Application of the Wavelet Spectrum of the Oscillations of Basal Blood Flow During Cold Pressor Tests on the Fingers

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***Abstract*— In the article we evaluated the possibility of using different methods of analysis of signals of laser Doppler flowmetry and tissue reflectance oximetry in the study of oscillations of basal blood flow before and after the cold pressor tests on the fingers. We conducted the experimental study and evaluated the results. The data revealed that the use of spectral analysis and adaptive wavelet transform allows for the tracing of the change dynamics of basal blood flow modulation and quantified adaptive changes in the blood microcirculation systems after the stress tests in the form of the cold pressor test.**

***Keywords*— non-invasive diagnostics; laser Doppler flowmetry; tissue reflectance oximetry; pulse oximetry; basal blood flow; cold pressor test; spectral analysis; adaptive wavelet filtering.**

I. INTRODUCTION

Today, different non-invasive optical diagnostic methods are employed to study the state of the basal blood flow of blood microcirculation systems [1], such as the method of laser Doppler flowmetry (LDF) and tissue reflectance oximetry (TRO).

The LDF method is based on the probing of biological tissue using laser radiation and the analysis of the reflected and scattered light from moving red blood cells. An important feature of this method is the possibility of obtaining *in vivo* whole spectrum recordings of rhythmic processes in the microvasculature from the pulse to the circadian rhythms, which play an important role in the functioning of the system blood microcirculation [2]. The TRO method is based on spectrophotometric analysis of the different fractions of hemoglobin and allows you to evaluate *in vivo* dynamics of transport and the amount of blood oxygen saturation in microvessels [3].

Spectral analysis has been increasingly used in recent years to interpret laser Doppler flowmetry and tissue reflectance oximetry analysis in studies of basal blood flow in blood microcirculation systems [4]. This approach provides information about time-averaged changes in the amplitude of oscillations in endothelial (0.0095-0.02 Hz), neurogenic (0.021-0.046 Hz), myogenic (0.047-0.145 Hz), breathing (0.2-0.4 Hz) and cardiac (0.8-1.6 Hz) ranges [5-7]. However, this approach does not allow the evaluation of the amplitude-time characteristics of the oscillation, which is important in the analysis of adaptive changes after various provocative testing (load tests). 3D analysis incorporating the adaptive wavelet filtering signal is currently used to estimate the changes in blood flow oscillation amplitude in time and frequency [8, 9].

As provocative testing (load tests) use different functional stress tests such as the occlusion test, respiratory test, postural test, thermal test, cold test, which allow to detect hidden hemodynamic disorders and evaluate the possible reactions of system blood microcirculation on this test [10-12]. The aim of this work was to evaluate the possibilities of this type of LDF and TRO signal analysis when using the cold pressor test as a provocative testing on the blood microcirculation system.

II. MATERIALS AND METHODS

To realize this aim we conducted the experimental studies. The experimental studies were carried out on 32 healthy volunteers – 16 male (mean age of 21.7±1.4 years) and 16 female (mean age of 21.6±1.6 years). The cold pressor test (CPT) was carried out in the form of complete immersion of the hands for 5 min in a container with cold water at a temperature of about 15 °C. This test creates the conditions for assessing the functional status of MTS and detects possible violations at an early stage. Studies were conducted on the palmar surface of the distal phalanx of the third finger of the right hand, in the sitting position, the right forearm on a table at heart level, with pre-adaptation to ambient temperature. Registration of basal blood flow parameters was carried out for 5 min before the start of the CPT, immediately after and 20 min after its completion. Following this, an amplitude-frequency analysis and adaptive wavelet transform were performed, with the analysis of changes in blood flow in time and frequency.

