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Automatic recognition of epileptic discharges based on shape similarity in time-domain

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ABSTRACT

Background: Epilepsy is a common neurological disease, and electroencephalogram (EEG) contains massive epilepsy information. Automatic recognition of epileptic discharges has great significance in diagnosis of epilepsy.
New method: This paper proposes a novel automatic recognition of epileptic waves method in EEG signals based on shape similarity in time-series sequence directly. Merger of the increasing and decreasing sequences (MIDS) was used to improve the recognition accuracy and reduce the computation cost. Then shape templates were designed, and the modified Hausdorff distance was employed to measure the shape similarity of waveforms in template matching part. This approach imitates human visual cognitive process to analyze EEG and employs image recognition method into one-dimensional signals, which is a direct, original and effective method.
Results: 373 epileptic discharge fragments marked by clinicians from 20 patients' EEG recordings were selected. By fusing significance rules, 98.39% of them were recognized, with the false recognition rate 1.1%.
Comparison with existing methods: Experimental results indicate that the proposed approach yielded better performance for interictal epileptiform discharges (IEDS) recognition compared with the previous methods.
Conclusions: The proposed approach has good performance and high stability in automatic recognition of epileptic discharges both in ictal and interictal period, which could support the diagnosis of epilepsy greatly.

1. Introduction

Epilepsy is the most common disease of neurology caused by brain neurons' abnormal discharge [1], which is harmful to human's health, and the most effective method for diagnosis of suspected epilepsy patients is EEG examination [2]. Clinicians need to observe EEG records page by page to analyze whether epileptic waves appear by their experience. The manual interpretation needs to consider many factors, such as the waveform of discharges, the position of abnormal discharges in scalp electrodes, as well as occurrence frequency of abnormal discharges in EEG recordings. Therefore, the manual interpretation is irreplaceable now [3]. On the other hand, due to that the manual interpretation is time-consuming, tedious and subjective, the research of automatic detection of epileptic waves has great significance in assisting clinicians to diagnose epilepsy.

In EEG recordings, patients with epilepsy are in two states: interictal period and ictal period, and mainly in interictal period. Thus, two aspects of automatic recognition of epileptic waves have been discussed for some decades: automatic seizure detection and automatic detection of interictal epileptiform discharges (IEDS) [3]. Epileptic seizure is very irregular unless specific stimulations involve. Epileptic waves that are mainly consist of sharp waves, spikes, spike-and-slow waves and sharp-and-slow waves, and appear both in ictal and interictal EEG recordings [4]. The unclear shape definition of sharp waves and spikes interferes the automatic recognition of epileptic waves [5]. Many automatic seizure detection methods have been developed, and some automatic seizure prediction methods have also been discussed [6,7]. Yatindra Kumar et al. [9] showed an automatic seizure detection method using discrete wavelet transform (DWT) based fuzzy approximate entropy in EEG signals. Wang et al. [10] proposed a new method for feature extraction and recognition of epileptiform activity in EEG signals.

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Yuan et al. [11] presented a new EEG classification approach based on the extreme learning machine (ELM) and nonlinear dynamical features. Fu et al. [12] developed a new technique for automatic seizure detection in EEG by using Hilbert marginal spectrum (HMS) analysis. Chen et al. [13] introduced a novel framework on ELM and wavelet-based nonlinear features computed by three methods, i.e., approximate entropy (ApEn), sample entropy (SampEn) and recurrence quantification analysis (RQA). Nonlinear features, wavelet transform and some pattern recognition methods have been widely employed in automatic seizure detection in recent years, and these researches all showed good performance. Acharya et al. [14] showed an algorithm for the automated diagnosis of epilepsy in EEG using continuous wavelet transform (CWT), Higher Order Spectra (HOS) and textures. They also introduced a method for the automated detection of normal, pre-ictal and ictal EEG signals with entropy features [15]. Then they used intrinsic time-scale decomposition (ITD) to compute energy, fractal dimension and sample entropy for automatic seizure prediction [16]. These three novel methods classified normal, interictal and ictal EEG automatically, and both showed high classification accuracy. For the automatic detection of IEDS, less approaches have been developed. Indiradevia et al. [8] showed a wavelet approach for automatic detection of epileptic spikes in 18-channels EEG. Zhang et al. [4] proposed a novel time-domain merging approach to detect IEDS in EEG time-series. All these algorithm can highly assist the diagnosis of epilepsy.

