestarazu et al. 2007). Whether or not HFOs co-occur with interictal spikes, HFOs
(especially fast-ripples) may be more specific than spikes as a marker of the seizure
Moreover, some studies have suggested a link between the removal of tissue
generating high HFO rates and favourable surgical outcome (Akiyama et al. 2011;
Jacobs et al. 2010; Klooster et al. 2015; Höller et al. 2015; Wu et al. 2010). However,
at the individual level, the real impact of HFO study is uncertain. A recent study using
quantification of the ictal zone, based on both spikes and HFOs revealed that HFOs or
any of its variants were not statistically better than spikes at the group or individual
level (Roehri et al., 2017).
More recently, it has been demonstrated that HFOs (ripple) can be detected in scalp
EEG in patients with focal epilepsies (Andrade-Valenca et al., 2011; Melani et al.,
2013; Zelmann et al., 2014; Pizzo et al., 2015; Cuello-Oderiz et al., 2017; Zijlmans et
al., 2017). Nevertheless, scalp HFOs analyses require careful methodology to avoid
muscular or movement artefact (Zijlmans et al., 2017), and regarding filtering in
order to avoid “false-ripple” detection (Bénar et al., 2010) Even although scalp HFOs
have better specificity than spikes they are less sensitive (Andrade-Valenca et al.,
Moreover, scalp HFOs are not detected on scalp in all epileptogenic lesions (notably not in mesial locations) (Cuello-Oderiz et al., 2017) and scalp HFOs are very rare in patients with low spike rates (Melani et al., 2013). Furthermore, HFOs detection in patient without epilepsy highlighted the importance of distinguishing physiological from pathological ripples in scalp (Mooij et al., 2017). These points suggest that the added-value of scalp HFOs in patient with rare/absent spikes will be very limited. On the other hand, scalp HFOs could be more useful in patient with widely distributed spikes. This approach demonstrated the possibility of lateralizing the seizure onset zone in patients with focal epilepsy and secondary bilateral synchrony (Pizzo et al., 2015). Further studies are required to estimate, in larger samples and in the context of clinical practice, the added-value of scalp HFOs in patients with focal epilepsies.

3. Ictal recordings in focal epilepsies

Analysis of scalp ictal EEG recordings aims at identifying the presence of abnormal rhythms (rhythmic activity), at lateralizing (i.e. the hemisphere in which seizures start) and if possible localizing the epileptogenic zone even approximately in a given brain region (e.g. frontal, temporal). Scalp ictal EEG patterns vary according to the type of
epilepsy and are thus most of the time helpful to define the epileptogenic zone (Foldvary et al. 2001; Lee et al. 2000). Moreover, ictal EEG modifications are more accurate than interictal EEG abnormalities for inferring EZ localization, because of the possible discordance between the areas generating the interictal spikes and the seizures (Bartolomei et al., 2016).

From the viewpoint of epilepsy surgery, ictal EEG provides essential information, in complement with other ancillary exams of the presurgical work-up (e.g. MRI, PET), to define which brain structures are potentially involved in the epileptogenic network and then need to be resected. On the other hand, if intracerebral EEG recording is required, this information is crucial to plan the position of the necessary intracerebral electrodes.

Although significant technical progress has been made in acquisition systems, it is noteworthy that the analysis of ictal scalp EEG signals (both visual and quantified) remains a difficult task due to the various sources of patient-related artefacts (muscle, movements, etc.), particularly during ictal episodes in which motor manifestations are frequent. Moreover, some seizure onset zones could remain invisible on scalp EEG because of various factors (see below). At worst, false localization and even lateralization are also not uncommon, occurring in about 6-18% of cases (Engel et al. 1980; Lee et al. 2000; Risinger et al. 1989; Sammaritano et al. 1987; Spencer et al. 1985).

There may be concerns with AED withdrawal routinely applied in most epilepsy surgery
centres during video-EEG, since this might affect the patterns of ictal onset and/or propagation. Although some patients have atypical seizures after AED withdrawal (Engel and Crandall, 1983), a large majority of them have no change in their seizure features (Spencer et al., 1981). Whereas medication clearly affects seizure frequency and secondary generalization, it does not affect the morphology of scalp EEG ictal discharges, the occurrence and/or duration to contralateral spread (So and Gotman, 1990). Therefore, ictal scalp EEG recorded during anticonvulsant withdrawal does not provide misleading information about epileptogenic zone localization hypothesis (Marciani & Gotman 1986; Spencer et al. 1981; Zhou et al. 2002).

3.1. Organization of seizures: contributions of intracerebral recordings

It is important to understand how a seizure may originate and ‘spread’ in the brain. Most of our knowledge comes from studies using direct intracerebral recordings.

