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A reliable approach to distinguish between transient with and without HFOs using TQWT and MCA

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HIGHLIGHTS

- We proposed an automated method to distinguish between transient with/without HFOs.
- The proposed method achieves a high sensitivity.
- The proposed method achieves a high specificity and low FDR.
- The proposed method is reliable and accurate for HFOs detection.

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ABSTRACT

Recent studies have reported that discrete high frequency oscillations (HFOs) in the range of 80–500 Hz may serve as promising biomarkers of the seizure focus in humans. Visual scoring of HFOs is tiring, time consuming, highly subjective and requires a great deal of mental concentration. Due to the recent explosion of HFOs research, development of a robust automated detector is expected to play a vital role in studying HFOs and their relationship to epileptogenesis. Therefore, a handful of automated detectors have been introduced in the literature over the past few years. In fact, all the proposed methods have been associated with high false-positive rates, which essentially arising from filtered sharp transients like spikes, sharp waves and artifacts. In order to specifically minimize false positive rates and improve the specificity of HFOs detection, we proposed a new approach, which is a combination of tunable *Q*-factor wavelet transform (TQWT), morphological component analysis (MCA) and complex Morlet wavelet (CMW). The main findings of this study can be summarized as follows: The proposed method results in a sensitivity of 96.77%, a specificity of 85.00% and a false discovery rate (FDR) of 07.41%. Compared to this, the classical CMW method applied directly on the signals without pre-processing by TQWT-MCA achieves a sensitivity of 98.71%, a specificity of 18.75%, and an FDR of 29.95%. The proposed method may be considered highly accurate to distinguish between transients with and without HFOs. Consequently, it is remarkably reliable and robust for the detection of HFOs.

1. Introduction

The EEG of epileptic patients characteristically contains some specific waveforms that do not exist in the normal EEG. Indeed, spikes, sharp waves and high frequency oscillations (HFOs) are the most common distinctive waveforms closely related to phenomena of epilepsy. According to the International Federation of Societies for Electroencephalography and clinical neurophysiology (IFSECN) in 1974, spike is defined as a transient with a sharp peak, clearly distinguished from the background activity, with duration between 20 and 70 ms and variable amplitude (Indiradevia et al., 2008; Vijayalakshmi and Abhishek, 2010). Sharp wave is similarly defined with duration between 70 and 200 ms (Indiradevia et al., 2008; Vijayalakshmi and Abhishek, 2010). HFO event is defined as spontaneous wave that consists of at least 3 cycles with frequencies ranging between 80 and 500 Hz, which can be distinguished from the surrounding background EEG (Bragin et al., 1999, 2002; Staba et al., 2002; Urrestarazu et al., 2007). These different abnormal waveforms may occur depending on the type of epilepsy, electrodes types (macro-electrodes, microelectrodes) and also depending on the location of the brain region to be investigated.

The research into high frequency bands was restricted due to hardware limitations and high computational power demands inherent to EEG systems (i.e. sampling rates, hardware filters).

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Nevertheless, advances in digital EEG recording techniques have opened new insights into the high frequency EEG rhythms over the last few years. By recording EEG at higher sampling rate with the aid of intracranial electrodes, HFOs waves in frequencies much higher than normal activities range have been discovered. Indeed, the investigation of HFOs in the range of 80–500 Hz has been of increasing interest since 1999. HFOs have been discovered in the last few years in epileptic patients (Bragin et al., 2002; Staba et al., 2002) and animal models (Bragin et al., 1999). HFOs are mostly recorded with intracranial electrodes (Worrell et al., 2008). Surprisingly, recent studies have also reported that HFOs patterns in the range of 40–200 Hz (Ellenrieder et al., 2012) and 80–150 Hz (Iwatania et al., 2012) may be recorded on the scalp EEG. They are commonly observed, either during ictal (Jirsch et al., 2006; Zijlmans et al., 2011; Salami et al., 2012), preictal (Jacobs et al., 2009b) and interictal periods (Urrestarazu et al., 2007; Jacobs et al., 2008; Zijlmans et al., 2011). HFOs are broadly classified into two sub bands, ripples and fast ripples and range between 80–250 Hz and 250–500 Hz, respectively (Staba et al., 2002; Urrestarazu et al., 2007). HFOs can coexist under physiological or under pathological conditions (Jefferys et al., 2012).

In fact, all the clinical evidences seem to suggest that HFOs might be specific surrogate markers of the seizure onset zone. Moreover, HFOs can have a pretty profound impact in the understanding of the fundamental neural mechanisms underlying epileptic phenomena. To date, during interictal periods, higher rates, higher durations and higher powers of HFOs were observed within the seizure onset zone (SOZ) than in other areas (Bragin et al., 1999; Urrestarazu et al., 2007; MacReady, 2008; Jacobs et al., 2008). In other hand, it has been revealed that HFOs bursts mark epileptogenicity rather than lesion type (Jacobs et al., 2009a). Moreover, two studies on human have also proved that there is a good correlation between resection of the brain region containing channels with high HFOs rates and post-surgical outcome (Jacobs et al., 2010; Wu et al., 2010). Recently, researchers and epileptogists have shown that HFOs could be useful in predicting the spatial location and possibly the timing of the onset of epileptic seizures (Khosravani et al., 2009; Kalitzin et al., 2012; Cuevas et al., 2013). More importantly, higher HFOs rates are significantly correlated with higher seizure frequency in epileptic patients (Zijlmans et al., 2009). The ranking of channels according to rate indicated that HFOs remained confined to the same region during ictal and interictal periods and seem to be a more reliable indicator of the seizure onset, while spikes and sharp waves presented a wider spread during seizures than interictal periods (Jacobs et al., 2008; Crepon et al., 2010; Zijlmans et al., 2011; Zelmann et al., 2012; Salami et al., 2012; Naeini, 2012; Gotman, 2013).

