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# Estimation of errors due to errors in the detection of reference points of the arterial blood pulsation signal

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## Abstract

The issues of detection of reference points of the arterial blood pulsation signal under the influence of physical and physiological artifacts are considered. Comparison of schemes for detecting the reference point of the arterial blood pulsation signal is carried out. As a criterion for the effectiveness of the scheme for detecting reference points of the arterial blood pulsation signal, the methodological error in determining the temporary position of the reference point from the true value was chosen. It has been shown that among the parametric means for detecting the reference point of the arterial blood pulsation signal, the most effective is the amplitude-time detector based on synchronous processing of ECG signals and arterial blood pulsation.

**Keywords:** Arterial blood pulsation; Reference point; Methodological error of estimation; Detection circuit; Circuit efficiency

## 1. Introduction

Detection and subsequent processing of the signal of arterial blood pulsation is widely used in instrumental systems of cardiological diagnostics for counting the heart rate, studying hemodynamic processes in the blood arteries.

When processing the signal of arterial blood pulsation, it is very important to detect a pulse wave, the main characteristic point of which is the systolic maximum. The correctness of detection and the subsequent accuracy of measuring the reference point of the arterial blood pulsation signal are decisive in assessing the error in determining diagnostic indicators, such as heart rate and blood hemoglobin saturation with oxygen.

The issue of minimizing errors caused by errors in detecting the reference points of the arterial blood pulsation signal remains quite important in cardiac diagnostics.

The main requirement for the means of detecting reference points of the arterial blood pulsation signal is the possibility of evaluating their more efficient operation under the influence of interference and strong variability of the signal shape [1]. The role of the reference points of the arterial pulsation signal, the most distinguishable against the background of interference and noise, can be assessed for the systolic maximum of the signal, the minimum of the arterial pulsation signal, and the maximum of the signal of the first derivative [2].

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## 2. Material and methods

When recording arterial blood pulsation signals using sphygmographic or plethysmographic sensors, interference of a physical and physiological nature is observed. Physical interference occurs in the amplifying path of the arterial blood pulsation signal registration systems, the reference signal as a result of the influence of external electromagnetic fields, created mainly by the electrical power supply network.

Physiological hindrances can be divided into two groups: hindrances created by human breathing, and hindrances created by human movement. The patient's respiration, present in the signal of arterial blood pulsation, distorts the isoline and shape of the biosignal. Motor movements are random in nature and they lead to the greatest distortions of the biosignal. Nutrition.

When processing the arterial blood pulsation signal against the background of the presence of motor movements, a number of difficulties arise, consisting in the fact that the nature of the appearance of motor movements is random, and their frequency components overlap with the main frequency band of the arterial blood pulsation signal [3]. .

The arterial blood pulsation signal generates an output pulse signal, the position of the front of which corresponds to the position of the reference point in time. The whole process of detection of reference points is often preceded by their selection against the background of interference and noise. The arterial pulsation signal reference point detector includes a serially connected pre-processing unit and a threshold detector.

The initial processing of the arterial blood pulsation biosignal includes a digital filtering stage to eliminate noise and interference, as well as a set of amplitude-time converters of the original biosignal into a form most suitable for subsequent analysis by a threshold device. When pre-processing a biosignal, arterial blood pulsation, filtering methods in the time domain, frequency filtering methods are often used; methods based on the analysis of the first derivative, as well as non-linear transformations

Sometimes methods based on correlation processing are used, wavelet transformation and the use of neural networks are also applicable.

Threshold devices extract reference points of the original biosignal from the processed signal. Additive threshold detectors have become widespread, in which the absolute value of the threshold depends on the amplitude of the input signal, due to which adaptation to the non-stationary nature of the arterial pulsation signal occurs.

There are methods for detecting a reference point, using a sliding window of a fixed duration, during which the detection of a reference point occurs using a threshold circuit, while the threshold value is usually set as a fraction of the maximum signal value in this window. Also, additional algorithms for the operation of threshold devices, schemes for detecting reference points of the arterial pulsation signal, using information about the frequency characteristics of the heart rhythm, for example, the half-cycle of contractility of the heart muscle, are used.