A model of seizure dynamics and anatomy is proposed in Figure 8 (Bartolomei, Chauvel and Wendling, 2005). A seizure originates from one or several regions in the brain (including or not a visible lesion) before to spread to a second set of structures generating lower frequency oscillation. Seizure may involve a very focal region (e.g. as the sole lesion in some focal cortical dysplasia) or a more distributed network of brain
structures (as in mesial temporal lobe seizures (Figure 9 and 10). These structures are the most epileptogenic and are called the “epileptogenic zone”.

In the epileptogenic zone, the possible patterns of interictal to ictal transition are variable. The most characteristic pattern is the emergence of a low voltage fast activity (LVFA) (Singh, Sandy and Wiebe, 2015). The frequencies in LVFA range from beta/low gamma ranges (15-30Hz) (mostly in mesial temporal seizures (Bartolomei et al., 2004)), to higher frequencies (gamma range, 30-100hz, generally observed in neocortical seizures (Alarcon et al. 1995; Allen et al. 1992; Fisher et al. 1992; Singh et al. 2015; Worrell et al. 2004). Most of the time the emergence of such fast activity leads to a desynchronization among the involved structures (Wendling et al., 2003). In some cases, this rapid discharge may be preceded by EEG changes in the form of pre-ictal spiking, burst of poly-spike or slow-wave/DC shift complexes. These changes are thought to synchronize the ictal activity in several distributed structures (Bartolomei et al., 2004). Finally, a significant number of seizures about 20 %, can start without any low voltage fast activity (e.g. slow rhythmic spikes/spike-waves or theta/alpha sharp activity) (Lagarde et al., 2016). Some examples of interictal to ictal transition are shown in Figure 11.

A second set of brain structures may be involved later in the seizure and constitutes the “propagation zone network”. This network may be more or less extensive, and is characterized by slower rhythms and higher voltage activities. The synchronization of
rhythmic activities at this stage has been shown to be maximal during the seizure (Guye et al. 2006; Schindler et al. 2007). Notably, the scenario of seizure onset and spread is generally remarkably reproducible in a given patient. Figures 9, 10 and 12 illustrate this showing a mesial temporal lobe seizures (the first mesial structures involved by the rapid discharge representing the “epileptogenic network”) spreading to the lateral temporal lobe (Figure 10); and also prefrontal cortex and insula (Figure 12) (these neocortical structures being involved later with discharge of slower frequency, representing the “propagation network”).

3.2. Correspondence between intracranial and scalp-EEG seizures recordings

It is important to understand the factors limiting the expression of seizures in surface (Ramantani et al. 2016; Tao et al. 2007), because it is often difficult to capture the activity of the epileptogenic zone directly from scalp electrodes. In one study, less than 50% of intracerebral EEG ictal discharges had early concomitant scalp EEG correlate (Tao et al. 2007). Most of the scalp EEG changes observed during a seizure therefore indirectly reflect the seizure onset in the “epileptogenic network” (ex: background slowing), or only show activity in the “propagation zone network” (Sakai et al., 2002). For example, the mean delay before the appearance of scalp EEG changes after a seizure onset within the mesio-temporal areas is of the order of 7 seconds (Tao et al. 2007). Thus, from the electroencephalographer’s point of view, it is important to “imagine” the
underlying intracerebral dynamics in order to interpret the surface recordings.

Five factors are involved in the surface seizure expression: the area of seizure onset zone, the synchrony within the seizure onset zone, the distance from the seizure onset zone to the surface, the level of background and the skull conductivity. Firstly, studies of simultaneous intracerebral and scalp EEG recordings have shown that sufficient source area (at least 10 cm$^2$) and high synchrony (expressed generally as slow frequency and high amplitude discharges) are needed to generate ictal patterns visible on scalp EEG (Cosandier-Rimélé et al. 2012; Tao et al. 2007 a,b). In fact, if sufficient source area and synchrony are achieved at seizure onset, then ictal rhythm appears simultaneously, or almost, on scalp and intracerebral EEG (Tao et al. 2007 a,b). The source-to-sensor distance is also an important factor and it is well-known that the amplitude of EEG signal is inversely proportional to the square of the source to surface’s distance (Cosandier-Rimélé et al., 2007). Notably, when the distance to the source increases, the low frequencies increase and the high frequencies decrease on scalp EEG (Cosandier-Rimélé et al., 2012). Moreover, the level of background activity appears as the most critical factor impeding the observability of rapid discharges on scalp EEG. In this respect, a slight increase in background level may result in a drastic alteration of the frequency spectrum and could easily overshadow a concurrently rapid discharge (Cosandier-Rimélé et al., 2012). Finally, low skull conductivity is only a minor factor in the lack of observable rapid discharges in scalp EEG, leading to attenuation of voltage amplitude without
altering the spectral content (Cosandier-Rimélé et al., 2012).