The experimental research was conducted using the «LAKK-OP» system (SPE «LAZMA», Russia) which is presented in Fig. 1a. This device was designed for research of biological tissue by simultaneously using methods LDF with a wavelength of laser probe 1064 nm, TRO with wavelengths sensing 530 and 630 nm and pulse oximetry. The location of

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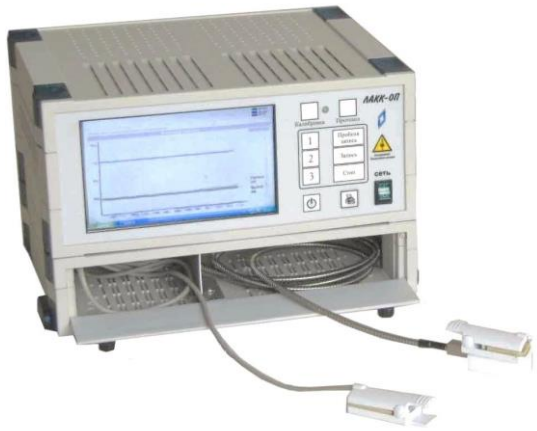
the optical sensors on the fingers during the experimental studies is presented in Fig. 1b. For the frequency analysis of the different regulatory mechanisms of the microcirculation (endothelial, neurogenic, myogenic, respiratory and cardiac oscillations), LDF- and TRO-graphs were registered using the LDF 3.0.2.384 software. This software uses a continuous wavelet transform, with the Morle complex valued wavelet being used as the analyzing wavelet [8].



a

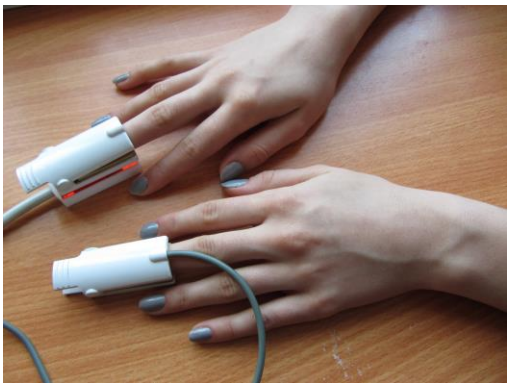


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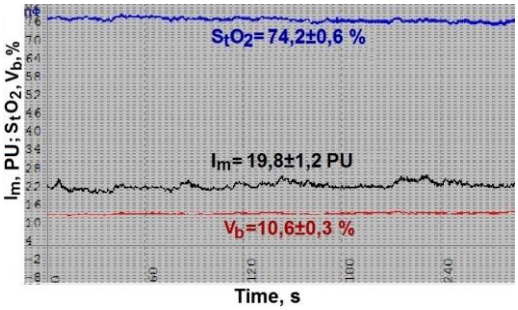
Fig. 1. The «LAKK-OP» laser analyzer of blood microcirculation used by general practitioners (a) and position of the optical sensors on the fingers of volunteer during the research (b)

Thus, in the course of experimental studies performed, the basic parameters of the basal blood flow of the blood microcirculation system registered were: index of blood microcirculation (I_m, PU), tissue oxygen saturation (S_tO_2, %), relative blood volume (V_b, %), arterial oxygen saturation (S_aO_2, %).

An amplitude-frequency analysis and adaptive wavelet filtering (3D-analysis) LDF- and TRO-graphs were then carried out. We determine the amplitude of the endothelial (A_e), neurogenic (A_n), myogenic (A_m), breathing (A_b) and cardiac (A_c) oscillations.

Fig. 2 shows examples of registered LDF- and TRO-graphs and their amplitude-frequency spectrums before and after the cold pressor test. Fig. 3 shows a 3D-analysis of perfusion before and after the CPT.



