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Adapted Mother Wavelets for Identification of Epileptiform Complexes in Electroencephalograms

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Introduction

One of the fields of application of the wavelet transform-based signal processing is the analysis of the electroencephalograms (EEG). EEG is the multichannel low-amplitude electrical signal accompanying the functioning of the brain. It can be obtained by recording the voltage differences of distinct locations of a scalp. EEG reflects the functional state of the human brain and it is widely used in clinical practice for diagnosis of brain diseases.

Among the most important applications of EEG processing is its employing in epileptology. In this case EEG can be used for localization in the signal the waveforms of special form (so-called epileptiform patterns). These patterns are often the markers of presence of epileptic focus in the brain. Proper differentiation, surface and time localization of the patterns can give a clinician the information about the stage of the disease, type of epileptogenic focus and its position in the brain volume. The example of the signal with many of such epileptiform patterns is given on the Fig. 1.

Analysis of the EEG signal like presented on Fig. 1 isn't difficult because the epileptiform complexes are prominent and could be founded even visually. But there are cases when in the current EEG are situated rare patterns of interest, or when they have uncommon appearance, distorted form, low amplitude or are shaded by the background activity. In such cases, the important patterns could not be easily founded in the signal and the automated localization of the epileptiform complexes is needed.

As the basis wavelets have compact time support (they are functions of limited time duration), the wavelet coefficients for different values of the translation parameter will correspond to the result of wavelet decomposition of the signal's part in different time instants. Thus the wavelet spectrum preserves the information about the signal's time properties, so temporal evolution and behaviour of signal can be tracked in the wavelet-spectral domain.

Fig. 1. Example of the electroencephalogram of the epileptic brain

Because the results of signal's wavelet decomposition is greatly dependent on the mother wavelet function that is employed, it is assumed that adapting mother wavelet to the signal's waveform of interest will result in larger wavelet coefficients in the time instants where the signal part has the same properties as wavelet function. Using of adapted wavelet function in decomposition and subsequent thresholding of the coefficients for selected scales imparts increased rate of successful detections of the waveforms of interest is proposed.

Thus the purpose of the present work is the consideration of the ways to improve time-localization of epileptiform complexes in EEG by using the adapted mother wavelet function. In the following research the new technique of creating the mother wavelets, which are adjusted to the epileptiform complexes of interest will be presented. The clinical studies verifying the usefulness of the technique for EEG processing are also presented.

The technique of creating adapted mother wavelet functions

The CWT of the continuous signal maps one-dimensional signal $f(t)$ to two-dimensional space of wavelet coefficients $Wf_{\Psi}(a,b)$ and is obtained as

$$Wf_{\Psi}(a,b) \equiv \int_{-\infty}^{\infty} f(t) \cdot \psi_{a,b}^{*}(t)dt, \qquad (1)$$

where asterisk indicates complex conjugate of wavelet function $\psi_{a,b}(t)$ obtained from initial mother function $\Psi(t)$ using the scale parameter a ($a \in \mathbb{R}, a \neq 0$) and shift parameter b

$$\psi_{a,b}(t) \equiv |a|^{-\frac{1}{2}}\Psi\left(\frac{t-b}{a}\right). \qquad (2)$$

The mother wavelet function must satisfy the admissibility condition:

$$C_{\Psi} = \int_{-\infty}^{\infty} \frac{\left|\widehat{\Psi}(\omega)\right|^{2}}{|\omega|} d\omega < \infty, \qquad (3)$$

where $\hat{g}(\omega) = \int_{-\infty}^{\infty} g(t)e^{-i\omega t}dt$ – Fourier transform of the function.

For the arbitrary function to be the mother wavelet it should satisfy such requirements (Daubechies, 2001):

– function $\Psi(t)$ should be substantially decaying at infinity;

– function $\Psi(t)$ should be sufficiently smooth.