Rapid discharges at seizure onset are often limited to restricted brain areas (James X. Tao et al., 2007) and transiently desynchronize the structures involved (Wendling et al., 2003), therefore their recording on scalp EEG remains very difficult and rare, because of the combination of small source area and lack of synchronized activity.

3.3. Dynamic patterns of scalp EEG seizures

3.3.1. Changes related to the epileptogenic zone

It is possible but very rare to observe the rapid discharge (as observed using intracerebral EEG) at the seizure onset on scalp EEG. If visible, such rapid discharge, reflects more superficial sources, generally neocortical (Figure 13) (Tao et al. 2007). Nevertheless, most of the time it is difficult to distinguish fast discharge from normal brain rhythms (e.g. rapid activities that are physiologic in fronto-central areas) or from muscular activity. Therefore, a focal or regional flattening of the EEG activity associated with the disappearance of normal background activity (often referred as ‘electro-decremental pattern’) is actually more often observed (Blume et al. 1984; Gastaut et al. 1953; Klass 1975; Jasper 1949; Jasper et al. 1951) (Figure 14). In these cases, the
Topography of focal flattening appears as an important clue to localize the epileptogenic zone. On the other hand, the slow seizure onset patterns (rhythmic spikes or theta/alpha sharp activity) are also very common and more easily visible on scalp because of their higher amplitude and synchrony (Blume et al. 1984; Ray et al. 2007; Tao et al. 2007). Similarly, the sequence of pre-ictal changes prior to the low voltage fast activity (visible or not on surface) may also be seen on scalp EEG (Figure 15 and 16). Finally, it is notable that several scalp EEG ictal pattern may be observed in a same patient (Risinger et al., 1989). Less specifically, seizure onset discharge might be invisible on scalp-EEG but produces changes in normal brain rhythms, such as the unilateral disappearance of alpha rhythm (Klass, 1975; Ebersole and Pacia, 1996), or changes in sleep activity such as diffuse flattening due to arousal (Derry et al., 2009). These indirect changes can be the first scalp EEG modification associated with focal seizure onset. Moreover, the absence of EEG changes during the initial clinical signs is already an indication that the seizure is generated from deep structures (e.g. mesio-temporal or orbito-frontal areas). It should also be kept in mind that non-epileptic seizures can also be the reason for the absence of EEG modifications.

In addition, concomitant muscular and ECG recordings can add crucial information. Muscular contraction associated with seizure onset can be captured by bipolar electrodes placed over the appropriate muscles and is particularly important to record in patients with pre-motor/motor cortex seizures (Mothersill et al. 2000; Tassinari &
Rubboli 2008). In addition to localize the seizure onset zone within these structures, it could help the semiology analysis and help lead to establishing the lateralization of seizure onset.

Similarly, ECG changes can be the sole manifestations of a focal seizure, revealing tachycardia (Di Gennaro et al., 2004) more often than bradycardia (van der Lende et al., 2015; Shmuely et al., 2017). For example, a seizure onset limited to the mesial temporal structures could express initially as a sole tachycardia without any concomitant changes on scalp EEG (figure 17).

3.3.2. Changes related to the propagation zone

The most evident changes observed in scalp recordings are related to the propagation of ictal discharge. At this stage, it is usual to observe more extensive, synchronized and ample activity (Figures 9-12). Moreover, the scalp EEG ictal pattern may evolve either as a change in morphology, amplitude or frequency (Blume, Young and Lemieux, 1984). The frequency of rhythmic discharge shows most of the time a gradual decline in frequency and an increase in amplitude, but these features are not constant (Anziska & Cracco 1977; Gloor 1975; Marsan 1961). Moreover, some authors suggested a link between the frequency and the localization (more often in the theta range in lateral temporal
epilepsies, and beta in occipital epilepsies) (Lee et al., 2000). This discharge is generally unilateral initially, but bilateral expression is possible and does not necessarily imply that the epileptogenic zone is bilateral (Napolitano and Orriols, 2008, 2010; Sirin et al., 2013). Notably, false lateralization is not uncommon, particularly in patients with extra-temporal epilepsies (Foldvary et al., 2001).

3.3.3. Changes related to the seizure ending

The ictal discharge generally ends abruptly and is followed by depression of EEG activity or/and a marked slowing. The post-ictal slowing has important value to lateralize and even help localize the epileptogenic zone, especially when clear ictal rhythm is lacking or difficult to analyse (Jan et al. 2002; Jan et al. 2010; Kaibara & Blume 1988; O’Brien et al. 1996; Sirin et al. 2013; Williamson et al. 1993).

