Determination of blood flow velocity by means of analysis of the laser speckle-field dynamics

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Abstract. In this paper the method of microcirculatory blood flow velocity registration is considered. The proposed method is based on speckle pattern analysis. The measuring setup of blood flow velocity is presented. Using this setup, blood flow velocity of a group of people under various conditions has been studied and the results of these studies are presented.

1. Introduction
Monitoring of person microcirculatory bed state is one of the important problems of modern medical diagnostics [1, 2]. Due to the fact that many diseases cause changes of microcirculatory blood flow velocity, and timely diagnosis of these diseases prevents the development of pathologies [3]. Currently, there are many methods for assessing of the capillary bed state [4-8]. However, the most effective diagnostic methods for determining the main parameters of microcirculation include the method of dynamic light scattering [9-11]. This method is non-invasive, which means it allows to diagnose any changes in dynamic [12,13]. Thus, it is its significant advantage [14].

2. Mathematical approach
Quasi-random signals are used to analyze the blood flow velocity. A distinctive feature of such signals is the impossibility of predicting their instantaneous value at a specific point in time [15-17]. Therefore, individual implementations of such signals can be described by random functions \( x(t) \). The values of which at any moment of time \( t \) are random quantities [18, 19]. The processing of such signals can be carried out with the help of statistical methods, namely, correlation analysis.

The autocorrelation function of the signal can be calculated as:

\[
R(\tau) = \lim_{T \to \infty} \frac{1}{T} \int_{0}^{T} [x(t) - m_x][x(t + \tau) - m_x]dt = \lim_{T \to \infty} \frac{1}{T} \int_{0}^{T} x(t)x(t + \tau)]dt - m_x
\]

where \( m_x \) is the expectation of a random variable calculated as:

\[
m_x = \lim_{T \to \infty} \frac{1}{T} \int_{0}^{T} x(t)dt
\]

The correlation time is the time shift \( \tau_k \) above which the correlation can be neglected under the conditions of a particular experiment [20]. The correlation time is calculated from the formula

\[
\tau_k = \frac{1}{\sigma^2} \int_{0}^{\infty} R(\tau) d\tau
\]
where $\sigma^2_x$ is the standard deviation calculated as

$$\sigma^2_x = \lim_{T \to \infty} \frac{1}{T} \int_0^T [x(t) - m_x]^2 dt$$  \hspace{0.5cm} (4)

As a result of processing of the recorded signals, the autocorrelation functions were obtained. From them the correlation time ($\tau_k$) was found from the level of 1/e, and the blood flow velocity was calculated using the following equation

$$v = \frac{\lambda}{2\pi \tau_k}$$  \hspace{0.5cm} (5)

3. Measurement setup
To study the dynamics of microcirculatory blood flow in the laboratory, a measuring setup was developed (figure 1).

![Figure 1. Measurement setup: 1 — semiconductor laser with a wavelength of 650 nm, 2 — a diaphragm, 3 — collecting lens, 4 — object of study, 5 — multimode fiber, 6 — photomultiplier tube (PMT), 7 — ADC, 8 — PC.](image)

As a source of radiation, we use the single-mode laser module with the power of continuous-wave [17, 21-23] radiation to 20 mW in the spectral range near 650 nm. The diaphragm is used to limit the cross section of the laser beam in a given optical system. Its application is necessary for more accurate focusing of the light beam on the object of study. The collecting lens is chosen in such a way that the focal length is 8 cm, which is selected on the basis of the technical possibilities for the implementation of the measuring setup [20, 24-25]. The technical parameters are selected experimentally, so that the scattered signal of maximum power is fed to the receiving part of the installation (table 1).
Table 1. Technical parameters of the measurement setup.

| Parameter                                                      | Value |
|---------------------------------------------------------------|-------|
| The distance from the aperture to the collecting lens: L1     | 6 cm  |
| The distance from the lens to the object of study: L2         | 8 cm  |
| The angle of diffusely scattered radiation: a                 | 30°   |
| The distance from the object of study to the receiving part (fiber): L3 | 7 cm  |

Laser radiation is scattered on the object of study, forming a dynamic speckle pattern [26-29]. The speckle-field is transferred to photomultiplier by an optical fiber, then the signal passes to the photomultiplier and the ADC, where it is amplified and digitized at the frequency 50 MHz. Data processing is carried out using a specially developed program on a PC, which is based on the method of autocorrelation signal processing [30].

4. Results
In this study, we measured the speed of microcirculatory blood flow by detecting a signal obtained by multiple scattering of laser radiation on erythrocytes. As a result of processing the detected signals, the autocorrelation functions were calculated, the form of which is shown in figure 2. The autocorrelation functions were calculated in a specially developed program [31] in the Python programming environment. Also, this software package automatically calculates the decay time of the autocorrelation function (correlation time), which is later used to calculate the speed of red blood cells in the capillaries.

![Figure 2. Autocorrelation function that was calculated.](image)
In figure 3 presents the results of a study of blood flow velocity in five volunteers. The experiment was conducted under three different conditions: under normal conditions, during physical exertion, and with a pinch of a finger.

Research results show that during exercise, the speed of capillary blood flow increases. And when a finger is clamped, the blood vessels are clamped, which leads to a sharp drop in blood flow velocity in the microvasculature.

**Figure 3.** The results of the study of blood flow velocity in 5 volunteers under different conditions: under normal conditions, during physical exertion, and during clamping of vessels.

5. Conclusion
This paper presents the measurement setup of blood flow velocity registration. The results of studies of blood flow dynamics in a group of volunteers under various conditions are presented. The measurement results showed that the installation is sensitive to external factors and allows you to record rapid changes in the speed of capillary blood flow. Under normal conditions, the blood flow rate in patients can reach 5 mm/s, the measurement results confirm this theoretical fact [2, 32-37]. Also, the rate of blood flow in patients varies, depending on the state of their microvasculature, this fact will allow doctors to monitor the state of the human capillary system.

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