The identification of HFOs in EEG is relatively new and has mostly been done by visual review (Urrestarazu et al., 2007; Jacobs et al., 2008). However, despite its valuable advantage of providing an advanced understanding of the relationship between HFOs and epileptogenesis, its reliance on manual processing makes it relatively tedious, complicated (Cuevas et al., 2013), inevitably subjective (Chander, 2007; Zelmann et al., 2012). Moreover, visual HFOs processing requires a great deal of mental concentration and experienced reviewers trained in electrophysiology and HFOs analysis (Chander, 2007; Naeini, 2012; Chaibi et al., 2013). Additionally, visual scoring of HFOs is highly time-consuming (Chander, 2007; Zelmann et al., 2009, 2012; Naeini, 2012; Chaibi et al., 2013). Indeed, the visual EEG processing of a 10 channels of 10-min recording would take approximately 10 h of hard work of an experienced reviewer (Zelmann et al., 2009, 2012).

Due to the recent explosion of HFO research, the development of algorithms for automatic detection of HFOs events poses a great benefit to researchers and clinicians. Recently, a handful of automated HFO detectors have been introduced in the literature. Some of these methods operate in the time domain. Some others detectors use time-frequency techniques, while others studies have applied neural network for their detection. Depending on the electrodes types, location of recording, and different definitions for HFOs (i.e. frequency bands), a large variety of performance has been reported for various methods. The sensitivity, specificity and false discovery rate (FDR) are the most commonly metrics that have been used for measuring the performance. Sensitivity is used to characterize the percentage of the true HFO events (Gold standard) that are detected by the detector. Specificity of a detector is defined as the proportion of negatives (absence of HFOs in the EEG) that are correctly rejected by the detector. FDR is used to controls the rate of false positives. It is defined as the proportion of detected HFOs overlapping with the negatives. Following paragraphs present a brief review of the most HFOs detection algorithms and their performances that have already been published.

The earliest automated HFOs detector was proposed by Staba (Staba et al., 2002). This method is based on linear finite impulse response (FIR) filter and the moving average of the root mean square (RMS) feature. Only a sensitivity of 84% has been reported. The sensitivity and FDR reported for this method implemented by another group (Zelmann et al., 2012) were 70.3% and 77.3%, respectively.

Khalilov et al. (2005) proposed an algorithm for HFOs detection which is based on the complex Morlet wavelet (CMW). Although, the performance of this detector was not reported by the authors, the sensitivity and FDR off this technique were reported in another study (Chander, 2007) to be 70.8% and 13.1%, respectively. For another report, sensitivity and FDR were reported as 87% and 14.12%, respectively (Chaibi et al., 2013).

Gardner et al. (2007) described an HFOs detection method which is based on short-time line-length (STLL) energy and Butterworth filter. This method is basically similar to the method proposed by Staba (Staba et al., 2002) but with a few modifications. Based on the author's report, this method is capable of detecting HFOs with sensitivity of 89.7%. However there was no report related to the specificity. The authors only validated their algorithm in gamma band (35–80 Hz), HFO band is not considered in their study. It was stated in another study (Worrell et al., 2008) that a high sensitivity of this detector was associated with a high false positive detection, for which 80% of the detected candidate HFOs events were false positives. It has been reported in another report (Zelmann et al., 2012) that this detector has 62.9% sensitivity and 66.3% FDR.

Crepon et al. (2010) proposed an algorithm which is based on the Hilbert transform in conjunction with FIR filter. The sensitivity and specificity of this detector were 100% and 90.5%, respectively. For another reports, this detector result in a sensitivity of 89.9% and a false positive rate of 2.1 per minute (Havel et al., 2013). However, in the study of Zelmann et al. (2012), a sensitivity of 61.1% and FDR of 71.4% were reported.

Another automated HFOs detector was presented by Doshi (2011). This method is based on bumps modeling technique. Its resulting sensitivity and specificity were 92% and 71%, respectively. In another study was reported by (Chaibi et al., 2013), the sensitivity and FDR were reported as 95.86% and 20.96%, respectively.

Zelmann et al. (2012) presented an algorithm is known as MNI detector (Montreal Neurological Institute). The MNI method consists of three detectors, a baseline detector and two HFOs detectors. The means of sensitivity and FDR in the best parameter set for this method were 90.5% and 71.8%, respectively.

Another type of HFOs detection method is based on the neural network was proposed by Dümpelmann et al. (2012). Sensitivity and specificity for this method were reported as 49.1% and 36.3%, respectively.

Recently, a set of HFOs detectors termed as 'slope', 'iterative-slope' and 'slope-causal' were presented by Naeini (2012). These