3.3.4. Importance of electro-clinical correlations

It is important to correlate EEG changes and semiology when seizures are studied on video-EEG recordings. As seen above, the seizure onset discharge is often invisible on
scalp-EEG. In this case, semiological analysis is the best way to provide hypothesis about the epileptogenic zone. Additionally, different cerebral source configurations could generate similar surface voltage distribution. Therefore, the maximal activity at a certain electrode does not systematically indicate that the generators are located in the underlying brain region (Ebersole, 2000; Michel et al., 2004). Thus, the concomitant analysis of semiology and scalp-EEG is highly more accurate than analysis of EEG alone for the definition of the epileptogenic zone (Serles et al., 2000).

3.4. Specific problems with some focal seizures

3.4.1. Temporal lobe epilepsies

The TLEs are the most frequent forms of focal seizures recorded in adult patients. Several subtypes of TLE have been described: mesial seizures in which the seizures start from the limbic medial part of the temporal lobe; lateral seizures starting from the lateral neo-cortex; mesio-lateral seizures arising concomitantly from mesial and lateral areas of temporal lobe; temporo-polar; and temporal “plus” involving also the neighboring structures (orbitofrontal cortex, insula, frontal and parietal operculum, or temporo-parieto-occipital junction) (Kahane and Bartolomei, 2010).

Many studies have proved that ictal scalp EEG is a reliable and accurate way to lateralize
and even localize the epileptogenic zone in patients with TLE (Ebersole & Pacia 1996; Foldvary et al. 2001; Pacia & Ebersole 1997; Pataaraia et al. 1998; Risinger et al. 1989; Sakai et al. 2002; Serles et al. 2000; Spencer et al. 1985; Steinhoff et al. 1995; Walczak et al. 1992; Williamson et al. 1993). Nevertheless, while false localization has been shown to be uncommon (Risinger et al., 1989; Williamson et al., 1993; Adamolekun, Afra and Boop, 2011), it remains possible especially in patients with large lesions (Lee et al. 2000; Sammaritano et al. 1987). Potential ictal rhythm patterns in TLE include:

- temporal rhythmic activity in the delta, theta or alpha ranges (the most prevalent) (Ebersole & Pacia 1996; Ebersole 1997; Malter et al. 2016; Pacia & Pataaraia et al. 1998; Sakai et al. 2002; Sirin et al. 2013; Steinhoff et al. 1995)
- unilateral (or even bilateral (Pacia and Ebersole, 1997)) background attenuation or interictal spikes cessation (Figure 16) (Sakai et al. 2002; Sirin et al. 2013);
- rhythmic localized spiking (Figure 17) or sharp wave (Figure 18) (Sirin et al., 2013);
- rapid discharge (rarely) (Sakai et al. 2002).

Whereas some authors suggested that ictal scalp EEG pattern differs according to the seizure onset zones (regular 5 to 9 Hz inferior temporal rhythm associated with mesial onset and irregular, polymorphic 2 to 5 Hz associated with lateral onset) (Assaf & Ebersole 1999; Ebersole & Pacia 1996; Pacia & Ebersole 1997), many discrepancies remain across published articles (Steinhoff et al., 1995; Sirin et al., 2013; Malter et al., 2016) and currently the accurate identification of epileptogenic zone cannot be based
only on the type of ictal scalp EEG pattern (Jin & Nakasato 2016; O’Brien et al. 1996).

The most common types of TLE involve the mesial temporal lobe regions (MTLE). In the case of pure MTLE, it has been found that about 95% of patients with TLE have EEG changes throughout the whole seizure course (Parsonage, 1974). Nevertheless, when the discharge is initially restricted to the mesial temporal region, it remains generally invisible on scalp EEG (Pacia and Ebersole, 1997) and at best background attenuation over the surface temporal electrodes could be observed (without rapid discharge; Figure 18a) (Pacia and Ebersole, 1997). Therefore, the scalp EEG tends to observe the ictal pattern corresponding to the propagation (generally at least 10 seconds after the seizure onset, Figure 18b) of the discharge to basal or lateral temporal cortex (Pacia & Ebersole 1997; Sakai et al. 2002;). The most prevalent propagated pattern is rhythmic temporal activity with a frequency ranging from delta to alpha. If this pattern is the first seen, it is very specific for TLE (Foldvary et al., 2001). Notably, the frequency of the rhythmic activity often varies in the same patient (Malter et al., 2016). This frequency increases with epilepsy duration (Malter et al., 2016) and the degree of hippocampal sclerosis (Vossler et al., 1998). Notably the ictal scalp EEG is not necessarily limited to the temporal electrodes. For example, seizure activity within basal or polar temporal area can produce ictal scalp EEG pattern predominant around the vertex derivations (Pacia and Ebersole, 1997). Actually, about 13% of ictal scalp EEG patterns are hemispheric or non-localizing (Lieb et al. 1976; Malter et al. 2016; Napolitano & Orriols 2010; Risinger et
al. 1989). The probability to observe a focal seizure onset is also lower among the patients with independent bitemporal IEDs (Steinhoff et al. 1995; Walczak et al. 1991). Some patients may also exhibit different ictal patterns on scalp EEG across seizures. In these patients, a reproducible and localized ictal scalp-EEG pattern is associated with favourable prognosis (Risinger et al. 1989; Tatum et al. 2008). Additionally, propagation of the scalp-EEG discharge is mostly within the ipsilateral hemisphere, but contralateral propagation is not uncommon (Napolitano and Orriols, 2010). In cases of bilateral ictal discharge, early (< 10 seconds) should be distinguished from late (> 10 seconds) propagation (Napolitano and Orriols, 2008; Monnerat et al., 2013; Malter et al., 2016). Actually, some patients have initial (within the first 3 seconds) bilateral seizure onset or switch of lateralization/asynchrony within a bitemporal discharge (Schulz et al., 2000; Sirin et al., 2013). Thus, early bilateralization, in addition to bilateral independent seizures, are indicative of bitemporal epileptogenicity and are thus associated with worst prognosis (Lee et al. 2000; Sirin et al. 2013;). On the other hand, delayed contralateral propagation is common and not associated with poor prognosis (Monnerat et al., 2013; Malter et al., 2016). Finally seizure termination patterns, when unilateral, add some information to the hypothesized epileptogenic zone localization (Kaibara and Blume, 1988; Jan, Sadler and Rahey, 2001). When bilateral, this is associated with poorer prognosis if contralateral (Sirin et al., 2013).

