A method for analysis of shape variation of visual evoked potentials based on Karhunen-Loeve transform

A. Kybartaitė[1], A. Kriščiukaitis[2], A. Gelžinis[3]

[1] *Laboratory of Ophthalmology, Neuroscience Institute, Lithuanian University of Health Sciences, Lithuania*

[2] *Laboratory of Biophysics and Bioinformatics, Neuroscience Institute, Lithuanian University of Health Sciences, Lithuania*

[3] *Eye Clinics, Hospital of Lithuanian University of Health Sciences, Lithuania*

[1] *E-mail: asta.kybartaite@lsmuni.lt*

Introduction. Visual evoked potentials (VEPs), registered as neuroelectric waveforms, are thought to be a reflection of summed activity of postsynaptic potentials produced when a large number, i.e., thousands or millions of similarly oriented cortical pyramidal neurons fire in synchrony due to a visual stimulus while processing information [1]. According to a hypothesis, VEPs are concurrent with background electrical activity of the brain, reflected as electroencephalogram (EEG) [2], which often exceeds VEPs in amplitude. So, analysis and evaluation of VEPs usually starts with signal pre-processing the aim of which is cancelation of the background EEG component. VEPs appear at the known time points, so averaging of the signal significantly increases deterministic part of the VEPs in relation to background EEG, which has a stochastic origin. Such a common technique is described in numerous publications, e.g., [3]. However, not only parameters of an averaged signal but also dynamics of a signal shape could provide clinically useful information [4]. Multivariate analysis methods show promising results in decomposition or noise cancelation in quasiperiodic signals realizing quantitative evaluation of shape changes [5].

The aim of this work was to elaborate a signal decomposition method for the background EEG cancelation in VEPs recordings and quantitative evaluation of shape changes in them. As a solution, Karhunen-Loeve Transform (KLT), which is closely related to Principle Component Analysis (PCA), was applied. KLT transforms original representation of a signal into space of optimal orthonormal components - eigenvectors of a covariance matrix. Truncated representation of the signal is a linear combination of these new basis functions (eigenvectors). So usually variation in some part of the signal shape is reflected by changes contributed by a certain eigenvector, reflected by its appropriate coefficient. Therefore, coefficients could be considered as quantitative estimates of the signal shape. Such multivariate analysis approach for VEPs analysis is the novelty of the proposed method.

Materials and Methods. A single channel EEG was registered using an active electrode placed on the scalp over the visual cortex at Oz with a reference electrode at Fz according to the International 10/20 system [6]. Four different stimulus types were applied: (1) pattern-reversal checkerboard with large 1 degree checks, (2) pattern-reversal checkerboard with small 0.25 degree checks, (3) dartboard pattern, and (4) onset pattern. Four different assemblies of data were obtained.

Signals were registered as 512 ms intervals after each visual stimulus. It is expected that VEPs will appear about in the middle of this interval as periodic, deterministic component. The background EEG activity, being a signal with stochastic origin, will be considered as a zero mean noise. A truncated expansion of such the signal using only the first basis functions obtained by means of KLT will represent only VEPs while the rest of the basis functions will represent the background EEG.

Samples of signal intervals formed two-dimensional array:

$$\mathbf{X} = \begin{matrix} x_{1,1} & x_{1,2} & \dots & x_{1,n} \\ x_{2,1} & x_{2,1} & \dots & x_{2,n} \\ \dots & \dots & x_{i,j} & \dots \\ x_{p,1} & x_{p,2} & \dots & x_{p,n} \end{matrix} \tag{1}$$

where $x_{i,j}$ is the i^{th} sample of the j^{th} interval. Every vector x_i representing ordinary interval of the signal is then represented by the linear combination of the basis functions φ_k multiplied by coefficients $w_{i,k}$:

$$\mathbf{X}_i = \sum_{k=1}^{p} w_{i,k}\varphi_k \tag{2}$$

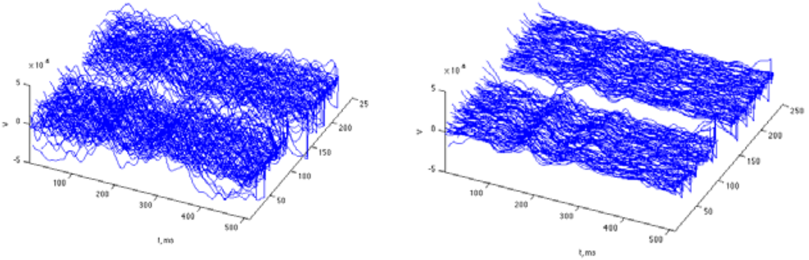
We calculated the basis functions as eigenvectors of the covariance matrix R_x:

$$\mathbf{R}_x = E\left[\mathbf{X} \times \mathbf{X}^T\right] \tag{3}$$

Calculation of the covariance matrix was performed by using MatLab^{TM} function "COV" which gave us a mathematical expectation E after removing the mean from each column. Variation or trend of coefficients $w_{i,k}$ represents changes of the shape of evaluated VEPs. To test this idea we analysed a synthetic signal consisting of the real registered background EEG with added VEPs changing in amplitude. As VEP we used the averaged real signal multiplied by a coefficient alternating in neighbouring intervals and having a certain trend.

