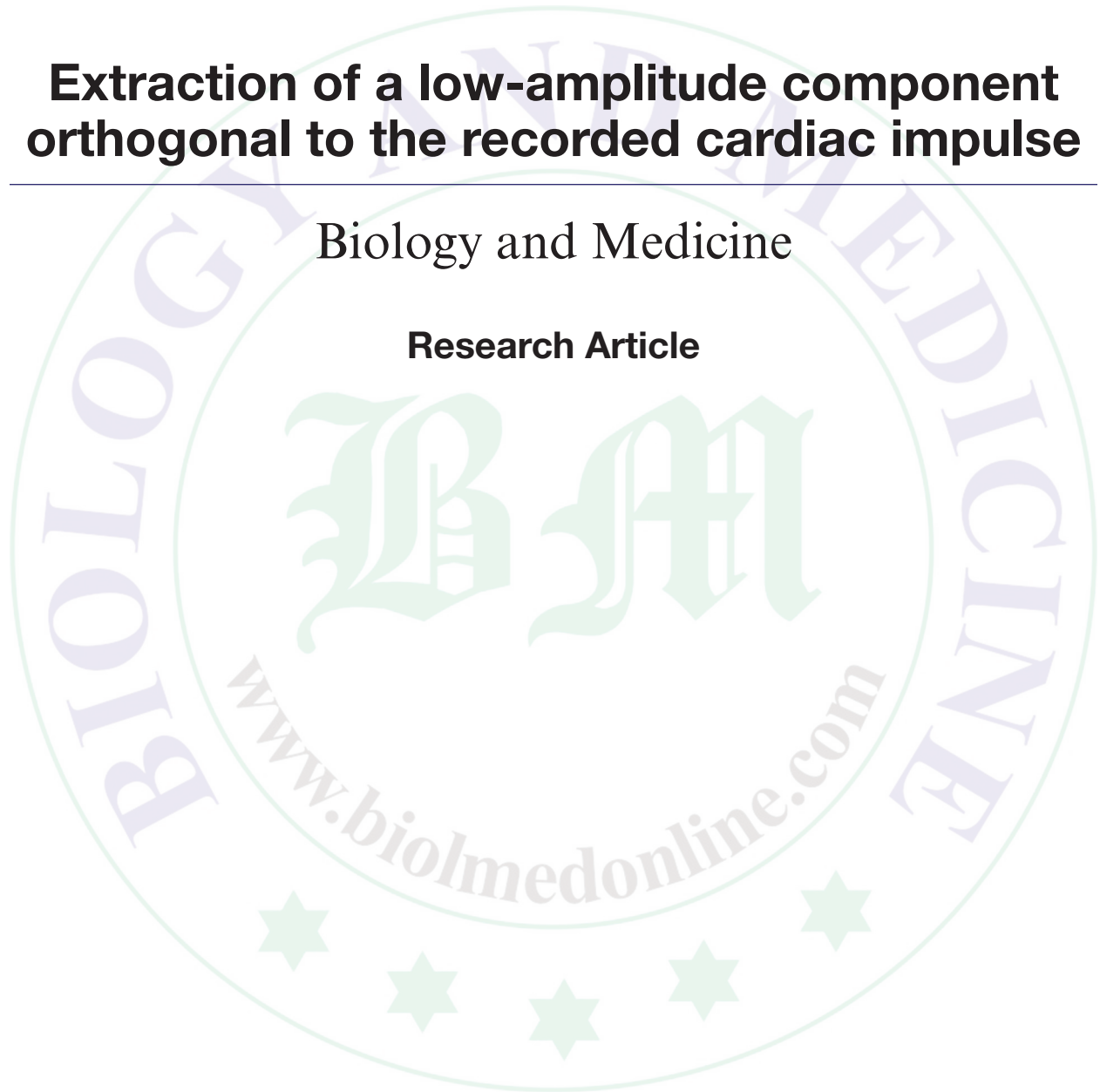


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Extraction of a low-amplitude component orthogonal to the recorded cardiac impulse

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Abstract

The problem of the cardiac signal extraction from a low-amplitude high-frequency component invisible on conventional electrocardiography (ECG) is considered. For this purpose, the original ECG model, which includes a high-amplitude component, a low-amplitude component, and random noise, is used. We have proposed the method to extract the orthogonal high-amplitude and low-amplitude components from the recorded cardiac pulse sequence in the form of the first two components of the matrix singular decomposition composed of a set of cardiac pulses. In contrast to Simson's method, the proposed method does not assume cardiac signal averaging over a large (about several hundred cardiac pulses) sequence as well as the averaged signal filtering. The low-amplitude component is extracted from a short (about 10 s) ECG recording. We have used a mathematical model to examine the stability of the proposed method to the correlation of the high-amplitude and low-amplitude components of the cardiac signal as well as to the influence of random noise. It is shown that the high-amplitude component is steadily extracted in the entire range of the change in noise level and correlation of the regular components of the cardiac signal. At the same time, the low-amplitude component is significantly distorted when the pair correlation coefficient with the high-amplitude component is greater than 0.2 or noise level is greater than 0.4.

