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New techniques for recording and processing laser radiation absorption signals in the far peripheral zone

© R.V. Davydov,[1,2,3] M.A. Yakusheva,[1] E.V. Porfir'eva,[1] V.V. Davydov,[1,3] D.D. Isakova,[3] S. Msokar[1]

[1] Peter the Great Saint-Petersburg Polytechnic University,
195251 St. Petersburg, Russia
[2] Alferov University,
194021 St. Petersburg, Russia
[3] Bonch-Bruevich St. Petersburg State University of Telecommunications,
193232 St. Petersburg, Russia
e-mail: davydov_vadim66@mail.ru

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The need to continue research is substantiated to expand the capabilities of the method for express diagnostics of the state of the human body in real time using an absorption signal that is recorded in the far peripheral zone. It is noted that modern instrument designs and methods of pulse wave signal processing have a number of disadvantages. This leads to a significant measurement error and not always reliable interpretation of the data. A new optical sensor design has been developed using a horizontal charge transfer CCD array to record a pulse wave signal in the form of steps with a higher signal-to-noise ratio. The use of a CCD array made it possible to establish the presence of a third peak in the structure of the pulse wave, in contrast to the case of its registration using a CCD matrix. It has been established that the parameters of the steps in the structure of the pulse wave line reflect the characteristics of the human cardiovascular system, which makes it possible to obtain new information, especially if the third peak is identified. To study changes in the shape of the pulse wave fronts and its peaks, a new technique has been developed, which is universal for processing pulse signals with different numbers of peaks. The patient's pulse waves recorded by two types of optical sensors and the results of studying their rising, falling and peak fronts are presented.

Keywords: blood flow, pulse wave, laser radiation, absorption signal, CCD array, oxygen, time, rising and falling front, measurement error.

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Introduction

People began to monitor their health more regularly in conditions of environmental degradation, acceleration of the rhythm of life and increased stress levels [1–3]. Rapid diagnosis of the body's condition in real time is one of the elements of such control [3–6]. It is important that a person could perform this diagnosis independently. Currently, pulse oximetry is broadly applied among express diagnostic methods, in addition to measuring temperature and pressure [3,4,7–9]. Its advantages include a non-invasiveness acquisition of data about the characteristics of the pulse and the percentage of oxygen saturation of hemoglobin in the pulsating blood stream. Also, unlike blood pressure measurements, there are no restrictions on the number of measurements over a certain period of time during express monitoring of human health [7–14]. The acquisition of information when registering a pulse wave requires significantly less time than when measuring blood pressure. The dynamic assessment of pulse waves (under loads during patient movement) is a separate field of pulse oximetry. For instance, a daily monitor, pulse wave sensors are more compact unlike other devices that are also used to make measurements under load, and they create fewer problems for the patient when moving than other devices. Therefore, they are often used in case of prolonged heavy loads, for example, long-distance running, cycling, etc. This shows another advantage of the use of a pulse oximetry compared to other methods.

Moreover, they have proved to be an extremely useful tool when testing patients during the COVID-19 pandemic as shown by the experience of usage of pulse oximeters.

It should be noted that modern pulse oximeter designs and pulse wave signal processing methods have a number of disadvantages [5,13–18]. The main disadvantage is related to the fact that to determine the reflection index RI, which is defined as the percentage ratio of the height of the diastolic component of the peripheral pulse wave to the height of the systolic component (the index reflects the state of tone of small arteries and the value of the pulse wave of reflection), analog signal processing data from a photodetector using analog-digital converter (ADC) [9,13,19–23]. The rigidity index SI is calculated as the ratio of the patient's height to the time interval Δt between the systolic and diastolic components of the pulse wave (indirectly estimates the pulse wave velocity), also using these data. There is a steady trend of the increase of the bit depth and ADC clock frequency (quantization by level) used to process the pulse wave signal [13,22,23] for increasing the accuracy of determination of the time intervals between the position of minima and maxima in the pulse wave, as well as for reducing the error of determination of the ratios between their amplitudes, while the sampling rate, which is determined by the structure of the photodetector, is 258 Hz and does not change. It is worth noting that the increase of the accuracy to $10^{-5}-10^{-6}$ s when determining time intervals through the use of ADC models with a high clock frequency, for example 200 MHz, does not allow the physician to obtain additional information, since such a frequency range does not contain pulse wave signal components. The structure of the pulse wave signal, as well as the method of its recording, do not change with an increase of the ADC clock frequency.