This research focuses on automatic recognition of epileptic discharges in time-domain. Information in time-domain has been widely employed in different EEG analysis fields for a few years. Feinberg et al. [17] introduced an extensive method of period-amplitude analysis (PAA) to segment periods of EEG signals. Jin et al. and Zhang et al. [18–20] proposed some time-domain approaches in brain-computer interface field. Fujimori et al. [22] put forward histogram method to analyze amplitudes of waves for sleep EEG analysis. In IEDS detection field, Olejarczyk et al. [21] developed an algorithm to detect the evoked Sharp Wave-Slow Wave (SWSW) in EEG time-series automatically. Zhang et al. [4] showed a novel time-domain merging approach to improve epileptic wave detection rate. All these methods showed excellent stability and adaptivity. For the detection of epileptic discharges in EEG time-series, time-domain methods have the following three advantages: (1) results of all the methods need to be compared with clinicians visual detection results, so the time-domain feature observed by human vision is a direct feature; (2) waveforms of each single wave have clear physical meanings; (3) the signal information may lose when transforming signals to other domains, while the time-domain method is a direct way. At seizure onset, massive epileptic waves appear continuously with high amplitude, which may change the signal component. Many signal features would be changed such as power bands features and nonlinear features, and the classification of these seizure EEG features has been discussed in [23]. While in interictal period, epileptic waves scatter in signals, and stand out of the background activity. The signal features in this period are only time-domain features observed by human vision. At present, there is no clear shape definition of epileptic waves, and many artifacts, such as electromyogram (EMG) and electrooculogram (EOG), could interfere the detection of IEDS. All these challenged the researches of automatic detection of IEDS. Thus, regarding automatic detection of IEDS as a pure digital signal processing problem and recognizing epileptic waves using digital signal processing methods are difficult. Moreover, an effective approach should recognize IEDS and epileptic discharges in seizure period simultaneously.

In this paper, a novel time-domain approach based on shape distance is proposed for automatic recognition of epileptic waves both in ictal and interictal period. This approach can detect each epileptic wave in EEG time-series in a single channel without transformation, which is a direct and effective method. In order to consider shape characteristic sufficiently, this approach regards the detection of epileptic waves as an image recognition problem rather than a pure digital signal processing problem. In this method, the one-dimensional EEG signal is treated as a two-dimensional image, which can describe epileptic waveforms exacter and is corresponding with the human visual cognition pattern [25,26]. MIDS was applied to segment periods and merge clutters to make sure that each wave is a complete wave, and a normalized database consist of massive shape templates of epileptic waves marked by clinicians was established to describe waveforms of epileptic discharges. Actually, template matching process imitates clinicians' visual interpretation process, and the normalized database corresponds to clinicians' prior experience. In template matching part, modified Hausdorff distance (MHD) [27] was employed to calculate the shape distance between pending waves and templates, which is the crucial innovation, and the experimental result showed better performance than traditional similarity calculating methods. The rest of paper is organized as follows: Section 2 describes the detail of the proposed approach; Section 3 shows experimental results; Section 4 proceeds with some discussions, and Section 5 concludes this paper.

2. Methods

2.1. Merger of the increasing and decreasing sequences

Merger of the increasing and decreasing sequences (MIDS) is a effective and adaptive time-domain method to highlight characteristics of waveforms by segmentation and merger, which has been introduced in our previous research [4]. This method is based on the theory of perceptual organizational principle, which extracts the visual features of waveforms to improve recognition based on merger rules. This method is briefly introduced here, which is divided into two parts: merger of clutters and merger of incomplete waves.

Merger of clutters. Set s_j as the jth sample point, and define s_{a_i}, $s_{a_{i+2}}$ as the local minimum points, $s_{a_{i+1}}$ as the local maximum point in a time-series sequence s_j. In both part of procedure, only these two kinds of points involve in calculation. The amplitude of normal adults scalp EEG changes between 10 μV and 50 μV. On the other hand, it has been discussed that the period of sharp waves and spikes is between 20 and 200 ms [2], so the waves with durations less than 20 ms and amplitudes smaller than 10 μV are clutters in automatic epileptic waves detection.

The merger rules are stated as follows: set $t = a_{i+2} - a_i$, if $t < 0.02/T_{sample}$, where T_{sample} is the sampling period, the wave $s_{a_i}, s_{a_{i+1}}, s_{a_{i+2}}$ is a clutter. If $s_m = \max(s_{a_{i+1}}, s_{a_{i+3}})$, $m = a_{i+1}$ or a_{i+3}, and rearrange the sequence $a_{i+1} = m$, $a_{i+2} = a_{i+4}, \ldots$, as in Fig. 1. Now this clutter is merged with the next wave.

Merger of incomplete waves. Different shapes of two combined single waves are showed in Fig. 2. Set $d_1 = s_{a_{i+1}} - s_{a_i}$, $d_2 = s_{a_{i+1}} - s_{a_{i+2}}$, $d_3 = s_{a_{i+3}} - s_{a_{i+2}}$, $d_4 = s_{a_{i+3}} - s_{a_{i+4}}$, in which s_{a_i} is a local minimum point after the merger of clutters. If one of the following conditions is satisfied, these two single waves are merged with the same method above.

(1) $d_1/d_2 < r$ and $d_3/d_4 < r$
(2) $d_2/d_1 < r$ and $d_4/d_3 < r$
(3) $d_2/d_1 < r$ and $d_3/d_4 < r$
(4) $d_2/d_1 < r$ and $d_3/d_4 \geq r$ and $d_4/d_3 \geq r$ and $d_2/d_3 < r$
(5) $d_3/d_4 < r$ and $d_1/d_2 \geq r$ and $d_2/d_1 \geq r$ and $d_3/d_2 < r$

where r is a merger threshold, ranged from 0.2 to 0.7 discussed in [4]. Small value of r would retain more fast waves while large