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Searching for hidden information with Gabor Transform in generalized tonic-clonic seizures

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Abstract

The analysis of generalized tonic clonic seizures is usually difficult with scalp EEG due to muscle artifact. We applied Gabor Transform to evaluate 20 seizures from 8 consecutive patients admitted for video-EEG monitoring. We studied the relative intensity ratios of alpha, theta and delta bands over time. In 14/20 events we found a significant decremental activity in the delta band at the onset of the seizure indicating that this is dominated by theta and alpha bands. We conclude that GT is a useful auxiliary tool in the analysis of ictal activity that sheds light on the underlying pathophysiological mechanisms. © 1997 Elsevier Science Ireland Ltd.

Keywords: Tonic-clonic seizures; Gabor; Fourier

1. Introduction

Epilepsy is a disorder that affects 1% of the population, the EEG being the most used tool for the evaluation of such patients. However, given that ictal recordings are rarely obtained, we usually rely on interictal findings. The introduction of video-EEG telemetry has been an important milestone providing not only the possibility to analyze ictal events, but also contributing valuable information in those candidates evaluated for epilepsy surgery. In this setting and following strict protocols, seizures are elicited by gradually reducing antiepileptic drugs, which frequently results in secondarily generalized tonic-clonic seizures. Visual inspection of these events is often troublesome due to muscle artifact, and in most cases the analysis is confined to the interpretation of electrical abnormalities that either precede or follow the tonic-clonic activity, therefore neglecting the ictal phase.

The introduction of digital data collection by the use of computers has contributed to the development of new and promising methods to analyze the EEG signal (Blanco et al., 1995a,b, 1996a,b, 1997). Some of these methods include spike averaging (Emerson et al., 1995), linear and non-linear correlation (Pijn, 1990; Pijn et al., 1991), non-linear dynamic methods (Babloyantz, 1986; Basar and Bullock, 1989; Blanco et al., 1995a, 1996a), wavelet transformations (Schiff et al., 1994; Blanco et al., 1996b) and Fourier spectral analysis (Gotman, 1986, 1990; Dumermuth and Molinari, 1987; Gevins, 1987; Lopes da Siva, 1987). The last one quantifies the amount of activity in frequency bands, but the information related to time evolution of frequency peaks is neglected. Gabor Transform (GT) (Gabor, 1946), also called Windowed Fourier Transform, is a time evolution of the Fourier spectrum. It may be regarded as a Fourier Transform applied to a short temporal window sliding along the entire signal. This provides information about changes in frequency patterns over time.

Our group recently showed the utility of GT in the evaluation of ictal activity recorded with depth electrodes (Blanco et al., 1995b, 1996ab, 1997), finding an optimal correlation between EEG visual inspection and GT in the

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characterization of paroxysms, spikes and other transient alterations of background activity. Up to now, only a few works have attempted to characterize scalp recorded tonic-clonic seizures due to the high noise introduced by muscle artifacts. Consequently, we report herein the application of GT in the evaluation of scalp Video-EEG recorded tonic-clonic seizures, with the great benefit of seeing patterns hidden under muscle artifact noise, just by leaving aside those frequencies related to them.

2. Methods and materials

2.1. Subjects and data recording

Twenty tonic-clonic seizures from 8 epileptic patients admitted for video-EEG monitoring were analyzed. The subjects consisted of 4 males and 4 females, age 30.87 ± 15.27 years (mean ± SD; range 6–51) with a diagnosis of pharmacoresistant epilepsy (see Table 1 for clinical data) and no other accompanying disorders. Interictal EEGs, MRIs (magnetic resonance imaging), ictal and interictal SPECTs (single photon emitted computer tomography), and psychological tests were also performed. Antiepileptic drugs were gradually reduced after the start of the video-EEG monitoring in order to stimulate the seizure appearance.