On the other hand, an ADC with a higher clock frequency is much more expensive. Moreover, the transfer function of an ADC with a clock frequency of 20 MHz introduces more distortion into the pulse wave signal than, for example, an ADC with a clock frequency of 200 Hz and 1 kHz. Therefore, ADCs with clock frequencies that are in order of magnitude close to sampling rate have been mainly used in devices for recording pulse waves based on a photodetector.

All this has led to the introduction of a new approach to the implementation of pulse wave recording using charge-coupled devices (CCD). The use of CCD is justified by the increase of the sensitivity of the photodetector device compared to photodiodes. There are prospects for increasing the sampling rate by increasing the number of pixels for studying various non-stationary processes. On the other hand, the pulse wave signal is formed in the form of „steps“ (discrete levels) in case of usage of CCD matrices which are now installed in optical sensors. The smooth and continuous nature of the initial physiological signal is disrupted, which, from the point of view of the physician, degrades the data provided to the physician. At the same time, the leading and trailing of the pulse wave signal contains not less information recorded using a photodiode is not less than the signal recorded by the CCD matrix. At low clock frequencies of the ADC used to process the signal from the photodetector, the use of an optical sensor with a photodiode to record the absorption signal of laser radiation is even more preferable than the use of an optical sensor with a CCD matrix. But there is one circumstance that is associated with a limitation in the radiation power of laser diodes in optical sensors: the laser diode is heated due to limitations of the heat dissipation capabilities. The heating of the laser diode results in a change of the wavelength and the angle of divergence of the laser radiation, which leads to errors in measurements. In addition, the reflection of laser radiation from the photosensitive layer of the photodiode is greater than the reflection from the CCD matrix. This leads to a deterioration in the signal-to-noise ratio of recording of a laser absorption signal.

In addition to the above justifications for the use of CCD matrices in the design of optical sensors, there are two more factors that most likely play a key role.

The first is associated with the fact that the CCD matrix is actively used in other optical systems, technologies for their production are rapidly developing, and their cost is already comparable to the cost of photodiodes, which for these optical systems are manufactured according to a separate specification. This makes CCD matrices more affordable in case of repair of optical sensors and more promising from the point of view of production.

The second factor includes the great capabilities of sensors with CCD matrices in case of testing of the cardiovascular system with mechanical signals of a different frequency (for example, higher than the operating frequencies of heart ranging from 0.8 to 2 Hz). In this case, it will be possible to see (register) vibrations created, for example, by a vibrator outside on the chest, only at high time resolution (at a high sampling rate of the signal, which should be on the order of 1 kHz and higher). The implementation of this test will allow the development of a non-invasive cardiac output monitor.

In such a situation, the importance and demand for new developments based on charge-coupled devices aimed at increasing the signal-to-noise ratio in the pulse wave signal and sampling rate are increasing. This is the purpose of our current work, which will also include the development of new techniques for processing recorded pulse wave signals using new optical sensors.

1. Modernization of the optical system design for pulse wave recording using a laser radiation absorption signal

The following was found based on the analysis of information about the results of human health studies, which used pulse wave signal processing using ADC [6,13,15–17,20,21], as well as experience with pulse oximeters. A line with the maximum amplitude value per pixel is cut out in the CCD matrix for generating a pulse wave signal on the monitor or in the display device of the device. With this formation in the pulse wave, the signal-to-noise ratio in the „steps“ curve is formed as the ratio of the pulse wave signal recorded at a pixel in the cut-out line to the entire noise of the CCD matrix (with frame-by-frame charge transfer, all noise of the CCD matrix from all pixels is transferred to the formed line). This method of pulse wave signal generation does not allow using a CCD matrix with a small value of electrons in a pixel (pixel well depth) for its recording. The use of a pixel with a small well allows obtaining high sensitivity when recording a laser absorption signal. The reliability of information in the pulse wave decreases with a low level of the laser radiation absorption signal. Small amplitude peaks may not be recorded or their identification in the pulse wave structure may be difficult.

