A new algorithm for processing the absorption and scattering signals of laser radiation on a blood vessel and human tissues

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Abstract. The article describes a new algorithm for processing the pulse wave, which is formed from the registered signals of absorption and scattering of laser radiation on a blood vessel or vein and human tissues. A new method of tuning the optical part of the pulse oximeter is proposed to increase the reliability of the rapid diagnosis results of the human condition. Experimental data on studies of the health status of various people are presented.

1. Introduction
One of the most popular methods for the rapid diagnosis of human health are non-contact measurements that do not make irreversible (albeit temporary) changes in the physical structure and chemical composition of tissues [1-7]. Many of such methods are associated with the use of laser radiation or the phenomenon of nuclear magnetic resonance (NMR) [6-14].

Instruments which are based on the NMR phenomenon (tomographs, relaxometers, etc.) are quite expensive, have great weight and require special operating conditions [4, 6, 7, 15-19]. This limits the ability of a person to use them to control his/her health, for example, several times a day. Therefore, for a personal control of health condition in humans, transmission pulse oximetry, in which blood is used as a source of information about the state of human health, has proved to be the most demanded [20-25].

Numerous blood tests have shown that there is a huge amount of information in blood. The analysis of this data volume can provide information about the condition of many human organs [21, 24-26]. But this task is quite difficult. When solving it, as shown by the results of numerous studies, it is required to consider many features of pulse measurement and to look for new methods to increase the reliability of the results. One of such solutions is proposed in our work.

2. Features of the pulse wave image formation and the method of reducing the influence of artifacts on its shape
The principle of operation of the pulse oximeter is quite simple. The photodetector registers the signals of absorption and scattering of laser radiation on the blood vessel and tissues. With the help of these signals, the oxygen content in the blood is measured. The pulse shape is constructed from the recorded image from scattered and absorbed laser radiation. After processing the pulse wave is determined by
the human pulse. In addition, methods, based on the use of absorption signals, have been developed to determine the blood sugar level, etc. It should also be noted that all methods using low-power laser radiation have a simple and painless measurement procedure.

Despite the large number of developed models of sensors with various photodetectors with high sensitivity [3, 27] for the pulse oximeter and methods for processing the information obtained, which is contained in the pulse wave, some difficulties arise in the diagnosis of the human condition. In most cases, they are associated with the appearance of artifacts in the recorded pulse wave image. In papers [3, 25], the main of them were considered in detail and several solutions were proposed to reduce their influence on the measurement results.

However, as shown by our research, there are still some patterns that need to be clarified, and in some cases offer an additional method for diagnosing a person's health using an image of a pulse wave to increase the reliability of the results. In figure 1 the scheme of filling the blood vessel or vein with the release of blood from the left ventricle of the heart is shown. Spreading from the aorta to the capillaries, the pulse wave fades. Its front is spreading. It is shown that the expansion of the vessel at the time of arrival of the pulse wave will depend on its rigidity and density. When using laser radiation to register it, this will create features related to the wavelength \( \lambda \) and \( \theta \) - the divergence angle of the laser radiation.

![Figure 1](attachment:image1.png)

**Figure 1.** The scheme of the expansion of blood vessels: a) corresponds to the initial expansion of the vessel in the zone of exposure to laser radiation; b) corresponds to the greatest expansion of the vessel in the area of exposure to laser radiation; c) corresponds to the process of attenuation of the expansion in the zone of exposure to laser radiation to the complete filling of the zone of exposure to laser radiation. Point A corresponds to the center of the optical system of the pulse oximeter sensor.

The received experimental dependences of the amplitude of the pulse wave for different wavelengths of laser radiation in the red region of the spectrum obtained in the diagnosis of the state of various people are shown in figure 2. For the experiments, a standard pulse oximeter sensor was used in which semiconductor laser diodes with different wavelengths were placed with a radiation power \( P = 0.2 \, mW \) and a flat angle of the radiation pattern from 10 to 12 degrees [28-30]. All laser diodes were manufactured based on In\(_x\)Ga\(_{1-x}\)P heterostructures.

Our results showed that for some people the maximum amplitude of the pulse wave is shifted to the region of lower wavelengths of the red range of laser radiation. The design of the device incorporates a feature of automatic adjustment of the photodetector by the signal of absorption of laser radiation in the blood, which is associated with the choice of the number of photosensitive sensors in the photoreceiver device for image registration. Therefore, the pulse oximeter can perform automatic tuning based on the signal decay (for example, graph 4 at \( \lambda = 666.2 \, nm \)) at the point where its amplitude is less by 30\% than at the maximum. If the heart does not work very well for a patient or the blood vessels are thin according to the specifics of the organism, the signal will be weak. In this case, the amplitude of the absorption signal from the blood vessel will sharply decrease, and the tuning will go according to the noise. This will cause artifacts in the pulse wave image.
The dependencies of the pulse wave amplitude $A_I$ on different wavelengths $\lambda$ of laser radiation. Curves 1, 2, 3, 4 correspond to patients of different sex and age: a 56-year-old man, a 21-year-old woman, a 47-year-old woman, a 54-year-old woman.

The analysis of the dependencies presented in figure 2 shows that for each person, a sensible solution to eliminate the appearance of artifacts will be to use a laser source with a particular $\lambda$ when conducting control of health state. We found that the criterion for choosing $\lambda$ should be the maximum signal-to-noise ratio in the recorded pulse wave. As a result of the research, we established another reason for the appearance of artifacts. It relates to the angle of incidence of laser radiation on a blood vessel. For example, the obtained by authors dependence of the ratio of the amplitude $A_I$ of the recorded pulse wave signal on the angles $\alpha$ and $\varphi$ is shown in figure 3.