One of the possible ways to study the methods and means of detecting the reference point of the arterial pulsation signal is to model the detection processes in the presence of disturbing influences. To study the means of detection, reference points of the arterial blood pulsation signal, signals obtained on the basis of a mathematical model of hemodynamic processes of pulse wave propagation along the arterial bed are used [4].

In addition to model signals of arterial blood pulsation, it is necessary to create models of interference signals present during registration and processing of biosignals in practical conditions. Interferences of an electrical nature arising from the influence of external electromagnetic fields, as well as interferences of physiological origin due to the patient's breathing, may differ in harmonic functions.

To simulate the influence of a physiological origin, due to the movement of the patient, it is proposed to use a harmonic signal with a fundamental frequency of 4 Hz, a smoothed Hamming window with a duration of 10 s, which makes it possible to simulate transient processes that occur in the amplifying cycle during sharp human movements during the registration of biosignals. Detection of the temporary position, the reference point of the arterial blood pulsation signal, is carried out with some error due to signal distortion by interference and noise.

As one of the criteria for evaluating the effectiveness of the scheme, detecting the reference points of the arterial blood pulsation signal, the methodological error in determining the temporary position of the reference point from the true value can be chosen. To estimate the error in determining the time position of the reference point, the quantile characteristics of the errors were used, at which the value of the errors with a given confidence probability P is within the uncertainty interval $\pm\Delta_p$.

The determination error was considered at a confidence level P = 0.9, since only in this case for a wide class of the most common probability distribution laws does it have an unambiguous correlation with the standard deviation, regardless of the type of distribution law. At P=0.9, the absolute error is defined as [5]:

$$\Delta_u = 1.6 \cdot \sigma_u$$

Where $\Delta_u$ is the methodological error in measuring the duration of interpulse intervals; $\sigma_u$ is the standard deviation of the duration of interpulse intervals from the true value, defined as

$$\sigma u = \sqrt{\frac{\sum_{i=1}^{N}\left[t_{op}^{1}(i) - t_{op}(i)\right]^2}{N}}$$

Where $t_{op}$ (i) - the true value of the time position of the reference point of the signal of the arterial blood pulsation; $t_{op}^1$ (i) - the measured value of the time position of the reference point of the arterial blood pulsation signal; N is the total number of reference points of the arterial blood pulsation signal.

The well-known schemes for detecting the reference points of the arterial blood pulsation signal include a band-pass filter, the task of which is to isolate the useful signal against the background of interference and noise. In the tasks of recording and processing arterial blood pulsation signals, a band-pass filter is necessary to minimize high-frequency interference caused by the influence of the electrical network on the amplifying path and low-frequency interference of a physiological nature caused by the influence of movement on the shape of the recorded signal.

The criterion for the effectiveness of the applied band-pass filter can be the ratio of the amplitudes of the signal and noise at the filter output. As digital filters for pre-processing of arterial blood pulsation signals, it is most expedient to use the Butterworth filter, the advantages of which include the most flat frequency response in the passband and low requirements for computing power, which makes it possible to develop a high-order filter to ensure sufficient steepness of the spectral response [6].

When determining the value of the lower and upper cutoff frequencies of the bandpass filter, one should consider an additive signal consisting of a model signal of arterial blood pulsation and interference signals. In this case, changes in the amplitudes of the signal and noise are evaluated when changing the parameters of the band-pass filter. To quantify the degree of signal or interference filtering, the filtering coefficient is used,which Defined as

$$K_f = \frac{A^1}{A},$$

Where $A^1$ is the amplitude of the signal or noise at the output of the band pass filter; A is the amplitude of the signal or noise at the input of the band pass filter.

## 3. Results and discussion

The dependences of the change in the value of the filtering coefficient of the signal, and the noise on the value of the lower and upper cutoff frequencies of the band-pass filter, respectively, are studied for different filter orders.

