Journal of Neuroscience Methods 241 (2015) 121–131

Contents lists available at ScienceDirect

Journal of Neuroscience Methods

journal homepage: www.elsevier.com/locate/jneumeth

# Seizure states identification in experimental epilepsy using gabor atom analysis

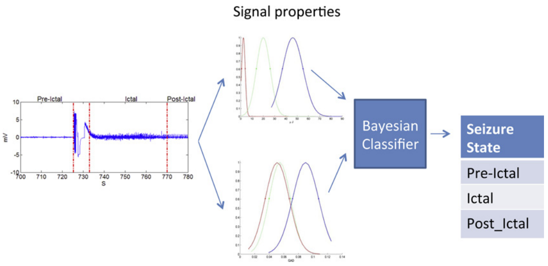
Arturo Sotelo[a,b,*], Enrique D. Guijarro[b,1], Leonardo Trujillo[a,*]

[a] Instituto Tecnológico de Tijuana, Blvd. Industrial S/N, Tijuana, BC, Mexico
[b] Universitat Politécnica de Valéncia, Cami de Vera S/N, 46022 Valencia, Spain

## HIGHLIGHTS

- We develop a classification method of the seizure states based on brain signal properties.
- Seizure states are actually revealed by the brain signal's dynamics.
- Epochs of 2 s duration has enough information to identify a seizure state.
- When the GAD and epoch energy are combined an improved classifier is achieved.
- We used a database of intracranial recorded seizures from an animal model.

## GRAPHICAL ABSTRACT



## ARTICLE INFO

*Article history:*
Received 4 June 2014
Received in revised form 1 December 2014
Accepted 3 December 2014
Available online 12 December 2014

*Keywords:*
Epilepsy
Seizure states
ECoG
Kindling model
Matching pursuit
Gabor atoms density

## ABSTRACT

*Background:* Epileptic seizures evolve through several states, and in the process the brain signals may change dramatically. Signals from different states share similar features, making it difficult to distinguish them from a time series; the goal of this work is to build a classifier capable of identifying seizure states based on time–frequency features taken from short signal segments.
*Methods:* There are different amounts of frequency components within each Time–Frequency window for each seizure state, referred to as the Gabor atom density. Taking short signal segments from the different states and decomposing them into their atoms, the present paper suggests that is possible to identify each seizure state based on the Gabor atom density. The brain signals used in this work were taken form a database of intracranial recorded seizures from the Kindling model.
*Results:* The findings suggest that short signal segments have enough information to be used to derive a classifier able to identify the seizure states with reasonable confidence, particularly when used with seizures from the same subject. Achieving average sensitivity values between 0.82 and 0.97, and area under the curve values between 0.5 and 0.9.
*Conclusions:* The experimental results suggest that seizure states can be revealed by the Gabor atom density; and combining this feature with the epoch's energy produces an improved classifier. These results are comparable with the recently published on state identification. In addition, considering that the order of seizure states is unlikely to change, these results are promising for automatic seizure state classification.

---

[*] Corresponding authors at: Instituto Tecnológico de Tijuana, Blvd, Industrial S/N, Tijuana BC, Mexico. Tel.: +52 664 6244743.
*E-mail addresses:* asotelo@tectijuana.mx (A. Sotelo), eguijarro@eln.upv.es (E.D. Guijarro), leonardo.trujillo@tectijuana.edu.mx (L. Trujillo).
[1] Tel.: +34 963877000x76065.

http://dx.doi.org/10.1016/j.jneumeth.2014.12.001

## 1. Introduction

There are several neurological disorders that affect the human brain, one of the most serious and common is epilepsy (Witee et al., 2003). According to different studies, the number of persons with epilepsy varies depending on the region and the considered population. In studies from *The World Health Organization* (WHO, 1995), the estimated mean of people with epilepsy per 1000 is 8.93. An epileptic seizure may affect the brain partially or completely, producing partial or generalized seizures respectively (Morimoto et al., 2004). Seizures will manifest in the electrical activity produced by the brain. Placing electrodes directly inside the brain or over the cerebral cortex allows the recording free from artifacts (Zaveri et al., 1992), that are called Electrocorticograms (*ECoG*).

Epileptic seizures are dynamic processes evolving throughout four main states (Franaszczuk et al., 1998; Iasemidis et al., 2003); those states are: (1) the Basal state (2) the Pre-Ictal state, (3) the Ictal state; and (4) the Post-Ictal state. Within the time-domain the *ECoG* shows amplitude changes while an epileptic seizure episode is in progress, and the signal's morphology is different at each state (Cockerell, 2003). In general, *ECoG* could be affected by the state of awareness of the subject. When the brain functions are normal it is considered the Basal state, the *ECoG* is characterized by a low amplitude and relative high frequency. In the Pre-Ictal state, the corresponding *ECoG* shows an amplitude increase with respect to the Basal state. There are spikes and transitory activity but no definitive evolution, known as recruiting rhythms (Kohsaka et al., 2002; Roso and Figliola, 2004). Though, during this state the individual may not exhibit clinical manifestations. The Ictal state is precisely when the individual exhibits more evident clinical manifestations of the seizure; in cases when these discharges become widespread enough it might resulting in a convulsive response (Morimoto et al., 2004). The *ECoG* during this state is characterized by high amplitude discharges, a low frequency and a predominant rhythmicity. The last state is the Post-Ictal, where the *ECoG* shows general amplitude depression and frequency increases, in this state it is possible to find spike-and-wave complexes; the amplitude keeps decreasing as the *ECoG* gradually returns to the Basal state.