The above requirements and can be combined into one: wavelet should have compact support in time and frequency domains. From the admissibility condition (3) follows the requirement for mother wavelet to have zero mean. Thus any technique of creating new mother wavelet functions should give the functions satisfying the requirements given above.

As it can be seen, the mother wavelet function $\Psi(t)$ completely defines the properties of the wavelet set derived with (2). Therefore to use the wavelet spectrum as the basis for localization of waveforms of interest in the signal, the proper choosing of mother wavelet function is necessary – the mother wavelet should be similar to this waveform. If this similarity will be assured, the values of CWT spectral coefficients can be used to localize the waveforms by some thresholding algorithm.

There are plenty techniques for creating adaptive wavelets, that usually require large amount of additional information about signal under consideration and about the waveforms to be found (statistical and spectral description), which is not always available to the researcher. Thus the presently available techniques have severe limitations and the problem of adapting mother wavelet functions to signals of interest is far from final solution.

The studies show that in many real-world applications the information about approximate templates of waveforms to be localized is known to the researcher, at least in the form of a few examples. The case when as such information some examples of the waveforms can be used to further localization in signals under investigation is considered. Such signal waveforms can be obtained a priori using other localization techniques (for example, by modelling or visual analysis). In the EEG processing case template waveform, recorded from different patients can be stored in database for further use.

Let we have N discrete templates of the waveforms from the predefined group L. Group of templates can be the set of predefined representative examples of the epileptiform complexes, belonging to the specific class of disease or to the stage of disease. The waveforms in the group could have especial form for the patient or for the epilepsy type or epileptogenic focus. The only requirement is to use as much as possible similarity of the waveforms, belonging to the particular set.

The samples of waveforms are arranged row-wise to form the matrix W_L with x_{Lik} – k-th sample of the i-th waveform in the group; m – length of the waveform.

For this matrix of templates the matrix of averaged correlations is obtained

$$C_L = \begin{bmatrix} C_{L11} & C_{L12} & \cdots & C_{L1m} \\ C_{L21} & C_{L22} & \cdots & C_{L2m} \\ \vdots & \cdots & \cdots & \vdots \\ C_{Lm1} & C_{Lm2} & \cdots & C_{Lmm} \end{bmatrix}, \qquad (4)$$

where $C_{Lqr} = \frac{1}{m}\sum_{i=1}^{m} x_{Liq}x_{Lir}$, $q,r = \overline{1,m}$.

Matrix C_L is symmetric with real elements, so it is the matrix of self-conjugate linear operator in the m-dimensional Euclidean space. Thus there exists the orthogonal basis of its eigenvectors. The characteristic equation $\det(C_L - \lambda \cdot I) = 0$ can be solved, where I – identity matrix and the spectrum of the matrix (4) can be found, consisting of its m eigenvalues $\{\lambda_{Lm}\}$. Choosing maximum eigenvalue Λ_L and substituting it in the equation $C_L \cdot \eta_L = \Lambda_L \cdot \eta_L$ the main eigenvector η_L of (4) can be obtained.

In the previous works [1] it was revealed that the correlation between any waveform of the initial group L and the main eigenvector of the matrix of averaged correlations is maximal and the time properties of all waveforms from L are retained and reflected in this eigenvector, regarded as time-varying function. In this research the use of this main eigenvector for building the mother wavelet function, adjusted to the set of known waveforms from group L is proposed.