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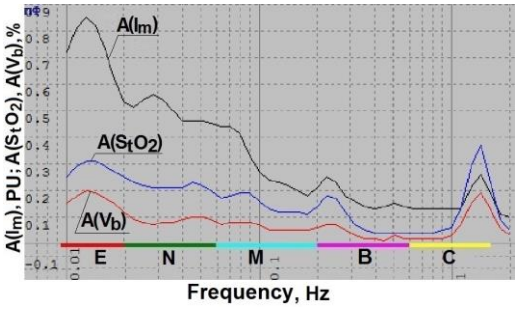

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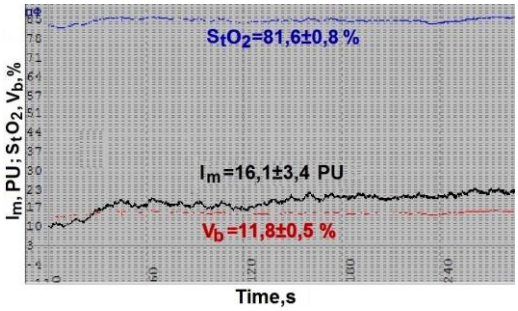

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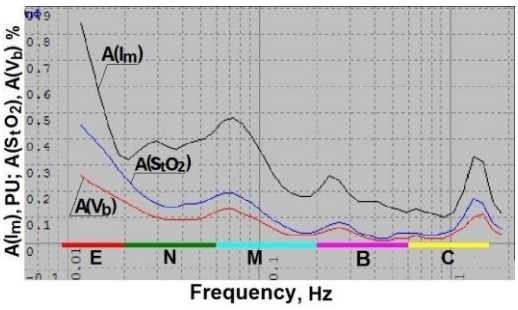
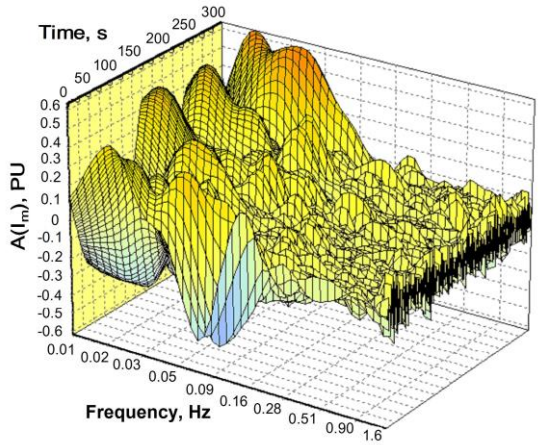


d

Fig. 2. Examples of registered LDF- and TRO-graphs and their amplitude-frequency spectrums before (a, c) and after (b, d) the cold pressor test; E – endothelial, N – neurogenic, M– myogenic, B – breathing, C – cardiac ranges



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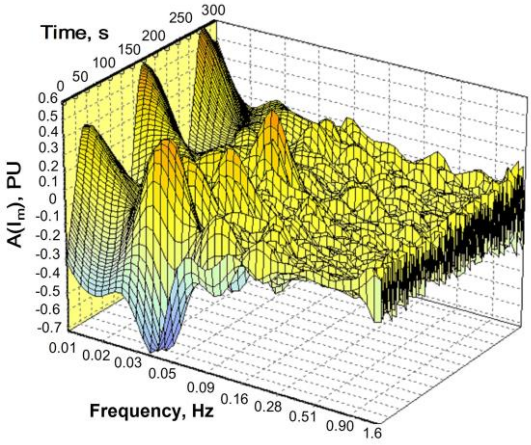

b

Fig. 3. Examples of the 3D wavelet analysis of perfusion before (a) and after (b) the cold pressor test

Due to the large range of measurements in the oscillation amplitudes of LDF- and TRO-graphs, comparison of the amplitudes of the oscillations and analysis of regulatory mechanisms requires the analysis oftheir amplitudes normalized in the standard deviation (σ) and the average value of the index of microcirculation (I_m) and tissue oxygen saturation (S_tO_2).