The angles $\alpha$ and $\varphi$ are defined as follows. Let the blood vessel be placed on the XY plane. Blood flows through it in the X direction. The angle $\alpha$ determines the deviation of the direction of laser radiation propagation from the Z axis in the ZY plane. The angle $\varphi$ determines the deviation of the direction of laser radiation propagation from the Z axis in the ZX plane. Analysis of the results shows that it is necessary to ensure the presence of the optimum position of the sensor on the finger during the research. In addition, we found that for each person this situation is different since the blood vessels of all are located differently (it is a feature of the structure of the organism). With a different sensor placement on a finger, the signal-to-noise ratio decreases. This can lead to artifacts, both when setting up a pulse oximeter and when taking measurements.
In addition, our experiments made it possible to establish that with reliable measurements in the case of holding the breath, the shape of the rising and falling edges of the pulse wave should change (even if the heart does not work properly). If an autonomous sensor is placed on the other finger of this hand, the readings of the oxygen content in the blood and the pulse values on the two instruments should change in the same way. If the distortions are caused by artifacts, then changes in the structure of the pulse wave (during breath-holding) will not be significant. In addition, there will be differences in the change in values (pulse and oxygen) on the two instruments.

3. New pulse wave image processing algorithm, experimental results and discussion

Our experiments showed that for each person, due to his individual body structure, the structure of the rise and fall front of a pulse wave is different. By changing the structure of the pulse wave (the appearance of distortions on the fronts), it is possible to establish deviations in the work of the heart. These abnormalities can be associated with both heart disease and the disease of other organs of the body that affect its work. In figure 4 as an example, the pulse waveforms obtained by us in the study of various people are presented.

Figure 4. The pulse waveform of men: (a) at the age of 22 years; (b) at the age of 24 years.

In figure 4(a) well visible distortions on the decay fronts of the pulse wave are observed. Distortions on the rise front of a given pulse wave are less noticeable. Based on the analysis of the pulse waveform we can assume the presence of heart disease. This assumption was confirmed during the clinical examination of this person. Image analysis of the pulse wave in figure 4(b) allows to conclude that the rise and fall fronts of the pulse wave signal are stable. Registered pulse wave peaks periodically repeat. The value of the human pulse is stable. The oxygen content in the blood is determined with an error of less than 2%. A person's condition can be qualified as good and stable.

Our additional studies of people in good condition (whose pulse waveform is not worse than in figure 4(b) using high-resolution devices (for example, MRT devices and NMR-relaxometers) allowed us to establish the following: some of these people have identified deviations in the work of the heart (disease at an early stage), which the body itself can cope with, if a person changes lifestyle and eliminates the causes that contribute to the development of the disease. With a more thorough study of the pulse waves of these people, differences in the rates of rise and fall of the various peaks of which the pulse wave is composed were noted. Therefore, we propose a new algorithm for processing the image of the pulse wave. To implement it, it is necessary to approximate the rise front of the pulse wave peak with the following function $\exp(FT)$ and the decay front $\exp(-CT)$, since the appearance of these dependencies is close to exponential. In figure 5 an example of the approximation of the one of the peaks of the pulse wave is shown.

Studies of the health condition of a man at the age of 24 years during a month (the person felt well, the clinical examinations did not record deviations in his health) allowed to establish that the values of the $F$ and $C$ coefficients can vary within certain limits $\Delta F$ and $\Delta C$. The pulse and oxygen content in the blood during these studies changed by less than 2%. At the same time, changes in the shape of the pulse wave peaks were observed. At different time intervals, the rate of decline and increase of the peak were different. Therefore, we assumed that it is more expedient to control the change in the state
of human health according to the new coefficient $K_p$, which is related by the shape of the peaks of the pulse wave:

$$K_p = \frac{F_0}{C_0}$$  \hspace{1cm} (1)

where $F_0$ and $C_0$ are coefficients measured by approximation of the pulse wave signal at a given time.

![Image of pulse wave with peaks labeled 1 and 2]

**Figure 5.** The peak of the pulse wave of men aged 24 years. Curve 1 – approximation of the rising front, curve 2 – approximation of the decline front.

To substantiate the use of this method, we conducted studies of people without harmful habits involved in sports and watching their diet. Based on the obtained results, the limits of coefficient change were established, which are not associated with the onset of any diseases in the human body:

$$0.95K_{FS} \leq K_p \leq 1.05K_{FS}$$  \hspace{1cm} (2)

where $K_{FS}$ is the value that most often corresponds to a good and stable health condition. For each human, the value of $K_{FS}$ is different (determined individually based on the results of long-term studies). The diagnostics of the state of people with a good health condition according to the dynamics of changes in the $K_p$ coefficient, measured pulse values and oxygen content made it possible to establish in some cases early stages of heart disease. The results of clinical examinations of these people confirmed that they have these diseases

4. Conclusion
Our studies have shown that the proposed method allows us to make the effect of artifacts on the pulse wave image irrelevant, especially in the case of weak and unstable signals, which are often associated with fatigue or indisposition of a person. In these cases, it is important to ensure the passage of a large part of the luminous flux through the dense layer of human skin to the blood vessel, and then to the photodetector.

The obtained results showed the validity of using to determine the state of a person the dynamics of changes in the coefficient $K_p$. Additional information obtained based on analysis of changes in $K_p$ values, as well as data on the oxygen content in the blood and pulse, reveal at an early stage several diseases associated with the work of the heart and other organs.

In some cases, our proposed method of pulse wave image processing could not reliably determine the early stages of certain diseases (for example, arrhythmia, etc.). This is because of the progresses of these diseases have not yet caused changes in the work of the heart, which can be determined using a pulse oximeter. This fact shows the need to continue research in the field of pulse oximetry to expand its functionality.

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