Scalp and sphenoidal electrodes with bimastoideal reference were applied following the 10–20 international system, and a seizure button manually activated by the patient was also available. Each signal was digitized at 409.6 Hz trough a 12 bit A/D converter and filtered with an 'antialiasing' 8 pole lowpass Bessel filter, with a cutoff frequency of 50 Hz. Then, the signal was digitally filtered with a 1–50 Hz bandwidth filter and stored, after decimation, at 102.4 Hz in a PC hard drive.

2.2. Gabor Transform and data processing

Off-line analysis was performed with characterization of

Table 1
Clinical data of patients studied

Patient	Age (years)	Sex	Number of seizures	Source of seizures	Antiepileptic drugs
CS	22	F	2	Right temporal	VGB, CZP
LP	39	F	3	Left temporal	CBZ, CZP
DLB	24	M	2	Bitemporal	LTG, OXCBZ, KBL
AS	49	M	4	Left temporal	VGB, LZP, GBP
MB	34	M	2	Bitemporal	CBZ, VPA
IV	22	F	1	Left temporal	VGB, VPA, AZT
FT	6	F	4	Non-localized	CBZ, VPA
JI	51	M	2	Non-localized	CBZ, PB

Abbreviations: LTG, lamotrigine; OXCBZ, oxcarbazepine; KBL, clobazan; VGB, vigabatrin; CZP, clonazepan; CBZ, carbamazepine; LZP, lorazepan; GBP, gabapentin; VPA, valproic acid.

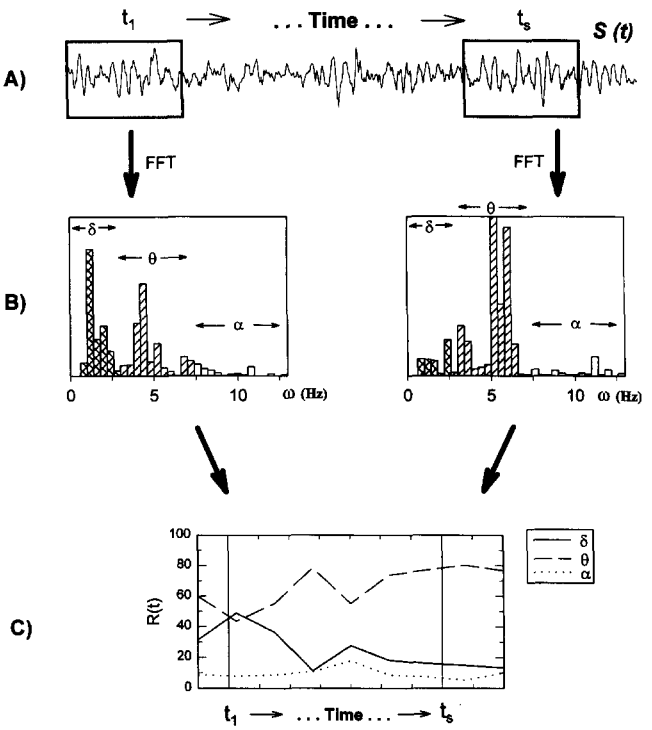

Fig. 1. Data processing procedure: step (A) consists of applying a Gaussian window centered in t_1 to the EEG data. In step (B) the Fast Fourier Transform of this windowed data is calculated, and in step (C) the band relative intensity ratio for this time is plotted. Afterwards the window is displaced a fixed time and the procedure is repeated, obtaining a time representation of the band relative intensity ratio.

semiological features, timing of the onset and definition, when possible, of the anatomical source for each event. Analysis for each event included 1 min of EEG before the seizure onset and 2 min which included the ictal and post-ictal phases. All 3 min were analyzed at the C4 electrode, choosing this electrode after visual inspection of the EEG as the one with the least amount of artifacts.

Fig. 1 illustrates the data processing procedure. First, a Gaussian window centered in t_1 is applied to the data denoted by $S(t)$ (step A) and the Fast Fourier Transform of this windowed data (GT) is calculated as:

$$G_D(\omega, t_1) = \int_{-\infty}^{+\infty} S(t') \cdot g_D^*(t' - t_1) \cdot e^{i\omega t'} \cdot dt' \quad (step\ B)$$

Note that $G_D(\omega, t_1)$ is the same as a Fourier transform but with the introduction of the sliding window $g_D\ (t' - t_1)$ of width D and center in t_1.

