RULES FOR SPIKE DETECTION IN MULTICHANEL INTRACRANIAL ELECTROENCEPHALOGRAPHY

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Abstract

This paper presents a possibility for quantitative evaluation of the electroencephalography (EEG) through searching for discharge artifacts in the intracranial electrocorticography signals of epileptic patients. Occurrence of the discharges as a spike-wave complex directly relates to affected parts of the brain. The described method uses the spike detector based on comparison of the energy envelope of the filtered signals and the individual settings of thresholds. The settings of the thresholds follow the rule which is dependent on statistical distribution and its MLE approximation of the envelope. Two patient results are introduced as a preview. The proposed algorithm is designed for automatic evaluation of intracranial EEG signals to increase objectivity and save time for neurologist examinations.

1 Introduction

Brain diseases with paroxysmal symptoms are known as epilepsy. The brain of the patient generates abnormal electroencephalography (EEG) signals in affected areas unlike among healthy persons. The pathological waveforms occur in EEG especially during a seizure. Neurologists visually seek out the signal artifacts for localization initiation of paroxysmal bearings – the seizure onset zone (SOZ). Accurate focusing of bearing and SOZ is necessary for surgical treatment.

One of the important epileptic markers is the occurrence of interictal epileptiform discharges in EEG that differ from background activity shorter than 70 ms [1]. The discharge is composed from a steep transient and a subsequent slow wave (the spike wave complex - SWC). The discharges may occur before an onset, as well as during a seizure. The spikes of the deep brain structure may not be clearly visible in scalp EEG, because the skull behaves like a low-pass filter for these signals and blurs their spread from the source. This problem can be solved through invasive implantation of electrodes on the brain cortex surface - electrocorticography (ECoG). The electrodes are composed of an array of electrodes to silicone grids and strips.

The pathological discharges can often simultaneously occur in extended parts of the brain; therefore neural structures are functionally connected. However, the spikes are probably triggered locally [1]. In focal epilepsy, the interictal discharges can be generated from the epileptic bearing or from the surrounding tissue that serves to control the epilepsy. Spatial localization of the pathological discharges correlates well with the SOZ.

An additional marker of the determination discharges source for localization of the epileptiform bearing is described by the occurrence of the discharges as SWC. Distribution of the spike in channels corresponds with sensitivity to epileptic propagation. The number of the spikes defines the quantitative evaluation of EEG (qEEG). Visual evaluating by a neurologist is time-consuming and depends on the subjective estimation of the evaluator, meaning that not all spikes with a small amplitude or atypical shape are marked. Therefore, the automatic evaluating system has been developed for objective and fast analysis.

2 Spike detection

Many differing methods exist for discharge detection; these are compared in the review [2]. Specific methods are based on spectra difference between the background activity and the discharges. Each evaluated patient and individual channels have different amplitude and spectral characteristics of the background waveforms that are the reference. The discharges have larger energy in higher frequencies than the baseline activity.

For better definition of the background, some authors adjust the EEG signals. The basic principles have been known for several decades. Gotman and Gloor (1976) described the background as the average amplitude from the five-second segment of the EEG signal of the foregoing spike [3]. This way was successful with slow activity of the small amplitude background. Guedes de Oliveira et al. (1983) exploited the standard deviations of the EEG signal amplitude and its first and second derivatives [4]. The procedure was used to normalize the corresponding amplitude, slope and curvature attributes of the spike. Similar methods were described by Wilson et al. (1999), who replaced derivatives by curvatures and angles for better representation of what the expert 'sees' [5].

Witte et al. (1991) developed a method that worked similarly to the visual spike evaluating of the hand-marker (neurologist) [6]. The neurologist marked a spike when a sharp wave had higher amplitude than the surrounding baseline activity. Thresholds are applied to define spike acceptance.

Sankar and Natour (1992) use an autoregressive (AR) model to isolate transients in each five-second window [7]. The EEG was modeled to define baseline activity. Non-stationary signal section-like discharges could not be modeled using inverse filtering, thus the error of the modeling was revealed on a potential spike. The AR model was found for a potential section again, which was compared with a representative model of the spike. When a difference was smaller than a defined threshold, the section was marked as the spike. However, the described method had a high ratio of false-positives to true-positives detection.