In case of temporal lateral seizure, ictal discharge is clearer and earlier seen on scalp EEG
(temporal electrodes) (Sakai et al., 2002). However, about 40% of temporal lateral seizures have no visible EEG onset (Pelliccia et al., 2013). Low-voltage fast activity and local flattening are more prevalent (about 20% and 30% respectively) (Pelliccia et al., 2013). More rarely, rhythmic spikes could also been seen (Pelliccia et al., 2013). Thus, in a large proportion of patients the main ictal EEG trait of temporal seizures remains the propagation pattern, mainly consisting of theta/delta rhythmic activity (Ebersole & Pacia 1996; Pacia & Ebersole 1997; Risinger et al. 1989; Tatum et al. 2008; Vossler et al. 1998; Walczak et al. 1992). Fast activity as a propagation pattern is also possible but is rather exceptional (Pelliccia et al., 2013).

In temporo-basal and temporo-polar epilepsies, ictal discharge may sometimes be somewhat misleadingly better observed on vertex electrodes.

Finally, in temporal “plus” epilepsies, ictal scalp-EEG changes tend to be more frequently localized over anterior frontal, temporo-parietal or central electrodes (Figure 19) (Barba et al., 2007).

3.4.2. Frontal lobe epilepsies

Epilepsies originating from the frontal lobe are traditionally divided into lateral frontal, orbitofrontal, and mesial frontal epilepsies. Distinction between these syndromes can be
challenging because of the complexity of functionally interconnected frontal areas and the variability of ictal propagation patterns (Bonini et al., 2014).

Frontal lobe seizures are often difficult to detect and localize on scalp EEG recordings, since about 42% of ictal scalp EEG are unable to localize or lateralize the epileptogenic zone in FLE versus about 13% in lateral TLE (Lee et al., 2000). Well-localized ictal EEG discharge in FLE is rare; most of the time it can be only regionalized or lateralized (Foldvary et al. 2001; Lee et al. 2000; Swartz et al. 1991;). In fact, spatially limited frontal lobe seizures could be expressed on scalp EEG as widespread changes over fronto-centro-parietal or fronto-centro-temporal electrodes, giving the illusion of a large epileptogenic zone (Quesney, 1991). Moreover, ictal discharge in temporal regions or in the opposite frontal lobe has been reported (but are rare in dorsolateral frontal seizures) (Quesney, 1991). Ictal scalp EEG analysis of frontal lobe seizures is challenging because of:

- frequent muscle artifacts from motor activity,
- rapid seizure propagation limiting the localization of the seizure onset zone
- the fact that discharges originating from mesial and orbital frontal regions are often invisible on surface
- paradoxical lateralization and secondary bilateral synchrony phenomena add to the complexity when interpreting EEG (more frequent in case of orbital, mesial or cingulate FLE (Quesney, 1991)).
Notably, frontal lobe seizures often occur during slow-wave sleep, sometimes following spindles or K complexes. Examples of seizures in frontal lobe epilepsy are shown in Figures 20 and 21. Moreover, duration of ictal activity is shorter than in other types of epilepsies (Lee et al., 2000).

