Optoelectronic method for optical diagnosis of the state of the vascular system

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Abstract: *In the present work we have investigated the parameters of peripheral blood flow by using a non-invasive method for processing photoplethysmograms (PPGs). The developed original technique allows us to register a photoplethysmogram, isolate the pulse wave and determine the duration of cardio intervals, the duration of the anacrotic and dicrotic phases, the duration of fast and slow blood filling, the expulsion period, the dicrotic and diastolic indices, temporal and amplitude parameters of vascular tone, etc. We observe three types of PPGs after taking medicaments Corvitol-50 and nitroglycerin. The analysis of the amplitude-temporal characteristics of PPGs allows the determination of key diagnostic parameters.*
KEYWORDS*: PULSE WAVE, VASCULAR SYSTEM, PHOTOPLETHYSMOGRAMS*

1. Introduction

Optical diagnostics of biological objects has gained wide application in recent years. The advantages of optical diagnostic methods consist primarily in noninvasiveness, rapidness and high accuracy. Unlike radiological and ultrasonic methods, optical irradiation is natural for the organism and does not cause any side effects with the powers used. Determination of the relative saturation of arterial blood with oxygen (SaO2) - pulse oximetry has become the gold standard in resuscitation and intensive care. The spectral range between 600 and 1000 nm (near IR) is well suited for optical tissue oximetry because at these wavelengths, the absorption spectrum of hemoglobin is closely related to its oxygenation state. Moreover, the penetration depth of biological tissues is high in this spectral range.

Today, cardiovascular diseases are the leading cause of death and disability. The most important tasks are the improvement of methods for diagnosing and monitoring, the development of effective methods for prevention. Doctors need non-invasive research methods that could record the main indicators of central and peripheral hemodynamics and would characterize the contractile activity of the heart. At the present stage of the development of medicine, it is no longer enough to take only electrocardiographic and blood pressure measurements to make a comprehensive diagnosis. In assessing the adaptive abilities of a person (physiology of labor and sports medicine, etc.), determination of basic hemodynamic parameters is necessary to establish rational modes of work and rest, optimal and maximum levels of physical activity.

There are many methods of measuring cardiac output, both invasively and non-invasively; each has advantages and drawbacks. Invasive methods are well accepted, but these methods are quite complicated, traumatic and often lead to changes in heart rate. Consequently, the focus on development of non-invasive methods is growing [1]. Ultrasound Dopplerography is most used by these methods. Being accurate and inexpensive, Doppler ultrasound is a routine part of clinical ultrasound; it has high levels of reliability and reproducibility, but it does not measure blood volume and is complicated to use. This method is most suitable for large clinics [2]. Electrical impedance plethysmography and electrical cardiometry are similar methods based on the model of electrical velocimetry, and non-invasively measures stroke volume, cardiac output and other hemodynamic parameters through the use of 4 surface ECG electrodes. The disadvantage of rheoplethysmography to determine the parameters of peripheral blood flow is the placement of current and measuring electrodes at a great distance. At the same time, the signal is influenced by the properties of vessels throughout the pathway.

Photoplethysmography (PPG) is a simple and low-cost optical technique that can be used to detect blood volume changes in the microvascular bed of tissue. It is often used non-invasively to make measurements at the skin surface. A PPG is often obtained by using a pulse oximeter which illuminates the skin and measures changes in light absorption. The PPG waveform comprises a pulsatile physiological waveform attributed to cardiac synchronous changes in the blood volume with each heart beat [3-5]. PPG offers significant potential for data mining and a range of innovative pulse wave analysis techniques.

The aim of our study is to determine the parameters of peripheral blood flow using an optoelectronic method for processing photoplethysmograms.

2. Materials and Methods

The photoplethysmogram is a change in the transmittance of light by a biological tissue under the influence of a pulse wave. The sensor for recording photoplethysmography is a light-emitting diode and a photodetector, between which biological tissue is placed. Taking into account the absorption spectra of blood and tissue, the use of near-infrared emitters is most appropriate. The use of photoplethysmogram allows local research of peripheral blood flow.