Keywords: Pulse sequence; random noise; low-amplitude component; reference signal; regular noise; electrocardiography.

Introduction

In recent years, high-resolution electrocardiography (ECG) has been increasingly developed. This is a diagnostic technique to record low-amplitude high-frequency signals invisible for conventional ECG by means of computer processing of the ECG signal.

Currently, the detection of low-amplitude components of the cardio-signal is extensively used. For this purpose, we have developed a special technique for ECG recording which provides signal filtering, its amplification by tens of thousands of times and obtaining useful information by the averaging method [1]. However, the problem to be solved is the development of methods to reliably detect as weak ECG components as possible in noninvasive examination [2].

Previously [3], we proposed a method for extracting the reference signal by the recorded sequence of cardiac impulses. A similar procedure is promising to be applied to extract

low-amplitude components, such as ventricular late potentials (VLP) and atrial late potentials (ALP) from the recorded ECG without complicated procedures of signal amplification by averaging large (100-400) sequences of cardiac impulses. To describe the low-amplitude components we have chosen the model of cardiac signals similar to that described in [4] in the form,

$$x(t) = a_1 \cdot S_{HP}(t) + a_2 \cdot S_{LP}(t) + a_3 \cdot \eta(t)$$

where $S_{HP}(t)$ is a high-amplitude signal component, $S_{LP}(t)$ is a low-amplitude signal component, $\eta(t)$ is random noise, a_1 , a_2 , a_3 are random coefficients determining the contribution of each component to the given cardiac impulse.

The model is based on the assumption that regular low-amplitude components caused by different pathologies impeding the process of changing the electric potential of the pericardium, such as VLP and ALP, are present in the

recorded sequence of cardiac impulses along with the random noise due to various reasons (including electromyographic signals, the recording equipment noise, etc.). Moreover, the contributions of these components in different cardiac impulses are different.

Methods

In the present study, we investigated the possibility of extracting not only a high-amplitude component of the cardiac impulse (reference signal) but also a low-amplitude component, in particular, the parts of the component orthogonal to the extracted referent signal. For this purpose,

the vector of the high-amplitude component of the signal presented in Figure 1 and the vector of the low-amplitude component shown in Figure 2 are synthesized. The pair correlation coefficient of the signal and noise is (-0.035) , i.e., the vectors of these signals are virtually orthogonal. The vector of the random noise is formed as a sequence of pseudorandom numbers normally distributed with a mathematical expectation of 0 and variance of 0.3. Figure 3 shows the graph of one implementation of the random noise. The length of each vector is 1800 counts, and the predicted frequency of the sampling rate is 1828.154 Hz. The norms of the dominant signal, regular and random noise are 4.77×10^3 , 3.63×10^2 , and 12.35, respectively.

Figure 1: Graph of the high-amplitude component.

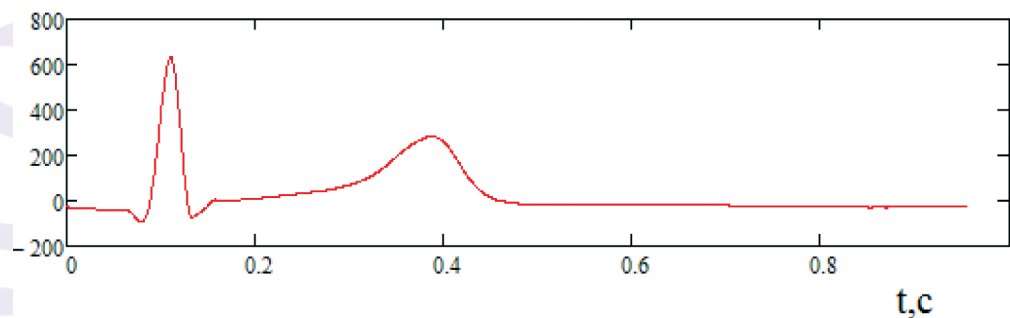


Figure 2: Graph of the low-amplitude component.

