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Algorithms of Brainstem Auditory Evoked Potential Extraction Based on Wavelet Information Entropy

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Abstract

To extract the brainstem auditory evoked potentials and remove the spontaneous electroencephalograph and other background noises, the paper proposed a new method of wavelet information entropy theory de-noising based on wavelet de-noising. In the method, the threshold function is improved by introducing the weighting factor and determine the weighting factor according to the wavelet information entropy to obtain a better de-noising effect. The simulation experiment shows, compared to the traditional wavelet de-noising method, the new method can preserve the details of the signal better and make the signal waveform smoother. At the same time, the new method can suppress the pulse signal, which make the system has a better de-noising performance and achieve higher quality extraction brainstem auditory evoked potentials.

Keywords*: brainstem auditory evoked potential (BAEP), wavelet information entropy, threshold functions, weight factor*

1. Introduction

Since the brainstem auditory evoked potentials (BAEP) were found, it has been widely used in newborn infants hearing screening direction [1, 2]. As the brainstem auditory evoked potential signal is often submerged in the noise from the spontaneous electroencephalogram (EEG) signals, the de-noising algorithm has been one of the most difficult problems in the field of EEG signals processing. From the 1950s, researchers have been devoted to the theory of brainstem auditory evoked potentials and signal extraction methods. Until the early 1980s, BAEP began to be applied to clinical practice with the development of the theory of computer technology, artificial intelligence and fuzzy and wavelet analysis. During this period, coherent averaging, independent component analysis [3, 4], the wavelet transform [5-9], time series analysis and neural networks were proposed to extract BAEP signal.

Coherent averaging technique is one of the most widely used methods in clinical practice [10, 11]. However, this method needs to be stimulated the subjects repeatedly, and it will cause nervous system fatigue and ignore the variation of the BAEP signal between each test, which will lead to the loss of the dynamic information of the extracted BAEP signals. Therefore, a few times or a single extraction signal has become a main research direction. In recent years, the development of wavelet analysis technology provides a simple and effective way to solve this problem. Wavelet analysis was an emerging discipline developed in the late 1980 , it inherits and develops the idea of localized of Fourier transform and has a good time-frequency characteristics. At the same time, it overcomes the shortcomings that the window size does not change with the frequency. Therefore, wavelet analysis is widely used in the field of weak signal extraction. Using Wavelet Analysis to extraction BAEP signal is based on the differences

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of the statistical properties of evoked potentials and background noises in the wavelet domain. Removing background noise component and retaining a useful signal component by a variety of threshold algorithm [12]. Compared with traditional coherent superposition averaging technique, wavelet analysis method could reduce the number of tests and avoid fatigue caused by excessive stimulation frequency response. But there are also details fuzzy of the signal waveform and poor impulse de-noising.

This paper presents a method of the extraction of brainstem auditory evoked potential based on wavelet information entropy [13,14] and combined with information entropy theory [15, 16], which maintains the original advantages of wavelet analysis. This method improves the smoothness of the signal waveform and the accuracy of the identification of the waveform without loss of useful information.

2. De-noising and Extracting Algorithm of Wavelet Analysis

Wavelet Analysis is a time-frequency analysis method. This method can solve the contradiction between time resolution and frequency resolution in the process of signal processing and amplify the local characteristics on a scale of the signal. It is especially suitable for non-stationary signal processing. Wavelet analysis is the optimal and less-calculation algorithm to extract EEG signal, and the algorithm can guarantee the frequency component of the signal not lose. So it is suitable for the extraction of BAEP signal.

Set standard BAEP signal for $s(k)$, noise for $d(k)$, the mathematical model of auditory evoked signal ($f(k)$) with band noise we get for:

$$f(k) = s(k) + d(k) \tag{1}$$

Using the wavelet analysis method to extract the BAEP signal is divided into three steps. Firstly ,wavelet decompose to EEG signals containing noise; Secondly, implement threshold processing to wavelet coefficients decomposed, concentrating the useful signal on the wavelet coefficients of a particular frequency band and other wavelet coefficients are set to zero or given a small weight value ; Finally, inverse wavelet transform, and reconstruct the original signal according to the processed wavelet coefficients.

According to the above three steps, implement $f(k)$ for wavelet de-noising, which can be described by formula (2).

$$\begin{aligned} & W(f) = W(s) + W(d) \\ & W_\lambda = H(W(f),\ \lambda) \\ & \hat{s} = W^{-1}(W_\lambda) \end{aligned} \tag{2}$$

In the above formula, $W(f)$ is the wavelet decomposition of the signal containing noise, $H(W(f),\ \lambda)$ function sets the threshold value λ and the threshold function, selects the wavelet coefficients according to the threshold and the threshold function; $W^{-1}(W_\lambda)$ is a wavelet inverse transform operation, get the reconstruction signal $\hat{s}$. The core of the whole algorithm is the second step: threshold setting and the selection of threshold function. The threshold function is mainly divided into hard threshold function and soft threshold function. The core idea is to remove the wavelet coefficient which is less than the threshold value λ, and keep the wavelet coefficients with large amplitude.