Thus, the definition of the contribution of the amplitude fluctuations of a definite frequency range relative to the average modulation of blood flow (A/σ) allows excluding the impact of non-standard conditions for research and evaluating the intensity of oscillation in different ranges in relation to the average oscillatory process. Determination of the contribution of the amplitude oscillation relative to the average value (A/I_m) allows to determine tension of regulation of the blood flow under the influence of the different active factors or modulation of the blood flow under the influence of the passive mechanisms [13].

III. Results and Discussion

The perfusion oscillation data were processed statistically and presented in the table 1, while for tissue oxygen saturation were statistically processed and presented in table 2. With the use of the Mann-Whitney test [14], the difference in value of the parameters analyzed before CPT (BT1), immediately after (BT2) and 20 min after CPT completion (BT3) were estimated.

TABLE I. The Results of Evaluation of Oscillation Parameters of Perfusion

№	Parameter	Basic Test		
		BT1	***BT2***	***BT3***
1	I_m, PU	18.0±4.5	12.0±6.2*	14.4±5.8*
2	$A(I_m)_e$, PU	1.053±0.589	1.135±0.887	1.114±0.709
3	$A(I_m)_n$, PU	0.929±0.445	0.951±0.499	1.223±0.602
4	$A(I_m)_m$, PU	0.753±0.316	0.591±0.361*	0.782±0.398
5	$A(I_m)_b$, PU	0.210±0.063	0.179±0.074*	0.193±0.083
6	$A(I_m)_c$, PU	0.310±0.124	0.249±0.093*	0.303±0.137
7	$A(I_m)_e/I_m$, AU	0.068±0.052	0.113±0.085*	0.097±0.077*
8	$A(I_m)_n/I_m$, AU	0.059±0.038	0.098±0.060*	0.102±0.065
9	$A(I_m)_m/I_m$, AU	0.047±0.028	0.058±0.039	0.061±0.037
10	$A(I_m)_b/I_m$, AU	0.012±0.005	0.019±0.015*	0.015±0.010
11	$A(I_m)_c/I_m$, AU	0.019±0.011	0.026±0.015*	0.026±0.016
12	$A(I_m)_e/\sigma$, AU	0.520±0.128	0.449±0.145	0.473±0.163
13	$A(I_m)_n/\sigma$, AU	0.475±0.135	0.440±0.195	0.542±0.118*
14	$A(I_m)_m/\sigma$, AU	0.397±0.113	0.263±0.145*	0.372±0.169
15	$A(I_m)_b/\sigma$, AU	0.127±0.072	0.088±0.049*	0.102±0.064
16	$A(I_m)_c/\sigma$, AU	0.175±0.086	0.121±0.056*	0.153±0.068

*- statistically significant differences of values of indicators after the CPT in relation to values of indicators before exposure with $p<0.05$ for the Mann-Whitney test

TABLE II. The Results of Evaluation of Oscillation Parameters of Tissue Oxygen Saturation

№	Parameter	Basic Test		
		BT1	***BT2***	***BT3***
1	S_tO_2, %	72.1±6.2	71.8±10.0	71.3±6.9
2	V_b, %	9.7±1.8	8.3±1.8*	8.7±1.8*
3	$A(S_tO_2)_e$, %	0.819±0.456	1.105±0.863	0.973±0.685
4	$A(S_tO_2)_n$, %	0.642±0.309	0.738±0.485	0.851±0.550
5	$A(S_tO_2)_m$, %	0.407±0.169	0.354±0.208	0.464±0.281
6	$A(S_tO_2)_b$, %	0.105±0.058	0.082±0.053*	0.092±0.072
7	$A(S_tO_2)_c$, %	0.298±0.148	0.154±0.087	0.246±0.154
8	$A(S_tO_2)_e/ S_tO_2$, AU	0.012±0.007	0.018±0.018	0.014±0.011
9	$A(S_tO_2)_n/ S_tO_2$, AU	0.009±0.005	0.011±0.009	0.013±0.009
10	$A(S_tO_2)_m/ S_tO_2$, AU	0.006±0.003	0.005±0.004	0.007±0.005
11	$A(S_tO_2)_b/ S_tO_2$, AU	0.002±0.001	0.001±0.001	0.001±0.001
12	$A(S_tO_2)_c/ S_tO_2$, AU	0.004±0.002	0.002±0.001*	0.004±0.002
13	$A(S_tO_2)_e/\sigma$, AU	0.531±0.143	0.505±0.165	0.556±0.157
14	$A(S_tO_2)_n/\sigma$, AU	0.434±0.137	0.396±0.198	0.508±0.162
15	$A(S_tO_2)_m/\sigma$, AU	0.296±0.124	0.200±0.121*	0.296±0.152
16	$A(S_tO_2)_b/\sigma$, AU	0.083±0.060	0.054±0.046*	0.068±0.067
17	$A(S_tO_2)_c/\sigma$, AU	0.240±0.161	0.108±0.098*	0.188±0.132