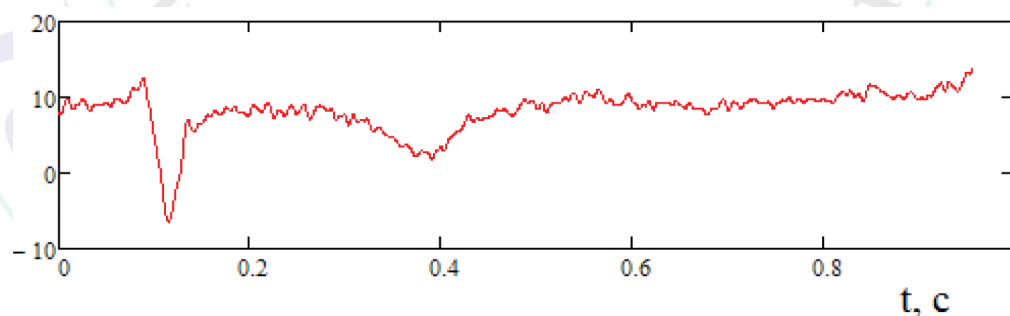
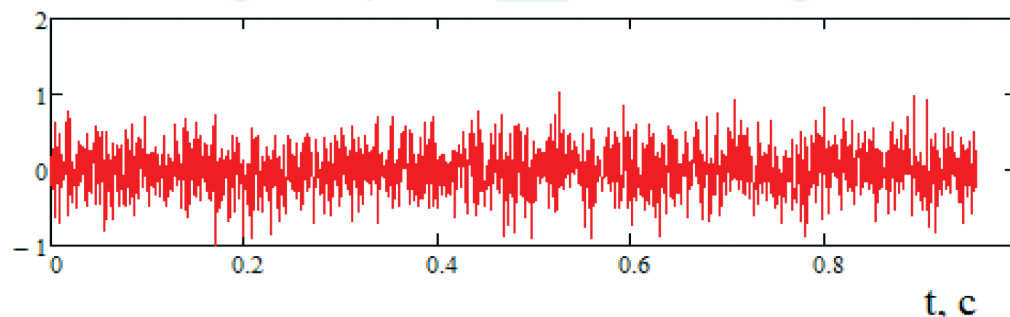


Figure 3: Graph of the random noise.



Results and Discussion

Ten model cardiac impulses are obtained from these vectors by weighted summation. The weight factors used in the weighted summation are shown in Table 1.

The obtained model cardiac impulses as column vectors are used to make a matrix which

Table 1: The coefficients for the components of a mixed signal.

A1	A2	A3
0.982	0.997	1.023
1.001	0.99	1.024
0.99	1.005	0.997
0.996	0.998	0.99
1.011	1.004	1.008
0.994	1.011	0.992
0.995	1.011	1.028
1.015	1.006	0.998
0.997	1.013	1.01
0.991	0.978	1

is subjected to singular decomposition [5,6]. In the absence of the random noise, as a result of the decomposition of the vector-cardiosignal matrix by singular numbers, the first left singular vector with a constant factor coincides with the initial high-amplitude component, and the second left singular vector coincides with the vector component of the low-amplitude component. Figures 4 and 5 show these vectors.

A goodness-of-fit χ^2 [7,8] is calculated as a proximity measure of the model signal vectors and the corresponding singular vectors by the

formula $\chi^2 = \frac{\|a - b\|_2^2}{\|a\|_2^2}$, where $\|a\|_2^2$ is the square of

the Euclidean norm of a vector, a is a model vector, and b is a singular vector. The calculated values of a goodness-of-fit are 0.0057 and 0.0022, respectively.

A number of the low-amplitude component vectors with different pair correlation coefficients with a dominant signal [9-11] are plotted to assess the correlation effect of the initial

Figure 4: Graph of the high-amplitude initial component (red) and a normalized first left singular vector (blue).