As discrete signals are used, the main eigenvector η_L will be discrete time function: $\eta_L(n) = [\eta_L(1), \eta_L(2), \ldots, \eta_L(m)]$. The function in the following form is proposed to be constructed

$$\Upsilon_L(n) = \begin{cases} \eta_L(n) - \dfrac{1}{m}\displaystyle\sum_{i=1}^{m} \eta_L(i), & n = [1,m], \\ 0. & n = (-\infty, 0] \cup [m+1, \infty). \end{cases} \qquad (5)$$

After consideration the construction (5), it is concluded that function $\Upsilon_L(n)$ has nonzero samples only for the time instants, where the initial main eigenvector has nonzero elements. Thus $\Upsilon_L(n)$ has compact time support. Furthermore, according to Rieman-Lebesgue lemma, the

Fourier transform of the function (5) satisfies the condition: $\widehat{\Upsilon_L}(\omega) \to 0$ while $\omega \to \pm\infty$ because in our case we can write the expression of boundedness as $\sum_{n=1}^{m}|\eta_L(n)| < \infty$. This is held by definition, hence the function (5) has compact support in frequency domain too. In addition, the function has zero mean, so the requirement to mother wavelet to have zero mean is also satisfied. All of this allows to consider the function $\Upsilon_L(n)$ as the wavelet function. Thus the technique of creating the mother wavelet function for the group L of waveforms is obtained by means of using the main eigenvector of the averaged correlations matrix.

Experimental results

In the experiments conducted in this paper the task to localize the epileptiform patterns using continuous wavelet transform was set. The technique proposed above is employed for creation adapted mother wavelet function for epileptiform complex, consisting of the couple of simpler waveforms: sharp wave – slow wave or spike – slow wave.

The clinical studies were carried out in the Department of Functional Diagnostics of Institute of Neurosurgery of Ukraine and in the Laboratory of Diagnostic Devices of the Department of Physical and Biomedical Electronics of National Technical University of Ukraine. Computerized 24-channel EEG recorder Galileo Planet 200 with sampling frequency 256 Hz and the derivation scheme with physical reference was used. One hundred EEG signals where recorded from different subjects with diagnosed epilepsy, of total 3 hours duration. The signals were examined by the experienced doctor and only artefact-free EEG signals were further used in experiments. The amount of physiological artefacts in the EEG under investigation was in agreement with averaged for such signals and satisfied the mandatory requirements for EEG examinations.

Using selected waveforms the matrix of the group was created and the matrix of the averaged correlations (4) was calculated. Then we have computed the main eigenvector of this matrix and created the adapted mother wavelet for the group using (5).

EEG signals were previously visually analysed by the doctor and time positions of all epileptiform complexes were manually determined. High-amplitude prominent epileptiform complexes in the EEG signal were divided into two groups: exact complexes and distorted complexes. The objective of the study was to detect all these waveforms without fail and possibly detect all other complexes, present in the signal (exact low-amplitude, distorted low-amplitude, complex-like artefacts).

The scales a in (2) were selected experimentally, $a = [0.7, 0.8, 0.9, 1.0, 1.1, 1.2, 1.3]$ to assure small-scale length deviations of wavelet functions from the duration of initial mother function. The translation step was chosen to be equal to sampling time of the EEG, b=3.9 ms. After the calculation of wavelet coefficients, we use them to create the supplementary measure of the occurrence of epileptiform complexes in the signal as the sum of the coefficients for all scales a. The value of the sum is the function of translation parameter. The same signals were analysed using the standard 4th order Daubechies mother wavelet function.

As the measure of localization performance quality we chose two parameters proposed in [2], namely the percentages of true positive (TP) and false positive (FP) found complexes. We stopped the experiment as soon as percentage of FP exceeded more than a quarter of TP. The results are given on Fig. 2-3, where the percentages of TP (circles) and FP (squares) are plotted versus the value of the threshold.