Technical characteristics of the prototype of the CCD line-up

Capacity	8 bit
Pixel well depth	250 000 e (voltage, applied to the electrodes for charge packed transfer -8 V)
Dark current (medium)	60 ke/pixel/s
Reading noise	100 e rms
Dynamic range (well depth /reading noise)	2500
Maximum output frequency with two-phase register	10 MHz

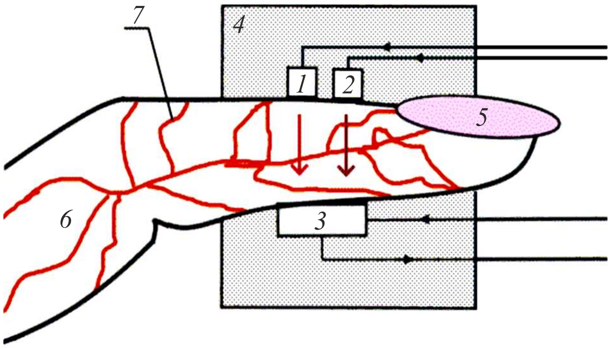

Figure 1. Block diagram of the laser absorption signal recording: *1* — semiconductor laser diode on $\lambda = 660$ nm, *2* — semiconductor laser diode on $\lambda = 940$ nm, *3* — CCD strip, *4* —sensor housing, *5* — nail, *6* — finger, *7* —blood vessels.

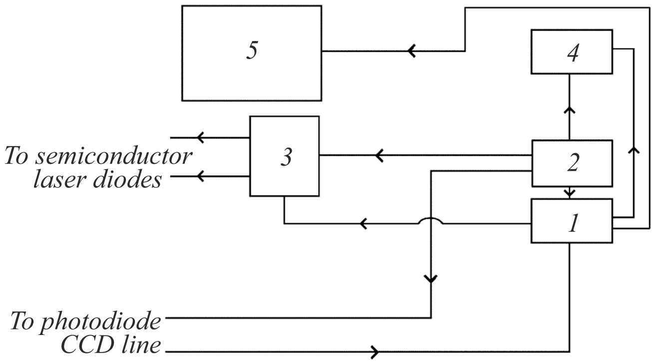

Figure 2. Block diagram for information processing and control of recording of the laser absorption signal: *1* — microcontroller, *2* — multifunctional power supply, *3* — electronic key, *4* — display device, *5* — personal computer.

We developed a system for recording the absorption signal of laser radiation using a line of CCD with the line transfer of the charge for solving this problem. The prototype of the CCD strip was fabricated by Central Research Institute „Electron“. It has an equivalent — the CCD strip produced by Hamamamatsu. The technical characteristics of its equivalent were taken into account for the fabrication of the prototype. The main parameters of the prototype CCD strip are listed in the following table. It should be noted that the block diagram of the recording of the laser radiation absorption signal (Fig. 1) in the far zone of human blood flow (in the finger) in case of the use of the CCD strip does not fundamentally change compared with the use of a CCD matrix in an optical sensor.

Such a scheme for recording the absorption signal of laser radiation with its further processing (Fig. 2) did not change the previously applied principles of pulse wave recording. Two laser diodes with $\lambda_1 = 660$ nm (red region) and with $\lambda_2 = 940$ nm (near infrared range) are also used in the design of the optical sensor. As in the case of usage of a CCD matrix, the pulse wave signal at the output of the CCD strip is formed in the form of „steps“ with quantization of each level. In this case, the amplitude and duration of the „steps“ depends on the energy of the quanta that arrive at the photodiode strip in a certain time in the laser absorption signal and the depth of the electron well, therefore, the recorded signal is individual for each person and depends on his state of health. Decoding it can provide more information about a person's health status than analyzing a signal recorded in another way.

Increasing the sampling rate is a further prospect for RD& in this field, since it is difficult to implement this in a photodiode photodetector without fundamental changes in the design of the zones. Increasing the frequency will make it possible to conduct study non-stationary processes that occur at the leading edges and peaks in the pulse wave, as well as to implement frequency testing of the cardiovascular system.

Taking into account the fact that the CCD strip is finding more and more applications in various fields, developments are constantly underway to increase the number of pixels used to register optical signals. We use a strip with 64 pixels per line, now we have developed strip for 1024 pixels. There is still the issue of reducing their size, which is related to production technologies. The use of such a strip in the optical sensor of the pulse oximeter will make it possible to realize a sampling rate of 1024 Hz, which will expand the possibilities of pulse wave research using this device and its practical application.