Dorsolateral frontal lobe ictal onset typically presents on scalp EEG as rhythmic fast activity (Figure 20) (Bautista, Spencer and Spencer, 1998); nevertheless rhythmic epileptiform activity, rhythmic delta, or background attenuation/flattening can also be observed (Foldvary et al. 2001; Lee & Worrell 2012). Scalp ictal EEG patterns are often lateralizing or localizing (contrary to other subtypes of FLE) and some post-ictal changes can be seen (Lee and Worrell, 2012). Furthermore, the absence of any visible scalp EEG ictal activity could almost exclude the possibility of seizures arising from dorsolateral frontal areas (negative predictive value of 93%)(Bautista, Spencer and Spencer, 1998; Lee and Worrell, 2012). In addition, a focal ictal beta-frequency discharge on scalp EEG was seen to be associated with favorable outcome after surgery both in lesional and non-lesional epilepsies (Lee & Worrell 2012; Worrell et al. 2002).

In mesial FLE, initial ictal scalp EEG discharge may consist of diffuse background attenuation followed by either no electrographic changes or rhythmic activity in the vertex channels occurring after clinical onset (Bautista et al. 1998; Foldvary et al. 2001; Unnwongse et al. 2012). In several cases, the ictal pattern appeared to have bilateral distribution (Unnwongse, Wehner and Foldvary-Schaefer, 2012). Moreover, mesial frontal seizures without secondary generalization commonly show no localized postictal changes (Unnwongse, Wehner and Foldvary-Schaefer, 2012).
In orbital FLE, scalp EEG ictal discharges are often invisible (Kriegel et al. 2012; Ludwig et al. 1975; Smith et al. 2004) or could be recorded from frontal (Rheims et al., 2005) or even from temporal electrodes (Shihabuddin et al., 2001). Low voltage fast activity has been reported (Rheims et al., 2005), but flattening or background attenuation are the most frequent scalp EEG ictal patterns (Figure 21) (Ludwig, Marsan and Buren, 1975; Rougier and Loiseau, 1988) and ictal scalp EEG without visible change is possible (Kriegel, Roberts and Jobst, 2012).

3.4.3. Other epilepsies

Localized scalp EEG ictal discharges are more limited in parietal and occipital lobe (Foldvary et al. 2001; Lee et al. 2000;), because false localization or even lateralization is more frequent, and bilateral scalp expression is not uncommon (Foldvary et al., 2001). No specific pattern of ictal scalp EEG has been described.

Parietal lobe seizures are rarely localizable on scalp EEG; they can be only lateralized (Figure 22). The localizing value is better in cases of lateral than mesial parietal seizures (Foldvary et al. 2001; Salanova et al. 1995; Salanova 2012; Williamson et al. 1992). The maximal ictal activity is classically seen over the centro-parietal or, less frequently, in temporal posterior electrodes (Figure 22)(Salanova, 2012). Notably, a subsequent proportion of seizures can be mislocalized (about 16%) or have rapid and diffuse propagation limiting their localization (Foldvary et al., 2001)

Occipital lobe seizures can be adequately localized in a limited number of patients (about 50%) because false localization, bilateral expression and widespread propagation are not uncommon.
(Foldvary et al. 2001; Salanova et al. 1992; Williamson et al. 1992).

In insular or insulo-opercular seizures, ictal discharges are rarely detected by scalp EEG, unless these discharges spread to adjacent peri-sylvian neocortex (Luders, 2008). Insulo-opercular ictal discharges can be observed with scalp EEG usually over the frontal and/or temporal lobes (Ryvlin and Picard, 2017). Seizure onset pattern are not specific and can include fast activity, rhythmic spike and wave activity or rhythmic alpha and delta activity (Levy et al., 2017). Scalp EEG ictal discharge can appear on temporal, frontal, fronto-temporal, or fronto-centro-parietal electrodes (Levy et al., 2017), leading to the impossibility of differentiating insular seizures from temporal, frontal, or parietal seizures (Isnard et al., 2008; Nguyen et al., 2009). However, ictal scalp EEG might fail to display epileptiform discharges (Levy et al., 2017; Ryvlin and Picard, 2017).

Motor seizures arising from the medial central area can be limited to muscular jerks (focal cortical myoclonus). Importantly, these seizures can be unapparent on scalp EEG because of the depth and spatially limited extent of the generator, even in cases of epilepsia partialis continua. In such case, back-averaging is required to prove a time-locked relationship between EEG activity and myoclonus confirming the epileptic nature of the myoclonus (Shibasaki and Kuroiwa, 1975; Shibasaki, Yamashita and Kuroiwa, 1978; Chauvel et al., 1986).

Even more complicated cases exist where seizures are often not limited to a single lobe and it is not rare to observe fronto-temporal, occipito-temporal or parieto-frontal seizures. In these cases, the visibility of ictal discharge on scalp EEG depends on the specific characteristics of each brain region involved. Therefore, the scalp EEG can be misleading, showing only one part
of the epileptogenic network involved. For example, an occipito-temporal seizure can be reflected by a temporal discharge, and a temporo-frontal seizure by a frontal discharge.