In order to improve the extraction effect of BAEP signal, this paper uses the soft threshold function method of information entropy adjusting threshold to realize the wavelet de-noising extract.

3. Signal Extraction Algorithm based on Wavelet Information Entropy

Application of wavelet analysis algorithm to extract the BAEP signal, due to the existence of noise in the wavelet coefficients, therefore the reconstructed signal contains noise interference. Specific performance for the extracted signal waveform details is fuzzy and not smooth, the tip pulse removal effect is not ideal. In order to make up for the above defects, this paper improves the traditional wavelet analysis algorithm, and proposes a new threshold function with weighted factors. As shown in the formula (3).

$$u_{j,k} = \begin{cases} \beta\hat{u}_{j,k} + (1-\beta)sign(\hat{u}_{j,k})(\left|\hat{u}_{j,k}\right| - \lambda) & \left|\hat{u}_{j,k}\right| > \lambda \\ 0 & \left|\hat{u}_{j,k}\right| \le \lambda \end{cases} \quad (3)$$

Among them, $u_{j,k}$ is the improved wavelet coefficient value, $\hat{u}_{j,k}$ is the wavelet coefficients of the traditional wavelet algorithm, λ is the threshold selection; β is the weighted factor, and $0 \le \beta \le 1$。 Improved threshold function can make the energy of the useful signal as far as possible to focus on the specific frequency band of the wavelet coefficient $u_{j,k}$, retain the details information of the BAEP signal , and greatly reduce the tip of the pulse noise in the signal。

The weighting factor is calculated according to the different characteristics of the signal, so this paper introduces the information entropy theory to determine the optimal value of the weighting factor.

Information entropy is used to evaluate the uncertainty of the information, and its size is a measure of the signal energy. For random variables x, the probability p_i is assumed at the time $x = x_i\left(i = 1, 2, \cdots, N\right)$, where $\sum_{i=1}^{N} p_i = 1$ the information entropy of the variable can be calculated as shown in the formula (4).

$$S\left(x\right) = -\sum_{i=1}^{N} p_i \cdot \log_2 p_i \quad (4)$$

Wavelet information entropy is combined with the characteristics of wavelet analysis and the principle of information entropy; the wavelet coefficients obtained by wavelet decomposition are used to estimate the signal energy.

Wavelet decomposition of the BAEP signal containing noise, scale is m, and each scale is decomposed into n wavelet coefficients. On the scale j, the improved wavelet coefficient vector is obtained by using the formula (3).

$$u_j = (u_{j,1}, u_{j,2}, \cdots u_{j,n}) \quad (5)$$

Using the improved wavelet analysis algorithm of (3) to deal with EEG signals, the definition of the total energy $E = \sum_{j=1}^{m} E_j$ of the BAEP signal is extracted, which E_j is the signal at the scale j of the energy, and $E_j = \sum_{k=1}^{n} \left|u_{j,k}\right|^2$ .After wavelet decomposition of EEG signals, the signal energy is directly proportional to its influence on the system. In the wavelet reconstruction, the greater the contribution of the energy value represents to the standard BAEP signal. The wavelet energy specific gravity p_j on the definition scale j is used as the contribution of the wavelet transform, and $p_j = \frac{E_j}{E}$ .According to the formula (4) of the information entropy, the wavelet entropy is defined as

$$S(u) = -\sum_{j=1}^{m} p_j \cdot \log_2 p_j \quad = -\sum_{j=1}^{m} \frac{\sum_{k=1}^{n} |u_{j,k}|^2}{\sum_{j=1}^{m}\sum_{k=1}^{n} |u_{j,k}|^2} \log_2 \frac{\sum_{k=1}^{n} |u_{j,k}|^2}{\sum_{j=1}^{m}\sum_{k=1}^{n} |u_{j,k}|^2} \qquad (6)$$

By formula (3) and formula (6) we can know that wavelet information entropy $S(u)$ is a function of the weighting factor β, so it can be determined by the wavelet information entropy to determine the size of the weighting factor β and the improved threshold function expression. When the maximum value of the wavelet information entropy is obtained, the effect of the BAEP signal is the best, and the corresponding weighting factor β is obtained.

BAEP extraction process based on wavelet information entropy is shown in Figure 1.