Results. An example of raw signal intervals eventually containing VEPs is presented in Fig. 1a. The truncated expansion of these signals using the first four basis functions is presented in Fig. 1b. The shape of the signals in Fig. 1b, already allows visual evaluation of VEPs shape and amplitude. The amplitude of VEPs evoked by the checkerboard with large checks is bigger than evoked by the dartboard. Also it is obvious that waveforms became cleaner, less noisy and is visible higher degree of consistency in detecting at least the P100 wave in both assemblies. This wave is used by clinicians to check the integrity of the visual pathways from the retina to the occipital cortex part of the brain.

Values of the coefficients of the first four basis functions are presented in Fig. 2. Variation of coefficients reflects variation in VEPs shape.



a b

Fig. 1. a: Raw signal intervals containing VEPs: the first assembly evoked using checkerboard with large 1 degree checks; the second assembly is evoked using dartboard pattern. b: The same signal intervals after a truncated expansion using the first four eigenvectors as the basis functions.

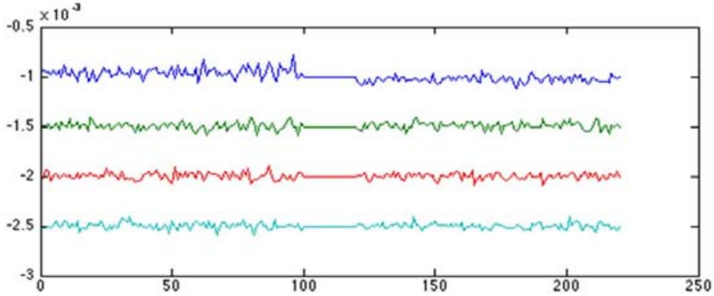


Fig. 2. Values of the first four coefficients of the basis functions (eigenvectors) used for the truncated expansion of signal intervals presented in Fig. 1 b. Axis x: signal interval number (of two assemblies); y: coefficient values.

Example of the synthetic signal is given in Fig. 3a. The coefficients of the first four basis functions (eigenvectors) used for the truncated expansion of the signal intervals are shown in Fig. 3b. These coefficients reflect alternations and trend in the amplitude of VEP. We synthesized this trivial example for presenting more clearly the principle of the proposed method.

Discussion. The truncated expansion of post stimulus EEG recording intervals reveals VEPs and allows further quantitative evaluation of their shape and amplitude on beat-to-beat basis enabling evaluation of dynamics of VEPs for diagnostics. We demonstrated that the coefficients of the basis functions were able to reflect VEP changes in the simulated recording. However, testing the idea on clinical recordings remains for further investigations. The basis functions of the truncated representation by means of KLT were calculated for each assembly of recording intervals separately. Usage of generalized basis functions could be useful for comparison of data from several recordings. However differences in shape and duration of VEPs between recordings were

too big and the first basis functions were reflecting only differences between the recordings but not the dynamics within the recording. Further investigations in this area also remain in future plans. The effects of different stimuli on VEPs components were studied by various authors, thus it is not only the stimulation type that affects the response strength, i.e., amplitude, latency of VEPs, the receptive field organization plays an important role [7]. Future work also involves analysis of different stimuli on VEPs.

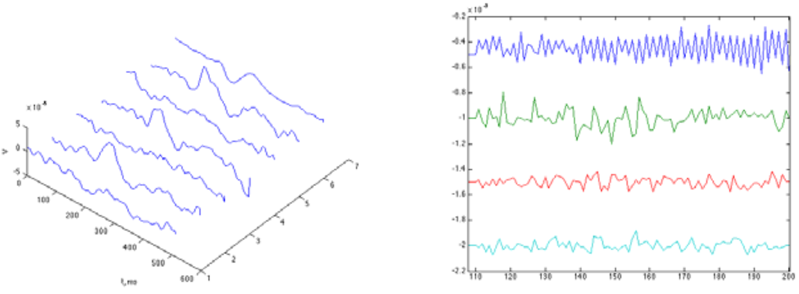


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Fig. 3. a: Intervals of the synthetic signal containing variation of VEPs in amplitude. b: The coefficients of the first four basis functions used for the truncated expansion of signal intervals.

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However, as the **conclusion** we can state that our results could be considered as promising taking into account that the truncated expansion of signal intervals eventually containing VEPs can significantly reduce background EEG component making possible further signal analysis on beat-to-beat basis, what is a new approach in this field.

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Visual evoked potentials (VEPs) are thought to be a reflection of a summed activity of postsynaptic potentials that are concurrent with a background electrical activity of the brain, reflected as electroencephalogram (EEG). Signal averaging is a common method for background EEG cancellation; however, not only parameters of the averaged signal but also dynamics of a signal shape could provide clinically useful information. We applied Karhunen-Loeve Transform for the background EEG cancelation in VEPs recordings and quantitative evaluation of shape changes in them. The obtained results could be considered as promising for reducing the background EEG component and making possible further signal analysis on beat-to-beat basis.