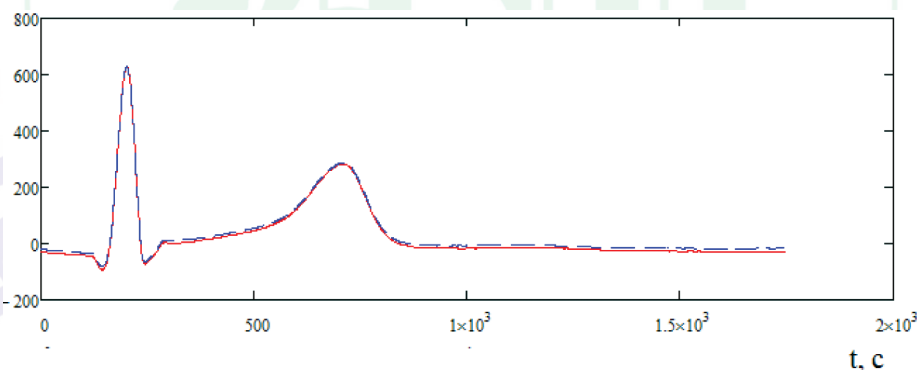


Figure 5: Graph of the low-amplitude component (red) and a normalized second left singular vector (blue).

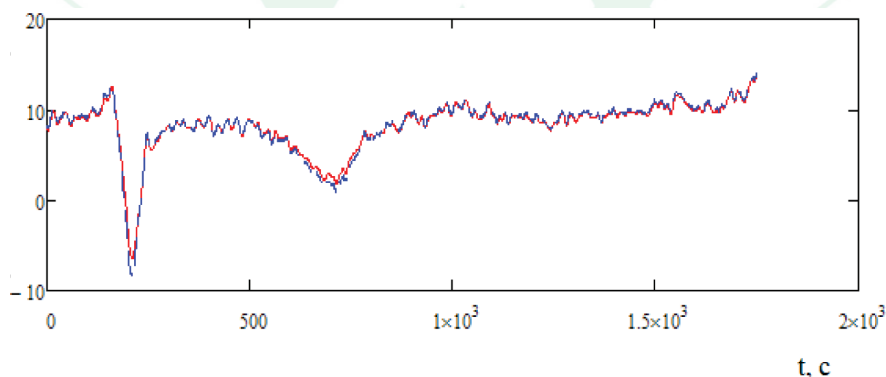


Table 2: Pair correlation coefficients of the high-amplitude and low-amplitude components and the calculated values of the goodness-of-fit for the vector of the low-amplitude component and normalized second left singular vector, and the values of the goodness-of-fit for the vector of the high-amplitude component and normalized first left singular vector.

Pair correlation coefficient	-0.035	0.031	0.097	0.162	0.228	0.294	0.359
Goodness-of-fit value χ^2 for a low-amplitude component	0.0022	0.013	0.033	0.061	0.091	0.139	0.185
Goodness-of-fit value χ^2 for a high-amplitude component	0.0057	0.0058	0.0058	0.0057	0.0057	0.0056	0.0057

Table 3: The goodness-of-fit values for the vector of the low-amplitude component and normalized second left singular vector, and the values of the goodness-of-fit for the vector of the high-amplitude component and normalized first left singular vector at different noise levels.

Noise factor	0.01	0.05	0.1	0.2	0.3	0.4	0.5
Goodness-of-fit value χ^2 for a low-amplitude component	0.0022	0.015	0.021	0.046	0.088	0.147	0.223
Goodness-of-fit value χ^2 for a high-amplitude component	0.0057	0.0058	0.0058	0.0058	0.0058	0.0058	0.0058

high-amplitude and low-amplitude components on the possibility to extract them using the considered procedure. Table 2 shows the pair correlation coefficients for the high-amplitude and low-amplitude components, a goodness-of-fit for the vector of the low-amplitude component and normalized second left singular vector, and the goodness-of-fit for the vector of the high-amplitude component and normalized first left singular vector.

As can be seen from Table 2, the increase in the correlation of the high-amplitude and low-amplitude components does not affect the proximity measure of the high-amplitude component and normalized first left singular vector. At the same time, the goodness-of-fit for the low-amplitude component and second left singular vector increases by nearly a factor of 90 from 0.0022 to 0.185.

The goodness-of-fit values for the low-amplitude component and first normalized singular vector, and the goodness-of-fit values for the low-amplitude component and second normalized singular vector at different levels of random noise are calculated in order to assess the effect of random noise on the proximity measure of the high-amplitude and low-amplitude components and the corresponding singular vectors. A reduction factor is used as a measure of random noise, which is multiplied by the noise factor in a mixed signal. The obtained results are presented in Table 3.

Thus, the obtained results prove the possibility in principle to assess the low-amplitude

component of the cardiac signal as the second left singular vector obtained under singular decomposition of the matrix composed of a set of the recorded cardiac signals as columns of the matrix.

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