Other authors used a classifier for spike recognition. Parameterization of EEG by means of the previously described way, fast Fourier transformation (FFT) or wavelet transformation were used as inputs of the classifier. For example, Goelz et al. (2000) apply the continuous wavelet transform (CWT) to generate background frequency spectra vs. time [8]. Searching for statistical deviations was used to identify transients.

Keshri recognized epileptic spikes in rats using deterministic finite automata (DFA) [9]. The DFA detected high amplitude transients similar to human hippocampal discharges. The DFA was based on a sequence of rules that compared EEG signals. When all of the rules were fulfilled, the sequence of the signal was classified as a spike.

All of the methods described have shared disadvantages. Methods based on the spectra analyses use for parameterization segments of the signal that are longer than the spike duration. The spike that is superimposed against strong baseline activity cannot be detected. Analyses that use the shape of the waveform for parameterization encounter the same problem. Therefore our rules have been developed to concentrate on detection of the spike and definition of baseline activity. The rules combine filtering of the continuous signal, its statistically distribution and finding of thresholds by means of maximal likelihood. The method is independent of patients, channels and amplitude of the baseline activity.

3 Materials and methods

The signal data were acquired from epileptic patients in the Department of Pediatric Neurology, in the Motol University Hospital. The patients were monitored through intracranial multichannel ECoG during one week. The total number of the electrodes could be as high as 122. Figure 1 shows the placement of the electrodes using x-ray radiography. The measurement system used at a sample rate 200 Hz. Neurologists subjectively analyzed ECoG signals and results of video-EEG, magnetic resonance imaging (MRI), positron emission tomography (PET), single-photon emission computed tomography (SPECT), subtraction ictal SPECT coregistered on MRI (SISCOM), etc. for localization of the epileptic bearing that was surgically removed. The implantation of electrodes and final removing of the bearing required double-planning operation.

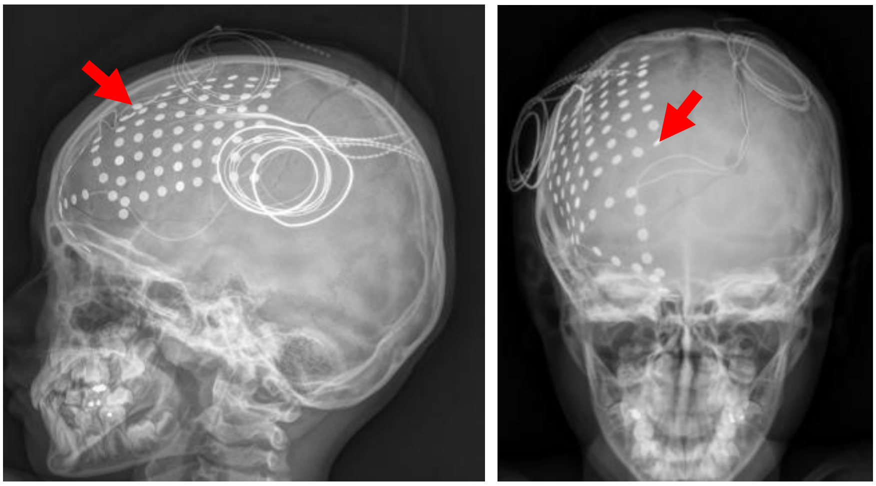

Figure 1: X-ray radiography of the first patient with implanted ECoG electrodes. The arrows mark the same electrode.

3.1 Patients diagnoses

The first male patient was 10 years old; his diagnosis was refractory right-sided frontal epilepsy caused by focal cortical dysplasia. The patient was examined by video-EEG, MRI, MRI spectroscopy, functional MRI, ictal and interictal SPECT and etc. for exact localization of the epileptic lesion. However, these methods all failed, so a double-planning operation was undertaken. The ECoG was monitored using 80 electrodes (a squared 8x8-grid, two 6-strips and a 4-strip).