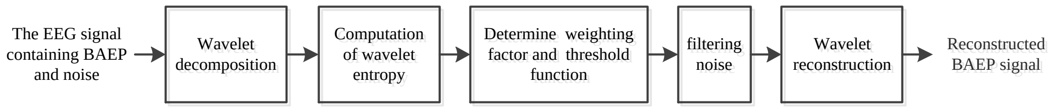

Figure 1. Schematic Diagram of the Wavelet Entropy Extraction

Figure 1 shows the wavelet information entropy method for extraction of BAEP signals is divided into five steps: The first step, wavelet decomposition of the BAEP signal containing noise; the second step according to the formula (6) computation decomposition of the signal after wavelet information entropy; the third step according to the maximum information entropy to determine the value of weighting factor β; the fourth step, put β into the formula (3) to determine the threshold function expression, and according to the expression of the decomposed wavelet coefficients threshold processing. Finally with the wavelet inverter change, reconstruction of the BAEP signal is obtained.

4. Simulation Experiment and Analysis

In order to validate the feasibility of the proposed wavelet information entropy method of the BAEP signal extraction effect, in the "standard" BAEP signal additive Gaussian white noise to simulation auditory evoked EEG for mixed signal, using the wavelet analysis method and wavelet information entropy method to extract the BAEP signal from mixed signal and comparing the accuracy of different algorithms ' results.

Assuming that the "standard" BAEP signal is generated by the mathematical formula (7), the simulation waveform is given in Figure 2, and the corresponding sampling time is 10ms. In order to make the simulation waveform and the real of the BAEP signal as close as possible, this paper defines three peak points (I, III, V)similar with the real signal, which the transverse coordinate said latency and longitudinal coordinate represents the amplitude.

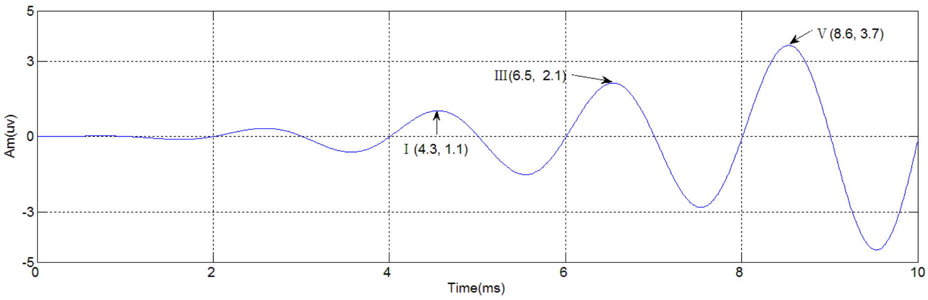

Figure 2. Standard BAEP Signal Waveform

"Standard" signal generated in the formula (7) additive Gaussian white noise can be obtained auditory evoked mixed signal, and the role of Gaussian white noise is simulated the background noise (including spontaneous EEG and other noise), and the waveform of simulation auditory evoked EEG under different signal-to-noise ratio(SNR) is as shown in Figure 3.

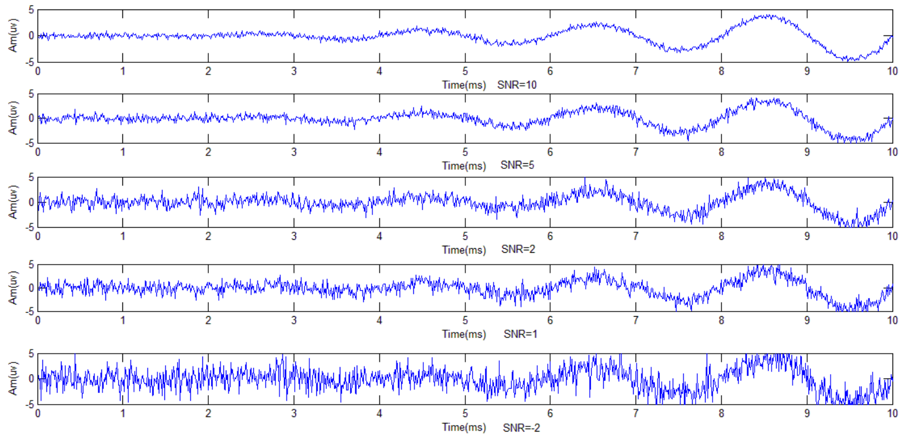

Figure 3. Waveform of the Auditory Evoked EEG under Different SNR

As can be seen from the figure, with the decrease of the SNR, the observability of BAEP signal is reduced, when the SNR of signal is below 1, the BAEP signal is heavily polluted by the background noise and submerged in the background noise, and can not be directly identified. This is similar to the fact that the BAEP signal is submerged by spontaneous EEG contamination in the actual experiment, which can be used in simulation research.

In this paper, we use the SNR and the root-mean-square error(RMSE) as the evaluation index of the experimental results. Compared to the original signal, if the SNR of the extraction of BAEP signal is higher, RMSE is smaller, the better the effect of extracting the signal.