The power spectral intensity for each frequency band i ($i = \delta, \theta, \alpha, \ldots$) will be

$$I^{(i)}(t_1) = \int_{\omega_{min}^{(i)}}^{\omega_{max}^{(i)}} G_D^*(\omega, t_1) \cdot G_D(\omega, t_1) \cdot d\omega \quad i = \delta, \theta, \alpha, \ldots$$

and the total power spectral intensity will be

$$I_T(t_1) = \sum_i I^{(i)}(t_1) \quad i = \delta, \theta, \alpha, \ldots$$

Then, the next step (step C) consists in plotting the band

relative intensity ratio (RIR), defined for each frequency band (i) as follows:

$$RIR^{(i)}(t_1) = \frac{I^{(i)}(t_1)}{I_T(t_1)} \cdot 100$$

Finally, the window is displaced by a fixed time and the procedure is repeated, obtaining a time representation of the RIR.

GT was performed by applying a Gaussian window with a width of 2.5 s and slide displacement steps of 1.25 s (half-overlapping windows). Traditional frequency bands were set to 1–3.5, 3.5–7.5, and 7.5–12.5 Hz, respectively. Given that beta 1 and beta 2 are closely related to muscle artifact those bands were excluded from the analysis.

2.3. Plateau criteria

Clear decrements in delta activity were seen during the seizures. In order to quantify this observation, mean relative intensity ratio (MRIR) for the delta band was calculated in the pre-ictal phase and compared with the value in the low intensity zones (plateaus) observed during the seizure. Pre-ictal MRIR was defined as the mean value of the RIR in the minute before the seizure, discarding those areas contaminated by artifacts (defined by visual inspection of the EEG). In the ictal phase, plateaus were defined according to the following criteria: (1) plateaus must last at least 10 s in order to avoid local variations; (2) the MRIR of the plateau must be less than 0.3 of the MRIR of the pre-ictal phase (ICTAL/PRE-ICTAL DELTA MRIR < 0.3); and (3) the standard error of the plateau MRIR (SEM) must be less than 1 to confirm low dispersion.

Although the choice of this criteria is arbitrary, no plateaus were identified in the pre-ictal phase, strongly indicating that the appearance of a plateau in the ictal phase reflects a dynamical change rather than a statistical phenomenon.

3. Results

Twenty secondarily generalized tonic-clonic seizure recordings were studied. The mean duration of the seizures was 92.8 s (SD 5.76) with a range of 52–160 s.

As an example of the analysis performed with GT we will describe the results of one of the seizures and then we will summarize the global findings.

Fig. 2A discloses 3 min of EEG data of seizure 3 (as labeled in Table 2) and the RIR of this signal is shown in Fig. 2B. Pre-ictal phase is characterized by a signal of 50 μV amplitude with a dominance of delta rhythms (pre-ictal delta MRIR ~50%). Seizure starts at second 80 (marked with an S in both graphs) with a discharge of slow waves superposed by fast ones with lower amplitude. This discharge lasts approximately 8 s, has a mean amplitude of 100 μV, and, as seen in Fig. 2B, produces a marked rise in delta band, which reaches 90% of the RIR. Afterwards, seizure spreads making the analysis of the EEG more complicated due to muscle artifacts; however, it is possible to establish the beginning of the clonic phase at around second 123 and the end of the seizure at second 155 (marked with an E in both graphs) where there is an abrupt decay of the signal.

Although it is difficult to extract any information from the EEG during the seizure, in Fig. 2B we can follow its frequency pattern. After second 90, delta activity decreases abruptly to values lower than 10% of the RIR, and theta and alpha bands alternately dominate. We also observe that the starting of the clonic phase is correlated with a rise of theta frequencies and after second 140, when clonic discharges become more separated, delta activity rises up again until the end of the seizure, also maintaining this behavior in the post-ictal phase.