It should be noted that when using the CCD strip, the main functions of the pulse oximeter (assessment of pulse characteristics and percentage of hemoglobin saturation with oxygen) are preserved. Also, it is possible to determine the time intervals between the positions of the maxima and minima using the recorded pulse wave shape in the form of „steps". An increase of the error of determination of these intervals from 10^{-5} to 10^{-3} s when using the CCD strip does not significantly affect the accuracy of determining the reflection and rigidity indices, as well as the reliability of the interpretation of the results obtained.

2. Results of experimental studies and new pulse wave processing technique

Figure 3 shows, for example, two pulse wave signals recorded from one patient who had abnormal deviations in the pulse wave structure for 3 min using two different optical sensors — with a CCD matrix and with a CCD strip. The figure demonstrates the potential use of the CCD strip.

The analysis of the obtained results shows that the registered pulse waves differ in their structure. The pulse wave contains two maxima and two minima in case of usage of a CCD sensor for recording (Fig. 3, *a*), the pulse wave contains three maxima and three minima in the case of using a CCD strip (Fig. 3, *b*). It should be noted that the positions of the two maxima and two minima in Fig. 3, a on the time axis are shifted relative to the positions of the same maxima and minima in Fig. 3, *b*. At the same time, the pulse wave period did not change for the two cases. For the convenience of comparing two pulse waves in Fig. 4 shows their shape after quantization of the levels. In this representation of the pulse wave period, changes in the parameters of the „steps" and their number are visually noticeable, which in the future, with an increase of the sampling rate, can be extremely useful. This shows that the use of the CCD line made it possible to reduce the intrinsic noise of the receiving device, which increased the sensitivity of the optical sensor to changes in pulse wave parameters.

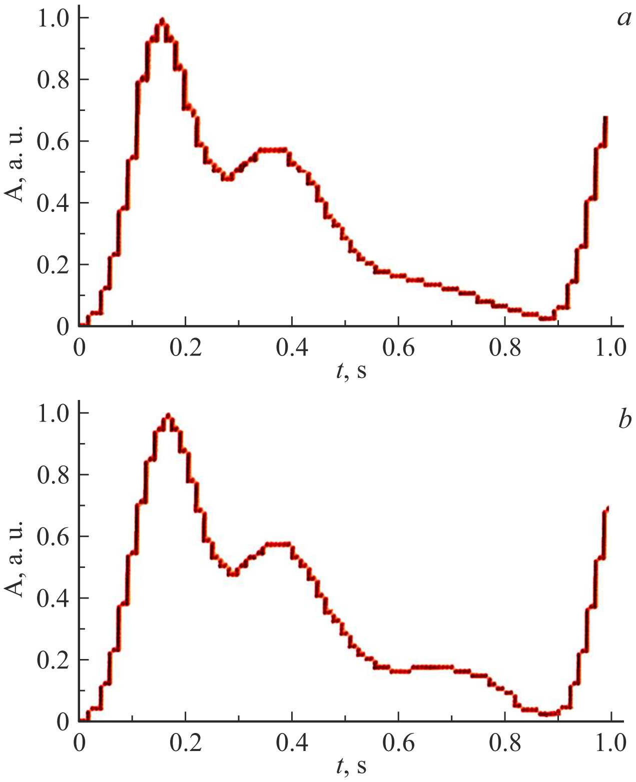

Figure 3. Dependence of the amplitude ratio A_I of the recorded pulse wave signal for various laser radiation detection devices in optical sensor design: *a* — CCD matrix, *b* — CCD strip.