The dependences obtained show that an increase in the lower cutoff frequency of the bandpass filter leads, on the one hand, to a decrease in the signal amplitude, and on the other hand, to a more significant decrease in the amplitude of the interference caused by human breathing during recording of biosignals. An excessive increase in the lower cutoff frequency of the bandpass filter can lead to distortions in the waveform of the arterial blood pulsation.

An increase in the upper cutoff frequency of the bandpass filter leads to a significant decrease in the amplitude of electromagnetic interference caused by the influence of the electrical power supply on the amplifying path of the signal recording unit. Thus, based on the analysis of the obtained dependences, 0.5 Hz should be chosen as the value of the lower cutoff frequency of the band-pass filter, and 15 Hz as the upper cutoff frequency.

With this filtering frequency band, there is a significant attenuation of the present interference (at least 45 dB attenuation for interference from the electrical power supply and at least 32 dB attenuation of respiratory interference) and a slight attenuation of the arterial blood pulsation signal (no more than 1 dB). The efficiency of detecting the reference point of the arterial blood pulsation signal is associated with various options for constructing detection schemes.

- RR is a detector based on the application of the first derivative operator [2]. At the preprocessing stage, the first derivative operator, defined as

$$y(n)=1/8\,[2x(n)+x(n-1)-x(n-3)-2xc(n-4)],$$

Wherex (n) is the original signal of arterial blood pulsation; y(n) is the output signal.

Further, the samples of the received signal y(n) are squared. As an algorithm for searching for maxima, a threshold method with an adaptive threshold is used, the value of which depends on the amplitude of the two previous successfully detected peaks as follows

$$L_{ev}(k) = \frac{A(k+1) + A(k)}{5}$$

WhereA (k), A (k+1) are the amplitudes of two neighboring successfully detected peaks, $L_{ev}$ (k) is an adaptive threshold.

If at a given threshold value no peak was detected within two seconds, then the threshold value will decrease exponentially to such a value when at least one peak is detected in this area.

- PF is a detector based on frequency filtering [7]. At the same time, at the pre-processing stage, the initial biosignal passes through an 8th order Butterworth bandpass filter with a bandwidth of 0.7….10 Hz.

The reference point is detected using the threshold method as the maximum output signal of the band pass filter in a 3-point pattern. The threshold value is defined as the 70th percentile of signal selection in a sliding window of 10 s duration.

- FSS - a detector based on the application of a moving average filter. At the pre-processing stage, the original signal of arterial blood pulsation passes through a moving average filter

$$y(n) = \frac{1}{N}\sum_{J=1}^{v} x(n-j),$$

Wherex (n) is the input signal; N is the width of the sliding window; y (n) - output signal,j - pulse signal number

Applying a moving average filter results in smoothing of the original signal and is commonly used to eliminate quantization errors and to eliminate high frequency noise in the signal. The properties of such filters are completely determined by the window width N.

Known are the results of studying the accuracy of detecting systolic maxima, the signal of arterial blood pulsation, depending on the window width N. It was shown that the maximum efficiency is achieved with a window width equal to ¼ of the sampling frequency [8]. With such a window width, the reference point of the arterial blood pulsation signal corresponds to the maximum output signal of the moving average filter, which is determined by the 3-point scheme

$$Max= x(k):x(k) > x(k+1) \,\&< x(k) > x(k-1).$$

- ATD - amplitude-time detector of the reference point of the arterial blood pulsation signal.

To ensure effective detection of the reference point, the signal of arterial blood pulsation, an amplitude-time detection scheme is proposed. At the stage of preliminary processing of the signal of arterial blood pulsation, the operation of differentiation and nonlinear transformation of the signal is applied.

In this amplitude-time scheme for detecting the reference point of the arterial blood pulsation signal, the image is the maximum of the first derivative of the original signal of the arterial blood pulsation and the ECG signal based on the use of a priori information about the position of the reference point of the arterial pulsation signal relative to the position of the corresponding R-wave of the ECG signal [9, 10].