Similar to the analysis of the rheoplethysmogram proposed in [6], the information parameters of the photoplethysmographic pulse curves can be divided into primary (amplitude and time) and derivatives of the primary, obtained by simple mathematical operations. The pulse curve depends on the systolic ejection, blood flow intensity, blood viscosity, condition of the vascular walls, the ratio of precapillary and postcapillary pressure, etc.

The pulse wave has the following main components (Fig. 1): a steep systolic ascent - the anacrotic phase and the descending part, which corresponds to the catacrotic phase. On the anacrot there are two sections - the period of rapid blood filling from the beginning of the anacrot to the point of maximum steep rise (maximum of the first derivative of the pulse wave) and the period of slow blood filling. On the catacrot is the so-called dicrotic wave.

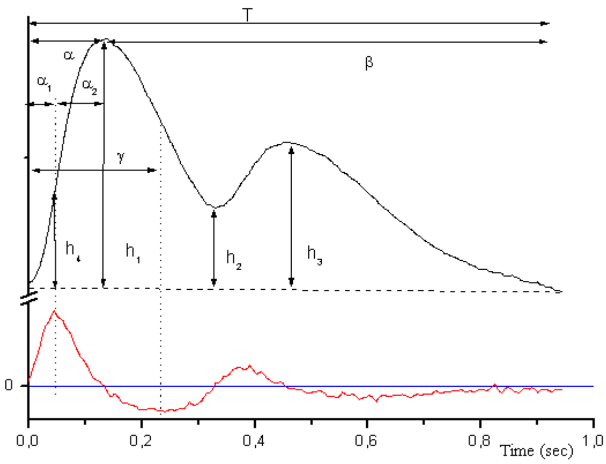


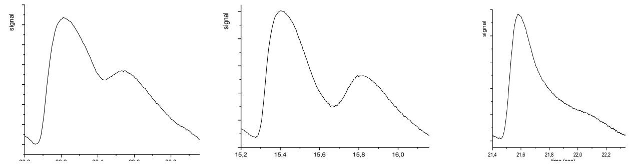
Fig.1 *Pulse wave (upper curve) and its first derivative (lower curve)*

Primary characteristics of the pulse wave:
T - the duration of the cardiac cycle.
α - the duration of the ascending part of the wave (anacrotic phase)
α_1 - the duration of rapid blood filling.
α_2 - the duration of slow blood filling .
β - the duration of the catacrotic phase
γ - the ejection period.
h_1 - the maximum amplitude of the pulse wave, the indicator of the magnitude of the pulse of blood.
h_2 - the amplitude of the pulse wave at the level of the incisura.
h_3 - amplitude of the pulse wave at the level of a dicrotic wave.
h_4 - amplitude of the pulse wave at the level of the projection of the maximum of the first derivative.
There are other secondary indices that are left out of our study.

In medical practice, the averaging of the SaO_2 value over 8 or 16 heartbeats is used, which simplifies the requirements for recording a photoplethysmographic signal. However, when we developed methods for determining changes in the relative volume of peripheral blood [7], the relative concentration of carboxyhemoglobin in arterial blood [8], and the relative oxygen concentration in venous blood [9], to reduce the error we need a lot of points, so it is necessary to record a photoplethysmogram with a frequency of 200-250 Hz [10]. Due to our original method of data processing, the accuracy of measurements is 3-4 times higher compared with standard systems. The system allows continuous photoplethysmographic monitoring, recording and data storage. Data acquisition was executed by a measuring block with a microcontroller connected to PC. The microcontroller includes a microprocessor, RAM, ROM, decoder, timer, quartz-stabilized clock generator, and input/output ports. The sampling frequency was 348 Hz, the LED flash pulse duration - 160 µs, the interval between pulses of red and IR emission 200 µs. Calculations were made on interval lengths of 200 to 400 points with a shift of 100 points. This procedure provides a measurement with a smaller increment than the cardiac cycle length. This system enables to implement the diagnosis of the cardiovascular system by analyzing the volume pulse wave. The developed original technique allows us to register a photoplethysmogram, isolate the pulse wave and determine the duration of cardio intervals, the duration of the anacrotic and dicrotic phases, the duration of fast and slow blood filling, the expulsion period, the dicrotic and diastolic indices, temporal and amplitude parameters of vascular tone, etc. All results are given as mean ± (SD). The Student's test for connected sampling was used for the statistical calculations. Statistical results with a value of $p < 0.05$ were viewed as being significant. The evaluation was carried out using the program “Origin 7.5”.