The second patient was a 16-year-old male with refractory focal MRI-negative epilepsy on the basis of the focal cortical dysplasia type IIa of the left hemisphere. The double-planning operation was performed because MRI, MRI spectroscopy, functional MRI, ictal SPECT did not show bearing. The ECoG monitoring was carried out by 64 electrodes (two 4-strips and a 7x8-grid).

3.2 Epileptic discharges

The brain structure in the vicinity of the epileptic bearing or SOZ is able to generate discharges as SWCs and high frequency oscillations (HFOs). The discharge artifacts are propagated to the nearest areas and also projected through the major neural pathways to more distant parts of the brain. Direction of the propagation is often uniform in interictal phases. Sensitive areas of the early propagation can take over generation of the discharges in ictal states. As a result, discharge sources can be found only in seizure-free signals. An example of the three-second ECoG signal with featureless and strong discharges is given in figure 2.

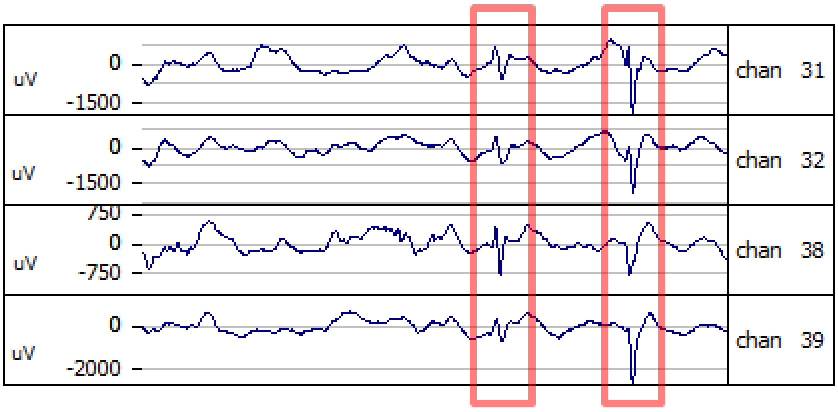

Figure 2: The SWCs discharges – time windows are 0.25 second.

3.3 Spike detector

A steep transient signal such as a spike contains high frequency components in its spectra. The significant part of its energy lies above 10 Hz. Therefore, each signal channel is filtered by a Butterworth 4th-order band-pass filter from 10÷70 Hz. The upper frequency corresponds with the anti-aliasing filter of the acquisition system. The main 50 Hz hum is eliminated using a biquad filter with poles on radius of 0.98 and zeros on unit circle of Z-plane. Zero-phase digital filtering compensates for the phase delay of the filters. The amplitude distortion is insignificant. ECoG spectrum has a decreasing trend of energy with increasing frequency. This fact is compensated using additional filtering by a simple digital differentiator. The ECoG signals envelopes show higher values at the points of the spikes. The envelope is calculated as an absolute value of the filtered signal using a 5-point median filter.

When the normalized envelope crosses a set threshold, a section of the ECoG signal is marked as a discharge. The envelope is normalized by the maximal value to the range 0÷1. The threshold value is different for each analyzed channel. The value settings are defined by a rule that is based on estimation of statistical distribution of the envelope, which itself is estimated using maximal likelihood (MLE) algorithm of lognormal distribution. Figure 3 shows a detail of the MLE estimation of distribution and histogram of an envelope that is normalized to the unit area. The distribution is different for records which contain spikes in opposition to records without spikes. A higher number of spikes in records causes greater deviation in the distribution, which then also becomes narrower and steeper. Unlike a channel without large fluctuations, it has flat distribution. The comparison of two opposite cases is shown in Figure 4. The part of the distribution to the left of the threshold (dashed lines) corresponds with background activity, the spike activity is on the right. The threshold divides the distribution into two parts, with background activity on the left and spike activity is on the right.

The point defining the thresholds was found as optimal strategy to minimize false-positive and maximize true-positive spike detection. Three experienced neurologists manually marked spikes in representative 8-minutes recordings independently of each other with 92% agreement. Their evaluation was used for finding the optimal slope of distribution. The slope is computed as an approximate derivative of the continuous MLE distribution. Figure 5 shows a dependence of false-positive detections and unmarked spikes on the slope. The optimal slope was chosen as the intersections of the curves. The chosen strategy has around 90% agreement with the "super-neurologist", which was created as the combination of the neurologists' record evaluations. The representative signal that was marked by the super-neurologist contained 264 events overall.