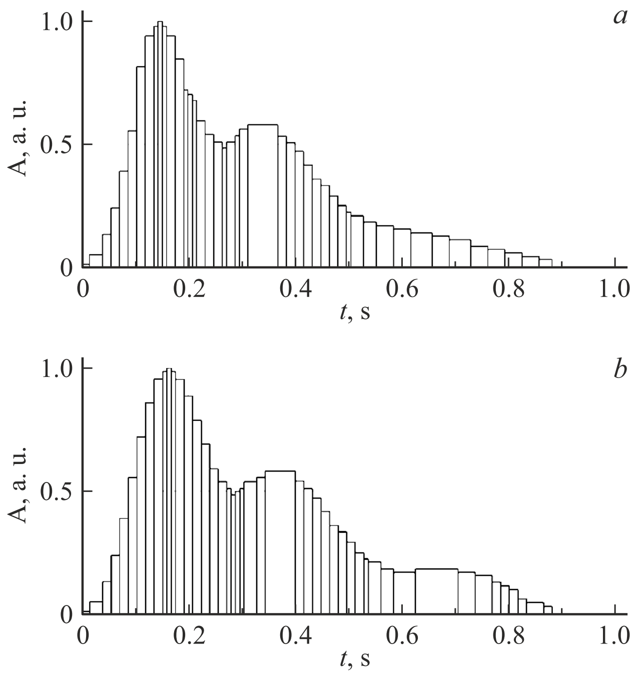

Figure 4. The shape of the pulse wave period after quantization of the levels according to the data presented in Fig. 3.

This made it possible to form levels in the „steps" in the area of absorption signals with a small amplitude, which was previously close to the noise level in case of usage of a CCD matrix, therefore such signals were not read before. All this made it possible to explicitly diagnose the third maximum and the second minimum in the pulse wave signal. The physician visually receives additional information about the work of the human cardiovascular system.

It is also worth noting that when changing an optical sensor with a CCD matrix to a sensor with a CCD strip, the ratio between the amplitudes A of the first and second maximum $(A_1/A_2)_{\text{matrix}} < (A_1/A_2)_{\text{line}}$. This experiment was carried out for two cases: the sensors alternately changed

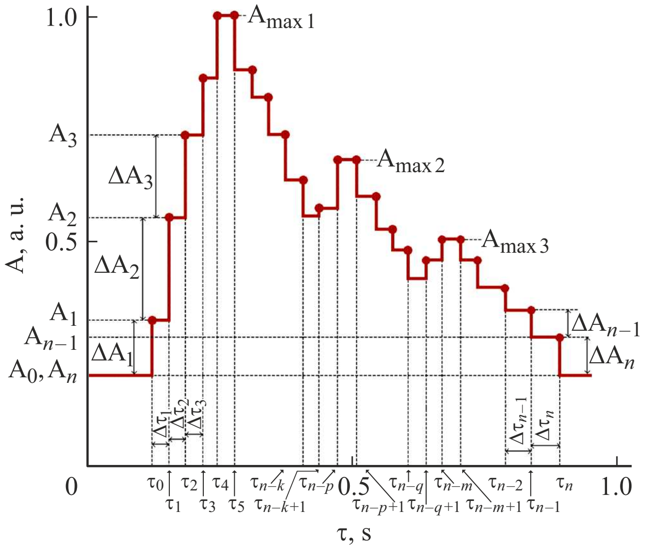

Figure 5. The shape of the pulse wave when it is recorded in the far peripheral zone on the finger of the hand.

on the finger of the hand and the sensors were installed on the same fingers of two hands (at the next measurement they changed: from the left hand the sensor was moved to the right, from the right — to the left).

All this shows that the use of an optical sensor with a CCD strip is more appropriate than an optical sensor with a CCD matrix, especially in case of recording of weak laser absorption signals on a human finger.

To process the recorded pulse wave signal with a different number of maxima (peaks), leading and trailing edges, a new universal technique has been developed, the application of which is possible for any number of maxima and their corresponding leading and trailing edges in the pulse wave period.

Figure 5 shows one period of the pulse wave recorded by the CCD strip with a line transfer of the charge, with marked time intervals. The number of maxima and edges in the pulse wave period, as well as the parameters of the maxima themselves (their amplitude and the interval between them) will be individual for each person. They depend on both his physical and emotional states. In accordance with the shape of the pulse wave (Fig. 5), we divide its period into 9 parts: the leading edges (in amplitude from A_0 to A_{max1}, from A_{n-k} to A_{max2} and A_{n-q} to A_{max3}), trailing edges (from A_{max1} to A_{n-k}, from A_{max2} to A_{n-q} and from A_{max3} to A_n) and the area of three peaks.

Since the principle of quantization of levels is implemented when forming a pulse wave signal during its recording using a CCD strip with a line charge transfer, it is more advisable to use mathematical functions based on series to describe the pulse wave. We have developed the following function F for describing the maxima:

$$F(t_n) = F\Big(\sum_{n=m-p}^{m+p} \Delta\tau_n\Big) = \left|\frac{A_n - A_{n-1}}{\Delta\tau_n}\right|, \qquad (1)$$

where m — the number of the „step" corresponding to the first, second and third maximum, τ_n — duration of the „step", p — coefficient varying from 1 to 4 depending on the age of the person (determined taking into account the shape of the pulse wave, and for the third maximum it may be less than for the first and second), then taking into account p, the value of t_n is determined for each maximum — the time interval in the pulse wave period at which this maximum is studied.

