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# Automatic seizure detection in long-term scalp EEG using an adaptive thresholding technique: A validation study for clinical routine

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H I G H L I G H T S

- An automatic seizure detection method for long-term scalp EEG recordings was validated under routine conditions in a large number of unselected epilepsy patients with various seizure types and epilepsy syndromes.
- The analysis was performed in a standardized fashion for all patients and all EEG data requiring no adjustment of parameters.
- The seizure detection algorithm provided high values for sensitivity and a low number of false positive events demonstrating its applicability in clinical practise.

A B S T R A C T

*Objective:* In a previous study we proposed a robust method for automatic seizure detection in scalp EEG recordings. The goal of the current study was to validate an improved algorithm in a much larger group of patients in order to show its general applicability in clinical routine.
*Methods:* For the detection of seizures we developed an algorithm based on Short Time Fourier Transform, calculating the integrated power in the frequency band 2.5–12 Hz for a multi-channel seizure detection montage referenced against the average of Fz-Cz-Pz. For identification of seizures an adaptive thresholding technique was applied. Complete data sets of each patient were used for analyses for a fixed set of parameters.
*Results:* 159 patients (117 temporal-lobe epilepsies (TLE), 35 extra-temporal lobe epilepsies (ETLE), 7 other) were included with a total of 25,278 h of EEG data, 794 seizures were analyzed. The sensitivity was 87.3% and number of false detections per hour (FpH) was 0.22/h. The sensitivity for TLE patients was 89.9% and FpH = 0.19/h; for ETLE patients sensitivity was 77.4% and FpH = 0.25/h.
*Conclusions:* The seizure detection algorithm provided high values for sensitivity and selectivity for unselected large EEG data sets without a priori assumptions of seizure patterns.
*Significance:* The algorithm is a valuable tool for fast and effective screening of long-term scalp EEG recordings.


## 1. Introduction

For presurgical evaluation of epilepsy patients the well-established long-term video/scalp-EEG-monitoring in epilepsy monitoring units (EMUs) often last several days up to one or even two weeks. Monitoring duration is largely depending on the number of seizures providing useful clinical and electrographic information. Long-term EEG-monitoring leads to enormous amounts of EEG data, which in general are inspected visually by experienced EEG technologists or physicians, in order to find all relevant seizures (ictal activity), as well as other EEG pathology (e.g. interictal epileptiform discharges). This off-line reviewing is time consuming, tedious and binds resources of medical staff.

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During the past decades several algorithms for automatic seizure detection (online, offline) of scalp EEG data were proposed (Gotman, 1982, 1990). For the detection of characteristic electrographic changes during seizures with respect to frequency, amplitude and/or rhythmicity various methods were established comprising linear and non-linear time–frequency signal analyses with numerous features (Greene et al., 2008; van Putten et al., 2005). Notably, most of the proposed algorithms are based essentially on single-channel analyses using bipolar montages (McSharry et al., 2002; Tzallas et al., 2007; Gotman, 2010).

Despite the fact that many algorithms provide rather high sensitivity values (typically between 75% and 90%), many epilepsy centres still do not use them in clinical routine due to the unacceptably high number of false-positive detections. This is often due to various artifacts, but may also be caused by recurrent rhythmic and high amplitude interictal EEG activity (e.g. FIRDA (frontal intermittent rhythmic delta activity) and TIRDA (temporal intermittent rhythmic delta activity) or sleep activity). One reason for this shortcoming may be that the majority of the proposed seizure detection algorithms were developed and optimized for high sensitivity by using selected EEG data. The trade-off was frequently a low percentage of non-ictal EEG data included in the analyses. Therefore, a reliable and valid estimation of their selectivity could hardly be achieved and the use in clinical routine was limited.

Therefore, we recently published an automatic seizure detection algorithm in long-term scalp EEG of adults which was developed using ictal and *all* interictal EEG data from unselected patients. It analyzed the frequency band 3–12 Hz using for the first time a Fz-Cz-Pz referenced multi-channel seizure detection montage (Hopfengärtner et al., 2007). The algorithm showed high values for sensitivity (90.9%) and its selectivity value (FpH) was as low as 0.29/h. The method is based on power spectral analysis techniques, incorporates an artifact rejection method and uses the same fixed set of parameters for all patients and all unselected EEG data recorded (even while eating) during presurgical evaluation. The results of the initial study were obtained from a small group of patients ($n = 19$) with 3248 h of EEG data. The identification of seizure and non-seizure events was performed by using fixed threshold values leading to a high number of false positive detections in patients with prolonged high amplitude rhythmic interictal activity, such as FIRDA and TIRDA.