The threshold of the record is defined in points with the optimal slope of distribution as normalized by the maximal value. Flat distribution achieves a higher value of the threshold than the narrow distribution. In other words, the channel without spikes has stringent rules for the spike-marking, while for spikes the opposite is true. Figure 4 shows the thresholds of two records with differing occurrence of spikes. The identical tangent slopes cause different thresholds for various distributions. An example of signal segment, its envelope and results of spike detection are given in Figure 6.

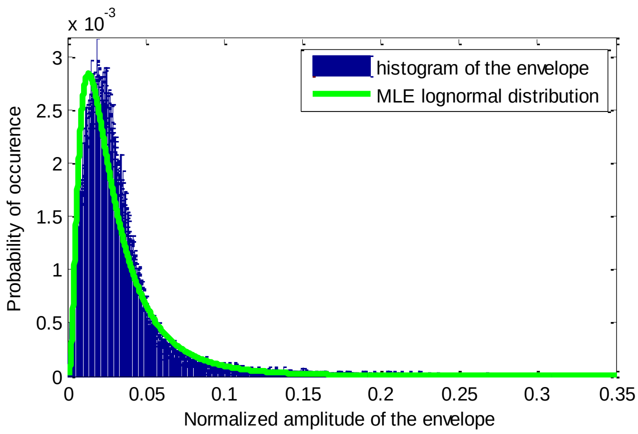

Figure 3: The detail of MLE estimation of the distribution of the normalized envelope amplitude.

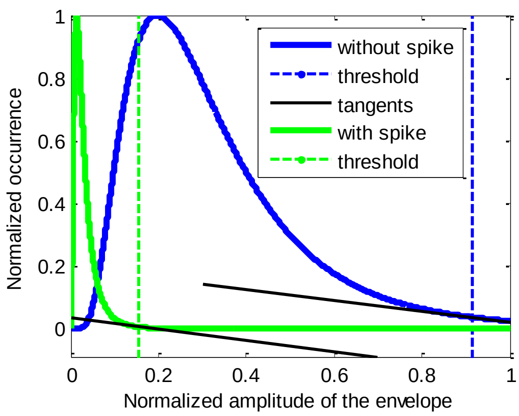

Figure 4: The determination of thresholds according to the optimal slope of tangents to distributions. The tangents are parallel.

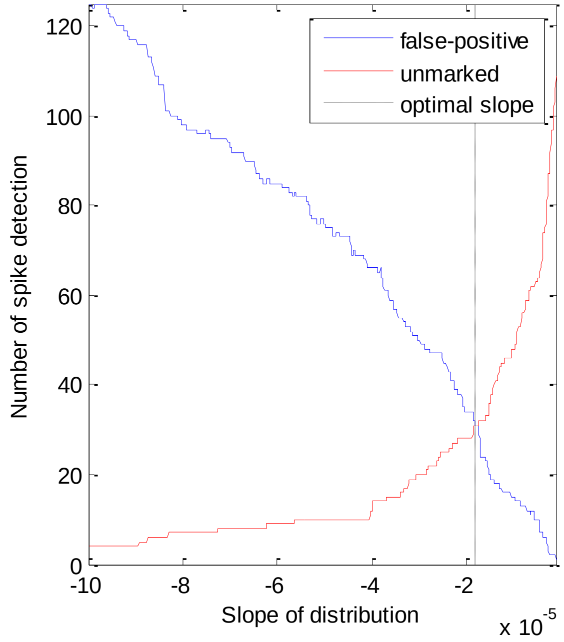

Figure 5: The assessment of the optimal slope of distribution to minimize false-positive and maximize true-positive spike detection.