The introduction of the coefficient p makes signal processing more universal, since in different circumstances the shape and number of maxima at the same time interval in the pulse wave can vary [7,9,12,15]. It is necessary to compare the processing of the pulse wave signal under the same conditions (in our case, by the number of maxima) for determining the evolution of the change (or long-term diagnosis). An increase of the duration of the interval where this number of maxima is now located is also recorded for statistics.

One more circumstance should be noted. Our comparisons have shown that with the increase of the age of a person, the parameters of the „steps" in the structure of the pulse wave change, their number also changes, therefore, age-related changes also need to be incorporated into the functions that will be used in describing the pulse wave leading edges. The function $\Phi_s(t)$ was developed to describe the pulse wave leading edge. The feature of the function $\Phi_s(t)$ is that for each leading edge in the time interval ΔT_s (where s — the number of the leading edge) within one period of the pulse wave, the function $\Phi_s(t)$ is formed with taking into account the number of maxima in the pulse wave. We developed the following function Φ_1 for processing the area from the beginning of the pulse wave period to the first maximum:

$$\Phi_1(t_n) = \sum_{i=1}^{m_1}\left(A_i \sum_{n=1}^{m_1}\left(\frac{\Delta\tau_n p}{\Delta T_{m_1}(m_1 - 1)}\right)^n\right), \qquad (2)$$

where m_1 — number of the „step" corresponding to the first maximum, $\Delta\tau_n$ — duration of the „step", A_i — amplitude of the „step", ΔT_{m_1} — duration of the first leading edge.

The next section from the first minimum to the second maximum can be described by the function Φ_2:

$$\Phi_2(t_n) = \sum_{i=k_2}^{m_2}\left(A_i \sum_{n=1}^{m_2-k_1+1}\left(\frac{\Delta\tau_{n+k_1-1} p}{\Delta T_{m_2}(m_2 - 1)}\right)^n\right), \qquad (3)$$

where m_2 — number of the „step" corresponding to the second maximum, k_1 — number of the „step" corresponding to the first minimum, ΔT_{m_2} — duration of the second leading edge.

The next section from the second minimum to the third maximum can be described by the function Φ_3:

$$\Phi_3(t_n) = \sum_{i=k_2}^{m_3}\left(A_i \sum_{n=k_2}^{m_3-k_2+1}\left(\frac{\Delta\tau_{n+k_2-1} p}{\Delta T_{m_3}(m_3 - 1)}\right)^n\right), \qquad (4)$$

where m_3 — number of the „step" corresponding to the third maximum, k_2 — number of the „step" corresponding to the second minimum, ΔT_{m_3} — duration of the third leading edge.

The analysis of various pulse wave signals (with a different number of maxima and minima recorded from people of different ages) showed that when describing the pulse wave trailing edges, it is also necessary to use a coefficient that takes into account the age of a person. In addition, we propose to use a function with an exponent followed by stitching values at boundaries. A variant of the function developed by us for any trailing edge time interval t within one period of the pulse wave is as follows:

$$\Psi(t) = A_m\left(e^{\frac{-\Delta\tau_k(n-m)}{mt}}\frac{n-m}{p(A_{k-1}-A_k)}\right), \qquad (5)$$

where the following restrictions are imposed on t $\tau_m < t$, $\tau_{k-1} \leq t < \tau_k$; k — the number of the „step" of the trailing edge $n - m$ is determined for each trailing edge (Fig. 4) and the corresponding value A_m.

The following is another feature of the methodology we developed. Each „step" on the pulse wave trailing edge, which is mainly determined by relaxation processes, is considered using (5) separately. Next, they are „stitched" at the boundaries of „steps" taking into account the duration of the time interval of each „step". This allows, when processing the pulse wave, to take into account the characteristics of the body that are inherent in each person, and are reflected in the pulse wave signal recorded using the CCD strip. It is worth noting that the account of relaxation processes in the method of analysis of the pulse wave trailing edge has been applied for the first time.