3. Results and discussion

Measurements of these parameters were carried out with a medicament impact on a 51-year-old volunteer with coronary heart disease. The registration was carried out in a calm state with a satisfactory state of health. The measurements were carried out 30 minutes after taking "Corvitol-50" and 2-3 minutes after taking nitroglycerin. The analysis revealed photoplethysmograms of several types (Fig. 2). The y-axis are arbitrary units, because we are only interested in the shape of the signal. We attributed the first type of photoplethysmogram (Fig. 2a) to a curve with a well-expressed dicrotic wave, the maximum of which is located approximately in the middle of the catacrotic phase. The difference between the amplitudes of the wave at the level of incisura and dicrotic wave is small. Photoplethysmograms of the first type were observed in a calm state and after taking Corvitol-50. The photoplephysmogram shown in Fig. 2b was attributed to the second type. In this type the dicrotic wave is also well expressed, but is shifted closer to the end of the catacrota. Incisura has a much smaller amplitude than in the previous case and the difference between the amplitudes of the wave at the level of incisura and the dicrotic tooth is very significant. Such photoplethysmograms were observed after taking nitroglycerin. The third type of photoplethysmogram (Fig. 3b) is characterized by the absence of a expressed dicrotic wave. This leads to the fact that it is impossible to isolate the incisura and dicrotic prong and measure their amplitudes. This type of photoplethysmogram was also observed after taking nitroglycerin.



a) b) c)

***Fig. 2** Photoplethysmograms: a) first, b) second, c) third type.*

After taking nitroglycerin, the second type of photoplethysmogram mainly occurs at the beginning of the recording, and the third is closer to the end.

3.1.Temporal characteristics

During the experiments, the following primary properties were determined: the duration of the cardio intervals, the duration of the anacrotic phase, the duration of the fast and slow blood filling, the ejection period. In a calm state, the temporal characteristics were: $\alpha 1 = 0.053 \pm 0.006$ sec., $\alpha 2 = 0.089 \pm 0.007$ sec., $\alpha = 0.142 \pm 0.008$ sec., $\gamma = 0.279 \pm 0.018$ sec., $T = 0.945 \pm 0.023$ sec. Changes in temporal characteristics after taking medications are shown in Fig. 3 and Fig. 4.