At the first stage, the differentiation operator is applied to the original signal of arterial blood pulsation

$$P(n) = \frac{1}{\Delta_d}\left[P_{pd}(n-1) - P_{pd}(n)\right],$$

Where n is the signal sample number; $\Delta_d$ - signal sampling interval; $P_{pd}$ (n) – initial signal of arterial blood pulsation.

Further, the signal obtained after differentiation is raised to the third power, then samples with a negative amplitude value are removed from the signal. The output signal after passing through all stages of pre-processing enters the input of the reference point detection circuit, which consists of a search interval formation unit, a reference point of the arterial blood pulsation signal, and a maximum detector.

The reference point of the arterial blood pulsation signal is detected at a fixed time interval from the position of the corresponding R wave: (TR+100ms…..TR+450ms), where $t_r$ is the time position of the R wave. The duration of the search interval for the reference point, the arterial blood pulsation signal is determined on the basis of a priori physiological information about the position of the R-wave of the ECG signal and the reference point of the arterial blood pulsation [11].

The maximum detector determines the time position, the maximum of the first derivative of the arterial blood pulsation signal in the search time interval, subject to the following conditions

$$P(n)>P(n+1);\ P(n)>P(n-1)$$

There are many different algorithms for detecting the R-wave of an ECG signal based on the use of the first and second derivatives, digital filtering methods, and the use of wavelet transforms, matched filters and neural networks. One of the most effective detectors of the R-wave of the ECG signal is the Pan-Tompkins algorithm; moreover, most modern detectors are, in fact, modified versions of this detector.

In order to ensure noise-immune detection of the R-wave of the ECG-signal, this method uses the method of detecting the R-wave of the ECG-signal based on one of the variations of the Pan-Tompkins algorithm, which includes the stages of band-pass filtering, calculating the first derivative, squaring and subsequent signal smoothing using a moving average filter.

Let us compare the efficiency of the described detectors of the reference point of the arterial blood pulsation signal on model signals under the action of physiological (respiratory) interference of various intensity.

The criterion for evaluating the effectiveness of detecting the reference point of the arterial blood pulsation signal in the presence of respiratory interference can be the amplitude ratio coefficient

$$K_a = 20lg\frac{A}{A_2}$$

Where $K_a$ is the amplitude ratio coefficient characterizing the ratio of the amplitudes of the signal and the respiratory noise, expressed in decibels (dB),

$A_2$ - normalized noise signal amplitude $n_2$ (t),

A is the normalized amplitude of the model signal of arterial pulsation.

We investigate the influence of the error in determining the temporal position of the reference point of detection in the case of preliminary processing of the biosignal by a bandpass filter. Band pass filter 0.5……15Hz; filter type - 12 order Butterworth filter. The analysis of the dependences obtained allows us to conclude that the use of band-pass filtering at the preliminary stage of biosignal processing leads to a decrease in the error in determining the time position of the reference point of the arterial blood pulsation signal for all detectors.

At the same time, the smallest error is still achieved when using the algorithm, detecting the reference point of the arterial blood pulsation signal based on synchronous processing of ECG signals and arterial blood pulsation. The effectiveness of schemes for detecting the reference point of the signal, arterial blood pulsation under the conditions of the simultaneous presence of motor artifacts and respiratory interference in the initial biosignal has been studied. An additive signal consisting of a respiratory interference signal and a respiratory artifact signal was used to simulate the interference signal.

## 4. Conclusion

The obtained dependences show that the presence of motion artifacts during the registration of biosignals leads to a significant increase in the error in determining the time position of the reference point. The detection scheme based on the use of the first derivative operatorand the used amplitude-time detector based on synchronous processing of ECG signals and arterial blood pulsation have the highest noise immunity to this type of interference.

Consequently, among the parametric means for detecting the reference point of the arterial blood pulsation signal, the most effective is the amplitude-time detector based on synchronous processing of ECG signals and arterial blood pulsation, which has the highest efficiency compared to other considered detection tools.

## Compliance with ethical standards

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Authors do not have any competing interest.

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