4. Conclusion

EEG investigations are crucial in the diagnosis and management of patients with focal epilepsies. EEG can detect interictal epileptiform discharges (IEDs) and record ictal discharges. Interpretation of the EEG requires knowledge of the factors influencing the scalp visibility of the source of these activities as well as a good knowledge of the dynamics of focal seizures. EEG is one of the most important elements in the diagnosis of focal epilepsy. As part of the presurgical assessment of focal epilepsy, video-EEG recordings are a cornerstone of localization diagnosis and possible surgery.

References


Gambardella, A. et al. (1995) 'Focal Intermittent Delta Activity in Patients with


Mooij, A. H. et al. (2017) 'Physiological Ripples (± 100 Hz) in Spike-Free Scalp EEGs of Children With and Without Epilepsy', Brain Topography. Springer US, 0(0), p. 0. doi: 10.1007/s10548-017-0590-y.


Rosati, A. et al. (2003) ‘Intractable temporal lobe epilepsy with rare spikes is less severe than with frequent spikes.’, Neurology, 60(8), pp. 1290–1295. doi: 10.1212/01.WNL.0000058761.12715.0E.


Walczak, T. S., Radtke, R. a and Lewis, D. V (1992) 'Accuracy and interobserver reliability of
recordings in epilepsy patients’, *Seizure*. BEA Trading Ltd, 29, pp. 20–25. doi:
10.1016/j.seizure.2015.03.012.
characteristics, seizure spread patterns, and results of surgery’, *Annals of Neurology*, 31(1),
and results of surgery’, *Annals of Neurology*, 31(2), pp. 193–201. doi:
10.1002/ana.410310210.
and ictal scalp electroencephalography, neuropsychological testing, neuroimaging, surgical
results, and pathology’, *Annals of Neurology*, 34(6), pp. 781–787. doi:
10.1002/ana.410340605.
Wu, J. Y. *et al.* (2010) ‘Removing interictal fast ripples on electrocorticography linked with
seizure freedom in children’, *Neurology*, 75(19), pp. 1686–1694. doi:
10.1212/WNL.0b013e3181fc27d0.
Zelmann, R. *et al.* (2014) ‘Scalp EEG is not a blur: It can see high frequency oscillations
although their generators are small’, *Brain Topography*, 27(5), pp. 683–704. doi:
carbamazepine and valproate in monotherapy’, *Epilepsia*, 43(4), pp. 386–393. doi:
Zijlmans, M. *et al.* (2017) ‘How to record high-frequency oscillations in epilepsy: A practical
Figures Legends

**Figure 1:**

In temporal lobes epilepsies, concomitant projection of inter-ictal spikes into vertex derivation suggests involvement of superior temporal gyrus.

In this example, observe the concomitant projection into vertex derivation (Fz, Cz) of right temporal spikes (T4) in a patient with spikes involving superior temporal gyrus on intracranial EEG recordings (electrodes T, P and L).

**Figure 2:**

Example of right temporal anterior spikes in mesial temporal lobe epilepsy. See spikes with phase-inversion on TP10 and T4 electrode in bipolar montage, in a patient with right hippocampal sclerosis.
**Figure 3:**

Example of patient with right temporo-lateral epilepsy showing spikes on electrode T4. Observe the maximum of amplitude on montage against mean reference and the maximum of negativity over T4 electrode.

**Figure 4:**

Example of abundant interictal activity (slow waves and spikes) localized in the right fronto-polar region (maximum on Fp2 in referential montage) in a patient with a dorso-lateral prefrontal focal cortical dysplasia visible on MRI (red circle).

**Figure 5:**

Example of left fronto-central spike-wave in a patient with premotor focal cortical dysplasia (note the phase-inversion over C3 in bipolar montage and the projection into vertex electrodes Fz-Cz).

**Figure 6:**
Example of spikes observed in right temporal posterior and centro-parietal electrodes in a patient with superior parietal lobule focal cortical dysplasia. Note the maximum of amplitude on T6 and P4 electrodes in bipolar montage.

**Figure 7:**

Example of spikes visible on right occipital electrodes (maximum over O2 electrode) in a patient with latero-occipital epilepsy (normal MRI).

**Figure 8:**

Model of focal seizure organization and dynamic: seizure start from a set of structures that generate high frequency oscillations (epileptogenic network, in red). Epileptogenic network may include or not an identified lesion. A second set of structures generates later slower, but highly synchronized oscillations (propagation network, in orange). Semiology and scalp EEG findings during seizure are dependant of these two networks.