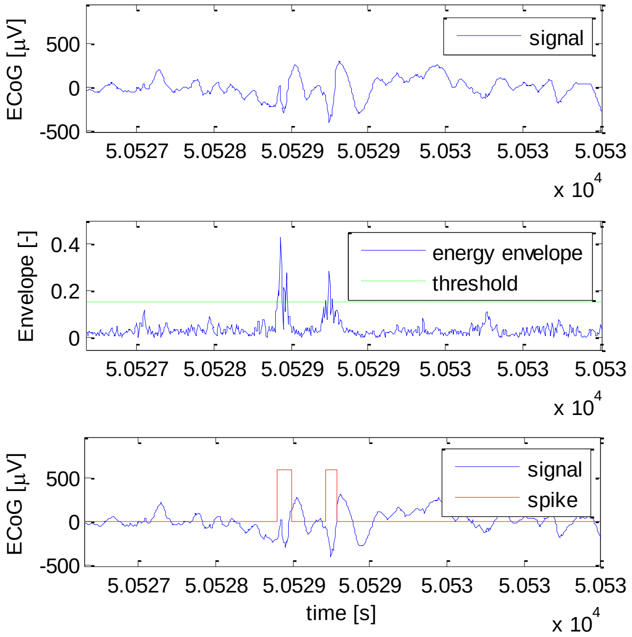

Figure 6: The segment of the ECoG signal, its envelope with detection thresholds and results of spike detection.

4 Results

The described method was applied to the interictal ECoG signals of two patients. Both signals contained hundreds of events as SWC and HFOs in a single channel. The shapes of the discharges were different for patients. Some electrodes were accidentally disconnected during ECoG monitoring, therefore the corresponding channels were removed from the analyses. However this procedure is not absolutely necessary, because the operation of the algorithm is robust.

A number of the spikes were investigated for each channel. Visualization of the cortical map can be useful for easy representation of the result. Figure 7 shows the cortical map of the placement of cortical electrodes.

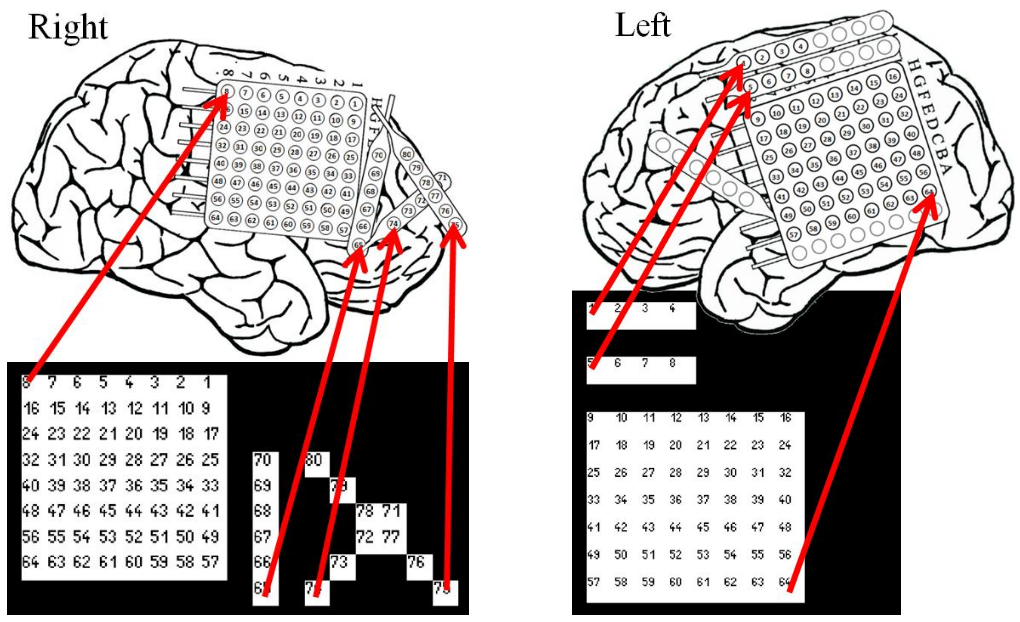

Figure 7: The visualization of the cortical map – the first patient is on the left, the second patients is on the right

The number of detected spikes of the first patient was found in almost five minutes using ECoG signals. The quantitative analysis clearly shows a difference between channels. The cortical map presents the number of the positive detections in color, see Figure 8 on the left. The maximal number of the marked spikes was 381.