We can conclude from this example that the seizure was dominated by alpha and theta rhythms with a corresponding abrupt decrease of delta activity. By applying the criteria explained in the previous section, a plateau of delta decrement was defined between seconds 99 and 138, lasting 39 s, having very low dispersion (0.14) and also having a very low ictal to pre-ictal delta MRIR (2%) (see Table 2).

Table 2 summarizes the results from all subjects. Delta band MRIR of pre-ictal and ictal phases and the ratio between them are shown. In two cases (seizures 12 and 15), no plateaus were found, and the ones on seizures 7, 11, 13 and 17 were rejected because they did not match the criteria: in seizure 17, plateau had high dispersion; in seizure 13, the ratio of pre-ictal to RIR was greater 0.3, and in seizures 7 and 11, both conditions were not satisfied.

Thus, considering the whole group, a stereotyped pattern was identified in 14/20 of the cases while applying GT. This pattern was characterized by a significant reduction in delta activity during the seizures, implying that they were dominated by theta and alpha rhythms until the ending of the seizure when delta activity rises up again.

4. Discussion

Our most robust finding is that in 70% of the seizures a significant reduction in delta activity was observed by applying the plateau criteria. This was usually seen at the beginning of the seizure, thus emphasizing the dominance of alpha and theta bands during the initial phases of a tonic-clonic seizure. This result is in agreement with our previous observations using GT to analyze ictal patterns recorded with depth electrodes (Blanco et al., 1995b, 1996ab, 1997). Although the selection of the plateau criteria might have influenced these results, slight changes in the definition of the plateau showed no significant variations. Also, the results do not depend on the patient studied, and owing to the great variation in age, antiepileptic drugs, and source of the seizure between the patients, we can conclude that the results are not dependent on these factors.