Figure 6 shows the results of a study of changes in the structure of the pulse wave in the vicinity of the maxima for two cases of its recording.

The data obtained as a result of processing the pulse wave maxima allow establishing that the use of a new laser absorption signal recording system with a higher signal-to-noise ratio makes significant changes to the histogram structure (Fig. 6, *b*) compared with the data in Fig. 6, a when considering the first and second maxima. These differences are barely noticeable in Fig. 4 (after processing with the maximum pulse wave, it can be argued that updated information has appeared for the physician). Separately, it should be noted that in the pulse wave zone with a low signal-to-noise ratio in the laser absorption signal, its processing makes it possible to identify clear differences in the third maximum. This maximum could not be detected by processing from the pulse wave waveforms, which is recorded using a CCD matrix (it is not visually observed). This maximum can be visually determined in the pulse wave signal recorded using the CCD strip (Fig. 4). It became more clearly defined after processing. This allows the physician to obtain reliable additional information about the state of the cardiovascular system based on the results of the analysis of the pulse wave, which has a third peak, which is not detected when using a sensor with a CCD sensor.

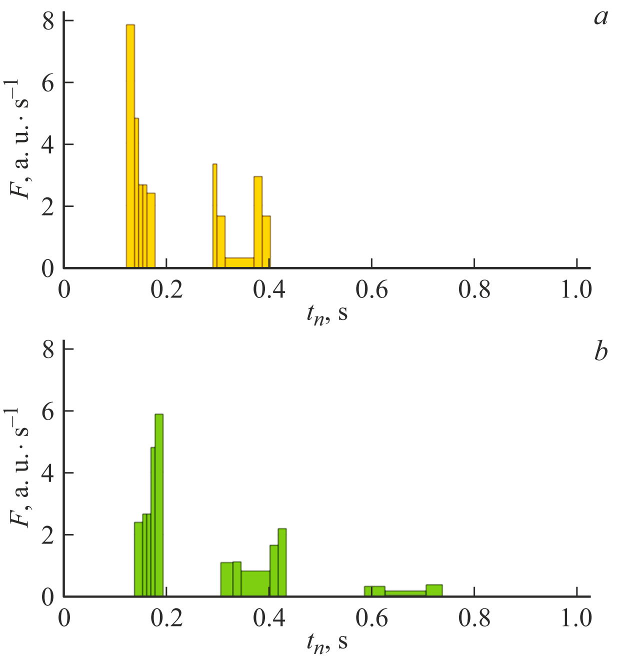

Figure 6. The results of processing the maxima of one pulse wave period: *a* — recording using a CCD matrix, *b* — using a CCD strip.

Figure 7 shows the results of a study of the pulse wave growth fronts for two cases of its recording using two types of sensors. The analysis of the obtained data shows that the structure of the pulse wave growth fronts after their processing for the first two maxima in cases of its recording by different sensors does not differ significantly, unlike the results of the study of the maxima themselves. If it is necessary to identify minor differences (Fig. 7), then it is necessary to consider the results of processing each front separately on an enlarged scale.

Figure 8 shows the results of a study of the pulse wave decay fronts for two cases of its recording using two types of sensors. Analysis of the results showed that a significant difference is observed in the fronts of the pulse wave decay from the first maximum to the first minimum when replacing the CCD matrix with a CCD strip (Fig. 8, *a*). There were no significant differences between the structures of the second trailing edge for the two pulse wave recording cases. Comparing the remaining differences in the trailing edges between the two pulse wave recording cases, due to the identification of the third maximum (the recession time has become shorter), is unreasonable: the signal structure has become different in this time interval. It should only be noted that the value of Ψ reaches a lower level in a shorter time.

The usefulness and necessity of the identified new changes in the structure of the pulse wave, which did not