*- statistically significant differences of values of indicators after the CPT in relation to values of indicators before exposure with $p<0.05$ for the Mann-Whitney test

Analysis of the data revealed that adaptive changes were different for all volunteers. Statistically significant differences

of the analysed parameters were observed immediately after the CPT. Most volunteers exhibited an increase of oscillation amplitudes within endothelial and (or) neurogenic ranges. For example, one of the volunteers on the background of inhibition of myogenic oscillation amplitudes (before CPT – $A(I_m)_m$=0.74 PU; immediately after – $A(I_m)_m$=0.42 PU) the values of the amplitudes of low-frequency oscillations were as follows: before CPT – $A(I_m)_e$=0.77 PU and $A(I_m)_n$=0.50 PU; immediately after – $A(I_m)_e$=1.68 PU and $A(I_m)_n$=0.90 PU. Also, there is a change in amplitudes of oscillations of tissue oxygen saturation: before CPT – $A(S_tO_2)_e$=1.03 % and $A(S_tO_2)_n$=0.70 %; immediately after – $A(S_tO_2)_e$=3.81 % and $A(S_tO_2)_n$=1.35 %. Activation of the blood flow oscillations of the sympathetic range mainly occurs as a result of stimulation of cold receptors within tissue and activation of adrenergic sympathetic nerve fibres [15]. The growth of the oscillation amplitudes of endothelial origin may be indicative of activation of the endothelium stimulated by the synthesis of nitric oxide by the reaction of cold vasodilation induced by cooling of the arms. But increasing neurogenic amplitudes with decreasing of myogenic oscillations there is an indicator of resistance reduction and activation pathways are not nutritive blood flow. 20 min after CPT, most volunteers showed stabilization of low frequency vibrations, for example, for the same volunteer ($A(I_m)_e$=0.67 PU and $A(I_m)_n$=0.84 PU; $A(S_tO_2)_e$=0.74 % and $A(S_tO_2)_n$=0.41 %) and recovery of myogenic oscillations ($A(I_m)_m$=0.96 PU). This may indicate the termination of adaptive changes and restoration of the functional state of the study area, which is also good to be seen in the timeline.

In addition, for some volunteers we observed an increase in the amplitude of low-frequency oscillations and reduced amplitudes of myogenic oscillations perfusion (for example, immediately after CPT – $A(I_m)_e$=1.15 PU, $A(I_m)_n$=1.37 PU, $A(I_m)_m$=0.84 PU; after 20 min of CPT – $A(I_m)_e$=2.84 PU, $A(I_m)_n$=2.61 PU, $A(I_m)_m$=0.35 PU). This may indicate a lack of recovery of functional status in the study area and the presence of possible violations of the basal blood flow.

IV. Conclusion

Thus, the analysis of perfusion oscillations and tissue oxygen saturation oscillations using adaptive wavelet transform allows us to trace the dynamics of changes in modulation of basal blood flow and to quantify the adaptive changes in the blood microcirculation system after stress tests in the form of CPT.

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