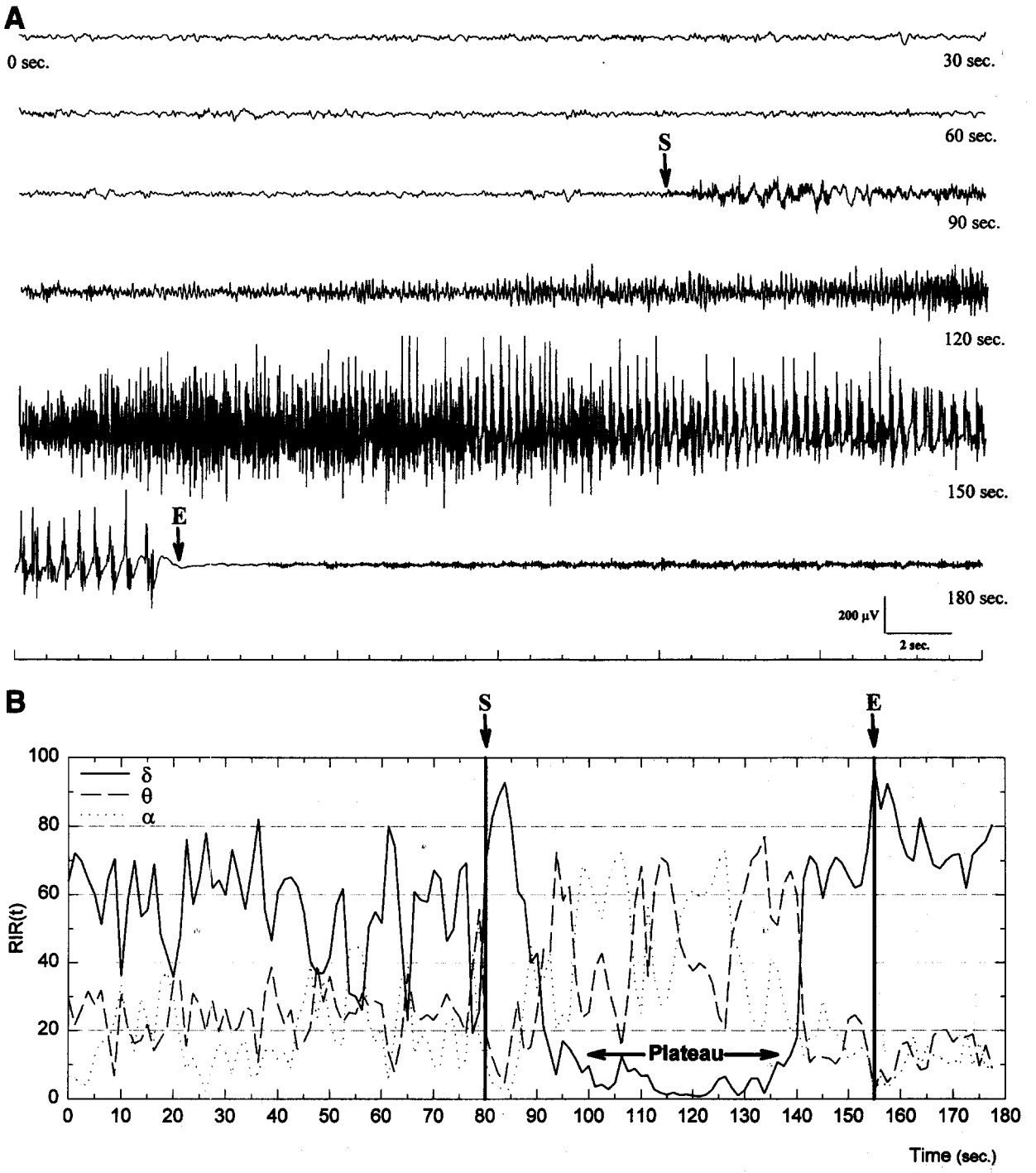

Fig. 2. (A) Three minutes of EEG data of C4 channel corresponding to seizure 3. Seizure starts at second 80 (marked with an S) and then after approximately 20 s muscle artifacts progressively obscure the recording. Clonic phase starts around second 123 and the end of the seizure (marked with an E) is characterized by an abrupt loss of voltage at second 155. (B) Band relative intensity ratio over time for the GT of the data shown in Fig. 1A. Full line corresponds to delta band, dashed line corresponds to theta band and dotted line corresponds to alpha band. S indicates the starting of the seizure and E its ending. The pre-ictal phase is dominated by delta band and 10 s after the starting of the seizure, delta activity has an abrupt decay owing to alternative theta and alpha increments, until the ending of the seizure when delta activity rises up again. The defined plateau is delimited by arrows between seconds 99 and 138.

A rise in delta activity was observed towards the end of the ictal phase. That pattern was also seen with depth recordings, thus making unlikely the possibility that it was generated by artifacts. Neuronal 'fatigue', decrement in neuronal firing and preponderance of inhibitory mechanisms are critical factors in the mechanisms underlying this observation, which prompts further research.

These results were obtained by avoiding muscle artifacts with GT, thus supporting their utility for the evaluation of tonic-clonic seizures, something difficult to assess with

Table 2

Band mean relative intensity ratio (MRIR) of delta band in the pre-ictal phase, in the ictal phase (in the plateau) and the ratio between them

Patient	Seizure no.	Pre-ictal delta MRIR ± SEM	Ictal delta MRIR ± SEM	Ictal/pre-ictal delta MRIR
CS	1	59.58 ± 3.51	4.11 ± 0.46	0.07
CS	2	45.15 ± 2.10	2.76 ± 0.33	0.06
LP	3	52.32 ± 1.84	1.22 ± 0.14	0.02
LP	4	47.79 ± 2.28	2.01 ± 0.21	0.04
LP	5	39.02 ± 2.27	1.80 ± 0.35	0.05
DLB	6	19.31 ± 1.74	2.30 ± 0.34	0.12
DLB	7	27.23 ± 1.29	15.48 ± **1.68**	**0.57**
AS	8	36.23 ± 1.91	3.75 ± 0.48	0.10
AS	9	48.89 ± 2.20	13.61 ± 0.76	0.28
AS	10	45.94 ± 2.00	10.75 ± 0.99	0.23
AS	11	32.43 ± 2.16	12.24 ± **1.32**	**0.38**
MB	12	24.55 ± 2.97	No plateau	–
MB	13	31.68 ± 2.16	14.80 ± 0.64	**0.47**
IV	14	21.35 ± 1.38	2.53 ± 0.38	0.12
FT	15	46.40 ± 2.28	No plateau	–
FT	16	67.18 ± 2.70	7.12 ± 0.53	0.11
FT	17	64.39 ± 1.89	9.26 ± **1.14**	0.14
FT	18	66.01 ± 2.03	3.89 ± 0.46	0.06
JI	19	35.04 ± 2.41	5.91 ± 0.62	0.17
JI	20	28.62 ± 1.70	6.61 ± 0.70	0.23