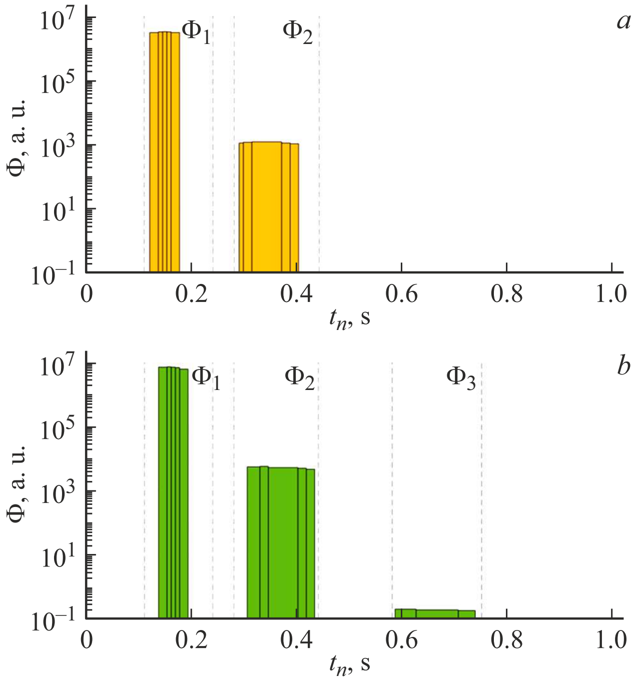

Figure 7. The results of processing the leading edges of one pulse wave period: *a* — recording using a CCD matrix, *b* — recording using a CCD strip.

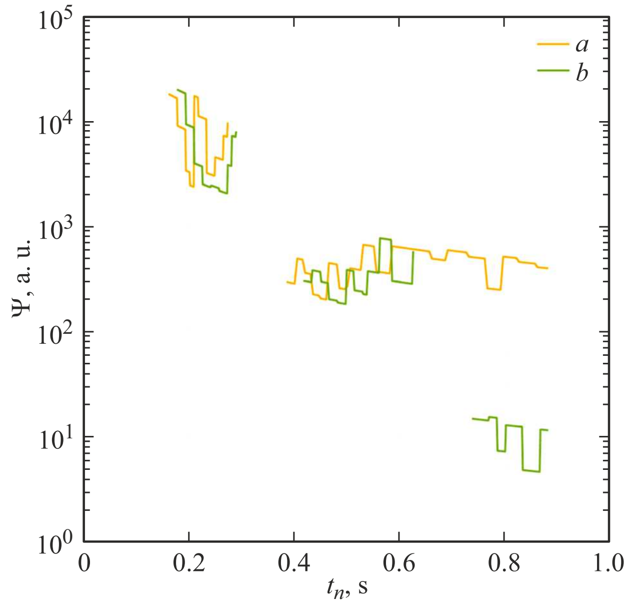

Figure 8. The results of processing the trailing edges of one pulse wave period: *a* — recording using a CCD matrix, *b* — using a CCD strip.

exist before (the third front of rise and fall, etc.), should be evaluated by a physician, since from a technical point of view there is nothing to compare them with (this maximum was not recorded when using an optical sensor with a CCD matrix).

Conclusion

Our research confirmed the validity of using an optical sensor with a line of CCD with line charge transfer to improve the signal-to-noise ratio in the recorded pulse wave signal, which allows obtaining new information about the state of the cardiovascular system.

On the other hand, the use of a CCD line allows increasing the sensitivity of the laser absorption signal detection system by at least an order of magnitude compared to the case of using an optical sensor with a CCD matrix and by more than 15–20 times compared with a photodiode. This opens up broad prospects in a number of areas of modernization of the design of both the optical sensor in the pulse oximeter and the implementation of new research using these devices. The following should be noted among the prospects. Increasing the sampling rate in the CCD range to 1024 Hz and the raster scan on the monitor screen will allow recording minor changes (in the form of outliers or valleys) in the structure of the pulse wave edges, which are now difficult to detect.

At this sampling rate, the pulse wave waveform will be continuous like now in case of usage of photodiodes in an optical sensor. Such a signal will be more familiar and convenient for physicians. Although, in fact, it will consist of small „steps“ that are not visible to the eye. This signal will also contain information about changes in blood flow rate, the work of the cardiovascular system, etc.

In addition, the use of the CCD strip opens up the possibility of implementing non-invasive calibration of cardiac output by pulse wave signal using an electromechanical pressure sensor. Signals with different frequencies from 10 Hz and different pulse ratio are sent to the sensor, after some time after exposure, a pulse oximeter records a response that is associated with the time of blood flow to finger. This design allows measurements to be carried out at different frequencies, as well as at different oscillation amplitudes at a resonant frequency. At the same time, a complete galvanic isolation between the recording system and the exposure system is implemented, which ensures high reliability of the results.

Conflict of interest

The authors declare that they have no conflict of interest.

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