The circa five-minute signal of the second patient was evaluated. The difference between channels was found in much the same way. The most active channel contains 172 events that were marked as spikes. Figure 8 on the right shows the number of the spikes in the colored cortical map.

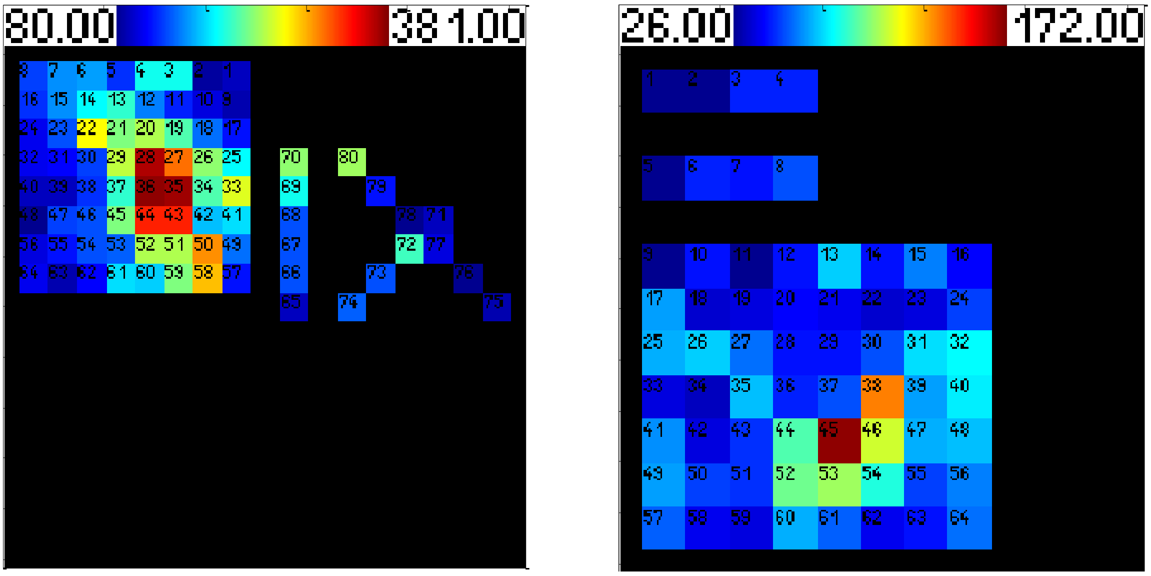

Figure 8: The number of the detected spikes in the colored cortical maps. The result of the first patient is on the left, the second on the right.

5 Conclusion

The results of the described algorithm have a close similarity with the subjective evaluating of the consulting neurologists. The channels with a large number of detected spikes are an inside area that corresponds with a removed bearing.

The analysis of the first patient shows the maximal number of the spikes occurring around electrodes 28, 35 and 36. The occurrence of the spike in the nearest vicinity is less; it is probably caused only by propagated spikes that are dampened. The neurologist localized the bearing under electrodes 28 and 36, which had the maximal number of the spikes together with 20 and 44. Figure 9 compares the results of the spike detector and the subjective evaluation of the neurologist. Red colors represent the electrodes as sources that contain a large number of the spikes; yellow colors mark an area of early propagation. The significant channels with a large number of the detected spikes are inside the area which was surgically removed.