Epileptic seizures are spontaneous and sometimes are triggered by an external phenomena, mostly happening without any warning, making it hard to study them in humans (De-Curtis and Avanzini, 2001). Therefore, elicited seizures are used for research purposes by means of animal models, mainly rodents. The epilepsy conditions are achieved in previously healthy (non-epileptic) animals as a result of applying short duration electrical stimulus to the brain, known as the Kindling model (Goddard, 1983; McIntyre and Gilby, 2009); which can produce seizures with precise focal activation (Morimoto et al., 2004).

The seizures elicited by the kindling model are rated according to the subject's clinical manifestation into a five level-scale, known as Racine scale (Racine, 1972). The less severe seizures are considered as focal and they are rated as stage one, as the abnormal discharges become widespread over the brain the clinical manifestations change. When the afterdischarge is capable of stimulating the nearby neurons reaching the cortex, it produces a generalize motor seizure, or stage five, the highest in the Racine scale.

The brain, like most physiological systems, produces signals which posses statistics that vary with time; i.e., they are non-stationary signals (Williams et al., 1995). Fortunately, the rate at which such systems can change is bounded; this allows breaking signals into segments of short fixed duration over which the statistics of interest may be assumed stationary. However, the signal may change within the duration of the window (Rangayyan, 2002). Therefore a method able to analyze signals with no apparent stationarity is required, in this paper we use the adaptive decomposition algorithm developed by Mallat and Zhang (1993) called Matching-Pursuit algorithm (*MZMP*). This algorithm decompose signals in terms of a function dictionary, primitive components called atoms that can provides information about the rhythmic and transient brain activity (Jouny et al., 2003).

The study of the seizure states is motivated by the interest in evaluating experimental epilepsy treatments. However, as a first step, this work focuses on identifying three of the main seizure states: Pre-Ictal, Ictal, and Post-Ictal as it is done in (Sotelo et al., 2007, 2012, 2013). For instance, this makes it possible to estimate when the Ictal state develops. Our approach is to compute the dynamics of short *ECoG* segments, acquired from elicited seizures using the Kindling model on Wistar rats. The signal dynamics are estimated by the number of frequency components found in the *ECoG* segment, using a derived measured from the *MZMP* designated as Gabor Atom Density (*GAD*) (Jouny et al., 2003). This numerical feature can be used to monitor changes in *ECoG* complexity (Jouny et al., 2004), which allows us to perform classification of the seizure states.

Over the past years, many researchers have attempted to develop algorithms for automatic analysis of the *EEG* with the purpose of identifying or predicting epileptic seizure activity. Using different approaches to analyze features, such as the short-term maximum Lyapunov exponent to reveal the dynamic characteristics of the *ECoG* during the seizure evolution (Nair et al., 2009). Niknazar et al. (2013) propose a unified thresholding approach using several features from time domain, frequency domain and non-linear properties, able to discriminate during seizure and after seizure states. López-Cuevas et al. (2013) propose an algorithm based on artificial neural networks for automatic detection of high frequency oscillations related to epilepsy. Some other uses a technique based on reservoir computing; for instance, Buteneers et al. (2013) propose real-time seizure detection from *ECoG* and trigger the treatment on a rat model, achieving an average error rate of 2.8%; and Fu et al. (2014) propose to identify seizure non-seizure activity in humans, reaching a classification accuracy of 99.125%.

## 2. Materials and methods

The signals data-sets were obtained from a database of the Centro de investigación del Hospital General Universitario de Valencia, working in conjunction with the Universidad Politécnica de Valencia, with the purpose of studding states in elicited seizures. The kindling procedure was carried out in compliance with current European directives for animal experimentation (86/609/ECC) and with those set by the Valencian Community Government, in accordance with the corresponding institutional animal care committee. The procedure was performed as described in (Gallego et al., 2010), using adult subjects weighing 270–310 g stereotactically implanted with a bipolar electrode made of twisted pair of Teflon-coated 0.25 mm diameter stainless steel wires separated by 0.5 mm at the tip and 8 mm in length, implanted at the left piriform cortex for the stimulation and recording purpose. These were placed at the coordinates: 0.8 mm posterior, 4.9 mm left, and 8.8 mm ventral from the bregma. With the purpose of signal recording and fixing the connector to the skull, three more electrodes were implanted, two of them 1 mm anterior to the coronal suture, 3 mm from the midline on both sides and one occipital and the third 1 mm posterior to the lambdoid suture, 3 mm right from the midline, allowing deep and frontal right signal recording. The standard kindling procedure started 10 days after the surgical procedure, the stimuli was applied on a daily basis consisting of a 1s train from a 50 Hz rectangular signal with a 5% duty-cycle and 500$\mu$A intensity, until more than three consecutive seizures of stage 5 were provoked. At this point, the subject was considered fully kindled. Then the seizure threshold (ST) is determined, this is achieved using a stepwise ascent method