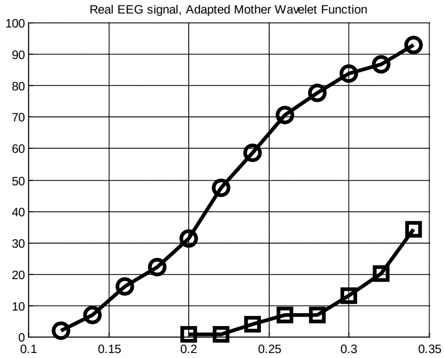

Fig. 2. The rate of true positives (○) and false positives (□) versus the threshold for CWT with adapted mother wavelet function

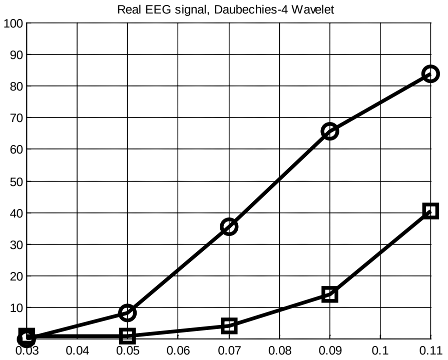

Fig. 3. The rate of true positives (○) and false positives (□) versus the threshold for CWT with 4th order Daubechies wavelet

Discussion

After comparison of Fig. 2-3 it can be observed that all mother wavelets are suitable for epileptiform patterns localization: at the end of the experiment the percentage of TP was 93 % with adapted wavelet, 84 % with 4th order Daubechies wavelet. Such rates are sufficient for clinical purposes.

But when the rate of false positives is considered, it can be observed that 4th order Daubechies wavelet gives finally 40 % of FP while adapted wavelet gives 34 %.

For the purpose of epileptiform complexes detection quality estimation, we should also consider the first appearance of false positive localization. With the 4th order Daubechies wavelet first FP arises while only one TP epileptiform complex is found and with the use of adapted wavelet function the first FP arose while 32 % of epileptiform complexes were already correctly localized.

The use of adapted wavelet function, created by the proposed technique gave the considerable rate of true localizations large enough amount of TP found before first appearance of FP and sufficiently low rate of localization faults simultaneously, which is optimal for the purpose of the study.

Conclusions

The new technique for obtaining the mother wavelet functions using the eigenvectors of averaged covariance matrix of the group of waveforms was presented. This technique is applicable for the cases when there is absence of spectral and statistical information about the waveforms to be localized in the signals. Localization of epileptiform patterns in electroencephalograms using adapted wavelet gave optimal combination of sufficient rate of true positive and acceptable rate of false positive localizations.

Due to the appealing simplicity of the proposed mother function creation's technique this approach should help in other cases of signal processing when the mother wavelet adapted for the group of waveforms is needed.

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The task of constructing adapted mother wavelet function is examined with application to processing the electroencephalogram of epileptic brain. The new technique of creating mother wavelets adapted for the time localization of epileptiform complexes is proposed. The technique is based on the use of main eigenvectors of the matrix of averaged correlations for the predefined class of complexes. The experimental results shown 94 % of true localizations of complexes in real EEG signal. Ill. 3, bibl. 3 (in English; abstracts in English, Russian and Lithuanian).

А. Попов, А. Канайкин, М. Жуков, О. Паничев, О. Бодиловский. Адаптированные материнские вейвлеты для идентификации эпилептиформных комплексов в электроэнцефалограммах // Электроника и электротехника. – Каунас: Технология, 2010. – № 8(104). – С. 89–92.

Рассмотрена задача построения адаптированных материнских вейвлет-функций применительно к обработке электроэнцефалограмм для эпилептологии. Предложен новый метод построения материнских вейвлетов, адаптированных для временной локализации эпилептиформных комплексов, основанный на использовании главного собственного вектора матрицы усредненных корреляций для заданного класса комплексов. В результате экспериментов по обработке реальных сигналов электроэнцефалограмм было получено 94 % верных позитивных детектирований комплексов. Ил. 3, библ. 3 (на английском языке; рефераты на английском, русском и литовском яз.).

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Analizuojami būdai elektroencefalogramoms apdoroti ir atpažinti, panaudojant adaptyviąsias pirmines bangeles. Įrodyta, kad šiuo metodu galima tiksliai atpažinti 94 % gautos informacijos. Il. 3, bibl. 3 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).