This algorithm was also used in a recent transcutaneous vagus nerve stimulation (*t*-VNS) study (Stefan et al., 2012) and for objective quantification of seizure frequency and duration in difficult to treat patients (Stefan and Hopfengärtner, 2009).

The goal of this extended follow-up study was to demonstrate the performance and clinical applicability of an improved algorithm using an *adaptive* thresholding technique on the basis of a large number of unselected patients with various epilepsy syndromes and great amount of EEG data.

## 2. Methods

### 2.1. Subjects

Patients with drug resistant focal epilepsy, who were admitted to the Epilepsy Center Erlangen (University Hospital Erlangen, Germany) for non-invasive long-term video-EEG monitoring as part of their presurgical evaluation, were included when they suffered from at least two clinically evident seizures with corresponding EEG seizure patterns during monitoring. A total of 159 patients (80 m, 79 f; age: 17–66 years, mean: 36.9 years) were enrolled. Diagnoses were based on all clinical findings acquired during presurgical evaluation. The patient group consisted of 117 patients with temporal lobe epilepsy, 35 patients with extra-temporal lobe epilepsy, 2 patients with multifocal epilepsy and 5 patients with undetermined seizure origin.

### 2.2. Dataset

All EEG data recorded from the patients were analyzed. No epochs were excluded, e.g. due to artifacts (movement, chewing, EMG, eye-blinks, deteriorated electrodes, etc.). Thus, a total of 25,278 h of scalp EEG recordings was analyzed including 794 clinically identified seizures. The seizures were accompanied by various seizure patterns in the EEG reflecting the unselected patient group in this study and a typical real-world situation in an EMU. Subclinical seizures or clinically manifest seizures without a visually recognizable seizure pattern in the EEG were not considered.

The long-term video-EEG data were acquired using a 64 channel system (NATUS Europe, Planegg, Germany). Sampling rate was 256 Hz with 16 bit resolution. The hardware filter settings were 0.08 Hz (high-pass) and 86 Hz (low-pass).

The standard EEG montage used for recording of TLE patients was based on the extended 10–20-system and contained the inferior and anterior temporal electrodes F11, FT9, TP9 and F12, FT10, TP10 in addition to the standard electrodes of the 10–20-system. Sphenoidal electrodes SP1 and SP2 were inserted in some patients with mesial TLE. For patients with suspected extra-temporal lobe epilepsy, additional electrodes according to the 10–10-system were attached over the convexities in order to provide higher spatial sampling of the EEG. In all patients, the ECG was recorded.

Routine identification and classification of seizures was performed in a stepwise fashion: First, all ictal and suspicious events detected by medical staff were marked online in the EEG. In a second step, the video-EEG data was again visually reviewed off-line by experienced EEG technologists using, among others tools, trend displays based on wavelet analysis, which were integrated in the standard review software. Finally, these preselected video-EEG epochs were analyzed and classified by two experienced epileptologists (BSK, WG, SG).

### 2.3. Data analysis

The improved automatic seizure detection method used in this study was based on the algorithm proposed and described in detail earlier (Hopfengärtner et al., 2007).

Briefly, the algorithm is based on Short Time Fourier Transform calculating the averaged and integrated power of special multichannel detection montages for different frequency bands. An efficient dynamical artifact rejection method on the raw EEG and the definition of three special multi-channel seizure detection montages (referenced against Fz-Cz-Pz, common average, bipolar) were introduced. No additional pre-processing of the data was applied. The standardized seizure detection montage included the electrodes F12, FT10, TP10, F8, T8, P8, O2, F4, C4, P4 and the homologous electrodes on the left side. The best seizure detection performance with respect to sensitivity and selectivity was obtained for the referenced Fz-Cz-Pz seizure detection montage in the frequency band 3–12 Hz.

For identification of seizures a thresholding technique for the integrated and averaged power with fixed parameters was applied. It was demonstrated that patients exhibiting epochs of prolonged (duration >10 s) rhythmic and high amplitude interictal EEG activity lead to an increased number of false positive detections. These false detections cannot be effectively suppressed by the fixed thresholding technique. Therefore, we extended the algorithm by using an adaptive thresholding technique, i.e. the threshold parameters were dynamically adjusted by calculating the corresponding