**Figure 9:**

Recording of a mesial temporal lobe seizure using depth electrodes showing the initial involvement of several mesial structures (A, amygdala; Hi, hippocampus; EC, entorhinal cortex;
TPi, internal temporal pole) and the delayed involvement of the neocortical sector (aMTH, anterior part of the middle temporal gyrus; pMTG, posterior part of the middle temporal gyrus; STG, superior temporal gyrus)

**Figure 10:**

This figure illustrates the complex organization of the epileptogenic network (here temporo-frontal) and the role of seizure dynamic in the emergence of semiology (SEEG recording).

In this patient, seizure starts simultaneously in mesio-temporal (fast discharge in the first contacts of TB, B and A electrodes) and orbito-frontal areas (fast discharge in first contacts of OR electrode).

Note that the first objective symptom (oral automatisms) appears after 4 seconds; and that the slowing and propagation of ictal oscillations correlated with emergence of patient's humming.

**Figure 11:**

Example of intracranial EEG seizure onset patterns (SEEG):

(A) Low-voltage fast activity (LVFA). (B) Pre-ictal spiking with rhythmic spikes of low frequency followed by LVFA. (C) Burst of polyspikes of high frequency and amplitude followed by LVFA. (D) Slow wave or baseline shift followed by LVFA. (E) Rhythmic spikes or spike-waves, at low frequency and with high amplitude. (F) Theta/alpha sharp activity with progressive increasing amplitude. (Adapted from Lagarde et al, 2016)
**Figure 12:**

This figure illustrates on a SEEG recording, the propagation of a seizure from left mesial temporal lobe (first contacts of electrodes TP’, TB’, A’, B’ and GPH’) to lateral neocortical temporal structures (last contacts of electrodes TP’, TB’, A’, B’ and GPH’); and then dorso-lateral prefrontal cortex (last contacts of electrodes CR’) and insula (first contacts of electrodes I’ and OC’).

**Figure 13:**

This figure illustrates the possibility to observe rapid discharge as seizure onset pattern on scalp-EEG in a patient with superficial neocortical epileptogenic lesion. Scalp-EEG shows the emergence of a right fronto-polar (Fp2) rapid discharge before movements’ artefacts at a seizure beginning. The MRI shows a dorso-lateral prefrontal focal cortical dysplasia visible on MRI (red circle, same patient than figure 4).

**Figure 14:**
An example of background flattening at the beginning of a right temporal lobe seizure. No other specific or localized EEG change is seen during the first 20 seconds of the seizure. Background flattening is more marked on the right hemisphere (arrow).

Figure 15:

Example of burst of polyspikes (red circle, well seen on T4: maximum of amplitude and phase opposition) at the beginning of a right temporal seizure on scalp-EEG, in a patient with neocortical right temporal focal cortical dysplasia (see red circle on MRI).

Figure 16:

A left temporal lobe seizure easily visible on the temporo-anterior electrodes (FT9–TP9 derivation) and is marked by a slow rhythmic spike discharge emerging from the background activity (arrow) before the patient reported his usual aura (epigastric sensation and « déjà-vu »).

Figure 17:

A left temporal mesial seizure visible on left temporal electrode (maximum amplitude and phase opposition over T3 electrode). Note the appearance of sharp waves on the left electrodes (red circle, **) before the emergence of a typical left temporal theta sinusoid discharge

Figure 18:
Example of left mesio-temporal seizure without early scalp-EEG discharge.

A) Patient has his usual aura (odour) without initial clear modification on scalp-EEG;

B) After 40 seconds, note the appearance of rhythmic muscle artefacts due to chewing (*) and the emergence of sinusoidal delta discharge on left temporal electrodes (best seen on T3 and TP9 electrodes, red circle).

**Figure 19:**

A right temporo-occipital seizure in a patient in whom stereo-EEG demonstrated a seizure onset in the posterior and mesial part of the temporo-occipital junction (posterior cingulate area and para-hippocampal gyrus). Note that, in this case, the emergence of the discharge appears more posteriorly affecting the temporal electrodes T6 (red circle), but also the posterior supra-sylvian derivations (C4-P4, black circle) and is preceded by a localized flattening (black arrow).

**Figure 20:**

Example of a seizure in pre-motor cortices.

Seizure starts by rhythmic slow waves on left fronto-central and vertex channels (1, green line); followed by alpha discharge (2, black line), then background flattening and appearance of rapid beta discharge (3, red line) and finally delta slow waves (4, blue line).

**Figure 21:**
Example of EEG seizure onset pattern in orbito-frontal epilepsies in a patient with left orbito-frontal focal cortical dysplasia. The beginning of the seizure (blue mark) showed only a diffuse bilateral background flattening (red circle) before muscle artefact and without clear discharge.

**Figure 22:**

Parietal seizure in a patient with focal cortical dysplasia in superior parietal lobule. Note the initial fast discharge not localized but only right lateralized (red rectangle), followed by a spikes’ discharge more visible on temporal posterior channels (red circle, maximum amplitude and phase opposition over T6, also well seen over O2, T4 and P4 electrodes).