The formula of SNR and RMSE is as follows:

$$SNR = 10\log_{10}\left\{ \frac{\sum_{n=1}^{N} F^2(n)}{\sum_{n=1}^{N}\left(F(n)-F(n)\right)^2} \right\}(dB) \tag{8}$$

$$RMSE = \left\{ \frac{1}{N}\sum_{n=1}^{N}\left(F(n)-F(n)\right)^2 \right\}^{\frac{1}{2}} \tag{9}$$

Type (8) and type (9), $F(n)$ is the non noise "standard" BAEP signal, $F(n)$ is the estimated signal after extraction, N is the sampling length for each group of signals, and N is 1000 in the experiment, and the corresponding sampling time is 10ms.

In this paper, the DB4 wavelet is used as the basis function of wavelet decomposition, and the decomposition level is 5 layers. Selecting 5 kinds of SNR signals, and 10 sets of data were collected for each signal. The signal extraction results from different kinds of SNR signals were compared between the traditional wavelet analysis method and the wavelet information entropy method. Due to the limited length of the paper, only the extracted signal waveform of when SNR is equal to -2 is shown in figure 4. At the same time, the evaluation indexes of the two methods are calculated, and the numerical value is the average of the 10 sets of data, with the results are shown in Table 1.

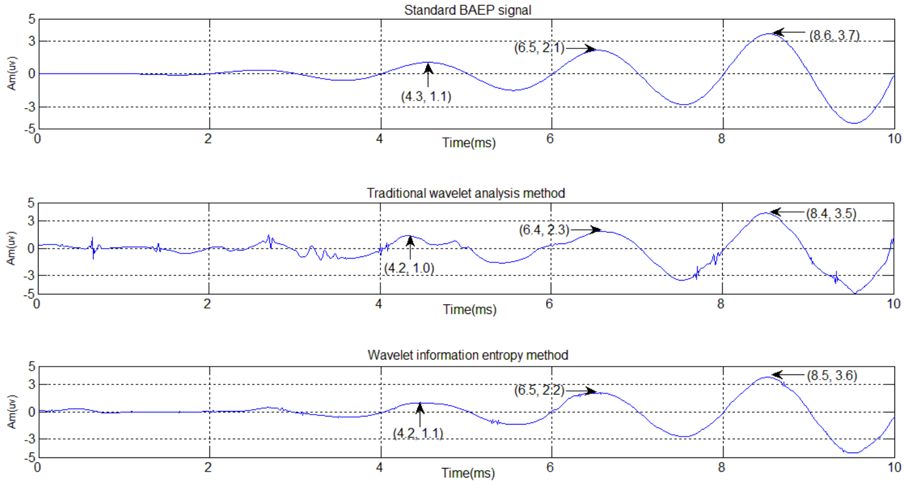

Figure 4. Waveform of the Signal When SNR Is Equal to -2

From Figure 4 we can see that the two methods can achieve the goal of removing background noise under the condition of reduce experiment times (single), the extracted signal waveform is basically consistent with the standard BAEP signal, and the mark I, III, V can easily identified, the latency and amplitude of the three points changed very little and within the limits of experimental error. Compared with the traditional wavelet method, the signal waveform extracted by wavelet information entropy method is more smooth, the three mark points are more prominent, and the effect of impulse noise is more obvious.

Table 1. SNR and RMSE of BAEP Signals from Two Methods

The original signal		Traditional wavelet analysis method		Wavelet information entropy method	
SNR	RMSE	SNR	RMSE	SNR	RMSE
10	0.158	13.25	0.093	28.76	0.067
5	0.410	10.19	0.149	17.84	0.084
2	0.597	9.21	0.163	16.47	0.093
1	0.965	7.50	0.225	12.39	0.146
-2	1.326	5.98	0.309	8.13	0.238

In order to further compare the advantages and disadvantages of the two methods, compare two precision evaluation index in Table 1 can be found that both methods can significantly improve the SNR of signal and reduce the RMSE of signals. The effect of improving the signal-to-noise ratio, the wavelet information entropy method is about 1.7 times higher than that of the traditional wavelet analysis method, the effect when the SNR of original signal equals to 10 is the most obvious, 2.3 times; while in terms of reducing the root-mean-square error the latter is about 1.3 times of the former.

The simulation results show that the wavelet information entropy method to extract the BAEP signal can make up the deficiency of the traditional wavelet analysis method, which can achieve a significant effect.

5. Conclusions

As can be seen from the theoretical analysis and experimental results in the application of the proposed wavelet information entropy method of extracting the brainstem auditory evoked potential signal, inherited the merits of traditional wavelet analysis method, greatly reduce the number of tests, shorten the detection time ,avoid fatigue response, and at the same time, compared with the traditional wavelet analysis method, the wavelet information entropy method extracts the signal waveform more smoother, improving its de-noising effect , and has a better filtering effect on the larger amplitude noise.

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