Bold numbers identify those parameters not satisfying the plateau criteria; 'no plateau' means that a plateau of more than 10 s was not found. Seizures 7, 11, 12, 13, 15 and 17 do not satisfy the plateau criteria; and in the other 14 cases (70%) a plateau of delta decrement was found.

scalp recorded EEGs. As Niedermeyer (1987) pointed out, 'Muscle activity rapidly obscures the recording; the vertex deviation, however, may remain artifact-free due to the lack of underlying muscles. Informative grand mal recordings can be secured only from patients with muscle relaxation from curarization and artificial respiration.' Gotman et al. (1981) avoided this problem by the use of filters. However, they pointed out that filtering the signal has several disadvantages. On the one hand it is impossible to separate brain and muscle activity in the EEG, and further, it is well known that filtering high frequencies also affects the morphology of the low ones. Gastaut and Broughton (1972) instead described a frequency pattern during a tonic-clonic seizure of a curarized patient. In the first seconds after the seizure onset, they found an 'epileptic recruiting rhythm' of 10 Hz associated with the tonic phase that lasts approximately 10 s; later, as seizure ends, there is a progressive increase of the lower frequencies (5–6 Hz) associated with the clonic phase. Our findings were similar to the ones highlighted by Gastaut and Broughton, but recruiting rhythms were observed to lie also in the theta range or, as seen in most cases, fluctuating between alpha and theta. Darcey and Williamson (1985) also obtained similar patterns analyzing seizures recorded with depth electrodes, finding an activity characterized by 10 Hz at the onset of the seizure, a frequency that decline as the seizure ended. One important point to note is that our results were obtained with scalp recordings and without the use of curare or any filtering method. Certainly GT is not intended to replace conventional EEG analyses, but rather to complement them and also to provide further insight into the underlying mechanisms for ictal patterns. An example of this is that GT allows a fast interpretation of several minutes of frequency variations in a single display, something difficult to perform with traditional scalp EEG.

A similar method was applied by Gotman et al. (1993) to study ictal onset with scalp and intracerebral electrodes, by computing average amplitudes and frequencies. However, the objective of their work was to find an alternative graphic representation of the EEG activity, especially applied to study the seizure onset, without establishing a frequency pattern of the entire seizure. Schiff et al. (1994) applied Wavelets and GT to EEG data obtained from subdural electrodes. Wavelets is equivalent to GT but with a variable window. Although one advantage of Wavelets over GT is the possibility to see more structures due to its varying window size, they found that excessive computational demands were an obstacle to practical implementation. In addition, GT has an easier interpretation due to its analogy with Fourier transform and in most of the cases brain activity has a limited frequency content already well captured using GT with an adequate window (Blanco et al., 1996b). Our work differs from Gotman and Schiff's in that a quantification of the GT is performed by dividing it into the traditional frequency bands, and analyzing the frequency content of the entire ictal pattern.

One critical point in our results is the possible distortion due to spatial propagation of the seizure, since we analyzed data of C4 electrodes and the sources of the seizures were mostly in temporal locations (see Table 1). In order to overcome this, GT was also applied to T3 and T4 electrodes, obtaining similar results to the ones reported with C4 electrodes.

Further research with GT to study the spatial propagation of different rhythms during a seizure is in progress.

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