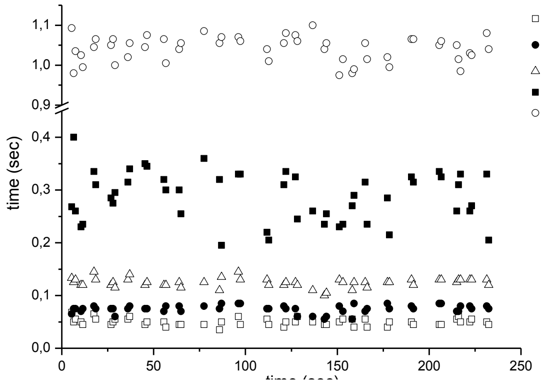


***Fig. 3** Temporal characteristics after taking "Corvitol-50".*

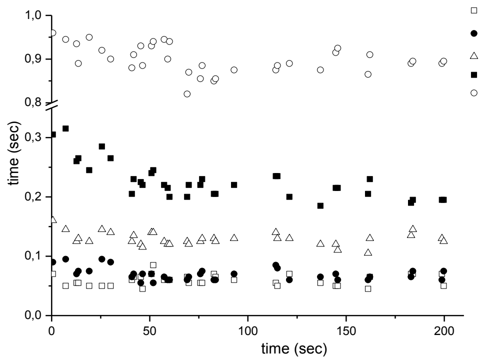


***Fig. 4** Temporal characteristics after taking nitroglycerin*

After taking Corvitol, the duration of cardio intervals increased ($T = 1.040 \pm 0.031$ sec), which corresponds to a decrease in heart rate. The duration of the anacrot decreased, the durations of the fast and slow blood filling were respectively $\alpha 1 = 0.050 \pm 0.007$ sec., $\alpha 2 = 0.075 \pm 0.007$ sec., $\alpha = 0.124 \pm 0.009$ sec. The ejection period increased slightly - $\gamma = 0.287 \pm 0.040$ sec., the spread of its values also increased.

The correlation characteristics between these parameters were determined. High correlation is observed between α1 and α and between α2 and α (0.53 and 0.67, respectively). The correlation of these values with the ejection period was 0.02 for α1, 0.31 for α2 and 0.29 for α. With the duration of the cardio interval, the correlation was 0.13 for α1, 0.01 for α2, 0.11 for α and 0.23 for γ.

After taking nitroglycerin, the duration of cardiointervals decreased (T = 0.899 ± 0.026 sec.), which corresponds to an increase in heart rate. The duration of anacrotic and the duration of slow blood supply decreased, but the duration of fast blood filling increased. They amounted to, respectively, α1 = 0.059 ± 0.007 seconds, α2 = 0.070 ± 0.008 seconds, α = 0.129 ± 0.008 seconds. It is noted, unlike other experiments, the excess of the duration of fast blood filling over the duration of slow blood filling. The ejection period significantly decreased - γ = 0.227 ± 0.023 sec.

The correlation between α1 and α and between α2 and α is slightly lower than in the previous case, but quite high (0.43 and 0.64, respectively). The correlation of the duration of fast blood filling with the ejection period became negative and amounted to -0.17, while the correlation between the duration of slow blood filling and the length of anacrot with the ejection period was high - 0.74 for α2 and 0.59 for α. With the duration of the cardio interval, the correlation was 0.06 for α1, 0.26 for α2, 0.31 for α , 0.55 for γ.

The secondary temporal characteristics were determined: the temporal index of the vascular tone and the specific time of the anacrot. The temporal index of vascular tone was 0.60 ± 0.10 for a calm state, 0.68 ± 0.11 after taking Corvitol and 0.88 + 0.18 after taking nitroglycerin, and the specific anacrot time was 0.15 ± 0.01 for a calm state, 0.12 ± 0.006 after taking Corvitol and 0.14 ± 0.01 after taking nitroglycerin.

3.2Amplitude characteristics

The amplitudes h1, h2, h3, h4 and secondary characteristics were determined: dicrotic index, diastolic index, amplitude index of vascular tone. At calm state, the dicrotic index was 0.48± 0.06, the diastolic index was 0.59 ± 0.03, and the amplitude index of vascular tone was 0.40 + 0.04.

After taking Corvitol all parameters slightly increased and amounted to a dicrotic index - 0.53 ± 0.10, diastolic index - 0.67 ± 0.05, amplitude index of vascular tone - 0.43 ± 0.03. Taking nitroglycerin leads to a decrease in the dicrotic and diastolic indices and is characterized by the appearance of a pulsogram without a dicrotic wave. The mean values were respectively: dicrotic index - 0.20 ± 0.06, diastolic index - 0.35 ± 0.11, amplitude index of vascular tone - 0.45 ± 0.04.

4. Conclusion

The method of optoelectronic determination of the characteristics of the cardiovascular system allows the analysis of the amplitude-temporal characteristics of the photoplethysmographic curve to determine such interesting diagnostic parameters as the duration of the anacrotic and dicrotic phases, the duration of fast and slow blood filling, dicrotic and diastolic indices, temporal and amplitude vascular tone. In contrast to the other methods, the use of photoplethysmography allows us to conduct local research, to determine changes in the state along the vessels, excludes electrical effects on the patient when conducting research.

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