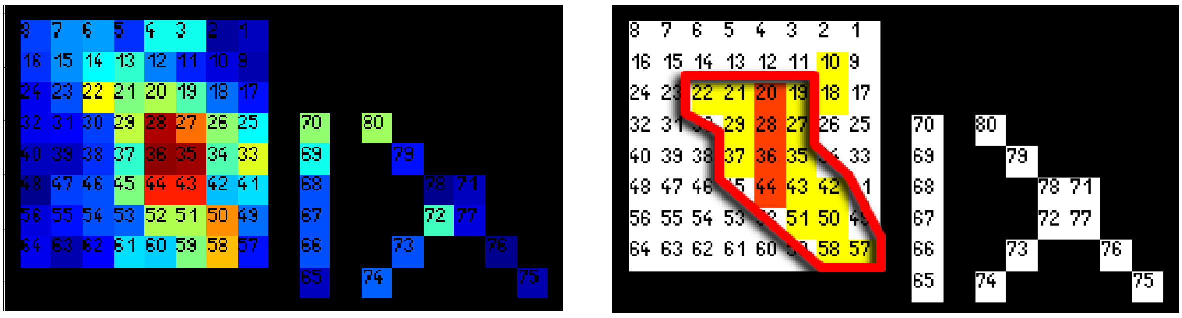

Figure 9: The comparison of the spike detector (left) and the neurologist's evaluation (right) in cortical maps of the first patient. Red colors represent the source of the spike, yellow ones show area of early propagation for the right figure. The red outline corresponds with the removed part of the brain.

The second patient had a slightly more complicated comparison. The neurologist's evaluation did not define the areas of the early propagation, because the time of the spike propagation was less than the sampling period of the acquisition of the ECoG. However, quantitative analysis through the spike detector reveals the source of the spike. The maximal number of the detected spikes was found in channels 38 and 45; less numerous occurrences were in channel 13, and around channels 26, 32, 46 and 53. The neurologist's evaluation is compared with the results of the analysis in figure 9. The marked electrodes do not precisely agree, but the occurrences of the spikes found correspond with the surgical removed area. Neurologists do not evaluate every channel, so certain electrodes are unmarked. In this case, the red electrodes in the cortical map define the border of the spike occurrence. The electrodes found through the detector are in the removed area, as in the case of the first patient.

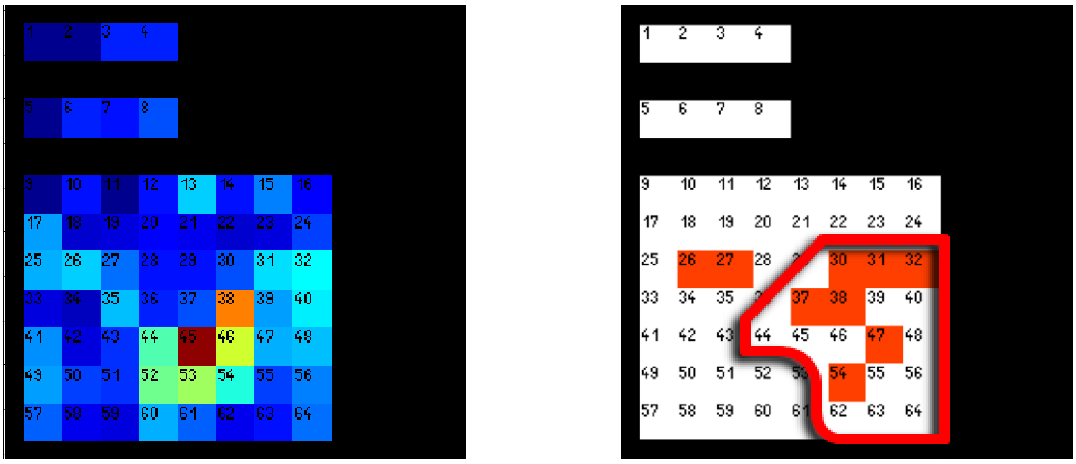

Figure 9: The comparison of the spike detector (left) and the neurologist's evaluation (right) in cortical maps of the second patient. Red colors represent the source of the spike that defines the border of the occurrence for the right figure. The red outline corresponds to the removed part of the brain.

The presented results of two patients are insufficient for more extensive conclusions, but offer a preview of the qEEG evaluating method for the ECoG. The method uses the spike detector which is based on a comparison of the energy envelope of filtered signals and individual settings of the thresholds. The settings of the thresholds follow the rule that is in dependence on the statistical distribution and its MLE approximation of the envelope. Our good preliminary results will have to be extended to other patients.

The improvements of the algorithm may include a multi-channel dependency to minimize false-positive detections. The decision-making strategies may be improved by the neurologist's hand-marking of short-time illustrative signals of a new patient to define the optimal point of the slope.

All of the algorithms and visualizations of results have been implemented in the MathWorks Matlab R2010b version, in the 64-bit edition.

Acknowledgments

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