

# Correlation of skin temperature and blood flow oscillations

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## ABSTRACT

Interrelation of skin temperature and blood flow oscillations of fingers under normal conditions in healthy subjects has been investigated. Oscillations of a blood flow were measured by means of photoplethysmography; oscillations of a temperature were registered by means of thermal imaging camera.

The method of blood flow reconstruction by temperature oscillations with the use of the Pennes bioheat transfer equation and a definition of delay time of a temperature in relation to blood flow signal has been described. Temperature oscillations have a lag in relation to blood flow oscillations of approximately 10-20 seconds. Delay time of temperature waves can be used for the definition of an effective thickness of a tissue layer separating blood vessels and skin surface.

Use of the described technique of comparison of finger blood flow and temperature oscillations allows to raise correlation coefficient of the signals from 0.35 to 0.63 on average, which testifies of high degree of conditionality of temperature oscillations by blood flow oscillations.

The considered method of non-contact restoration of blood flow oscillations by means of temperature oscillation measurements might find practical application in skin thermal lesions research, research of influence of physical and chemical factors on a skin microcirculation.

**Keywords:** temperature oscillations, blood flow oscillations, thermal imaging, photoplethysmography, correlation coefficient, bioheat transfer equation

## 1. INTRODUCTION

Results of investigation of temperature and blood flow oscillations contain restricted and frequently contradictory details of determining of temperature oscillations by blood flow oscillations. For example, in [1] reported similarity of blood flow oscillations and temperature oscillations waveform and presence of 20-30 second lag between the signals. On the other hand, in [2] it was said about absence of lag between slow oscillations of temperature and level of blood flow. Thus, the question about the degree of dependence between temperature oscillations and local blood flow remains open. What are the possibilities of blood flow restoration by means of temperature oscillations? How can best correlations between blood flow and temperature oscillations be achieved?

The aim of the study is to investigate the interrelation between temperature and blood flow oscillations of fingers in healthy subjects under normal environmental conditions, define the correlation of the two signals in time domain, and possibilities of restoration of blood flow oscillations by means of temperature oscillations.

For investigations of physiological functions of a body through temperature measurements it is preferable to use non-contact infrared thermal imaging methods, which allow determination of temperature with high time, spatial, and temperature resolution<sup>3</sup>.

For estimation of blood flow oscillations alongside with uses of laser and ultrasonic Doppler methods there is a well known method of photoplethysmography (PPG) which measures infrared radiation absorption by hemoglobin of blood that circulates in surface tissues.

Amplitude of PPG depends on microvessels tonus and heart stroke volume. Our investigations is carried out under conditions of minor variations of a stroke volume, therefore changes of PPG amplitude describes variation of blood flow as a result of microvessels tonus variation. Earlier<sup>4</sup> high correlation of PPG signal and blood flow oscillations has been established (correlation coefficient  $r=0.94$ ), that testifies to high opportunities of photoplethysmography in blood flow investigations.

When blood propagates from the heart through main vessels to the periphery, it transfers heat to surrounding tissues, heat energy loss raises as microvessels blood supply increases, thus heat transferred from blood to surface of the body. Accordingly, it stands to reason to expect that blood supply oscillations should be accompanied by corresponding temperature oscillations.

Thus, the main interest of the paper is to investigate a correlation between temperature oscillations by means of thermal imaging method and blood flow oscillations estimated by means of photoplethysmography.

## 2. METHODS

Simultaneous measurements of finger temperature and blood flow oscillations were made for 11 healthy subjects under normal environment condition during 20 minutes. The blood flow (pulse volume) was measured by means of a photoplethysmography sensor KL-79102 as a component of the biomedical measurement system KL-72001(Taiwan). Temperature measurements were carried out by means of thermal imaging camera ThermoCam SC 3000 Flir Systems (Sweden) with thermal sensitivity  $0.02^{\circ}\text{C}$ .

Measurements were performed after adaptation of subjects to lab conditions in the course of 10-15 minutes. The age of the subjects was 20 to 35 years old. The subjects didn't consume any tonic or alcoholic drinks before measurements were taken. There were no smokers in the group of subjects. All measurements were carried out in the sitting position, hands placed on the table with the surface made of material with small heat capacity (foam plastic). All measurements were carried out from the index finger. Index finger located on the top of the PPG sensor. Sample rate of thermal imaging camera is 2 Hz, and of PPG measurements is 50 Hz.

The sequence of signal processing of photoplethysmography and thermal imaging data are illustrated by the diagram in Figure 1.

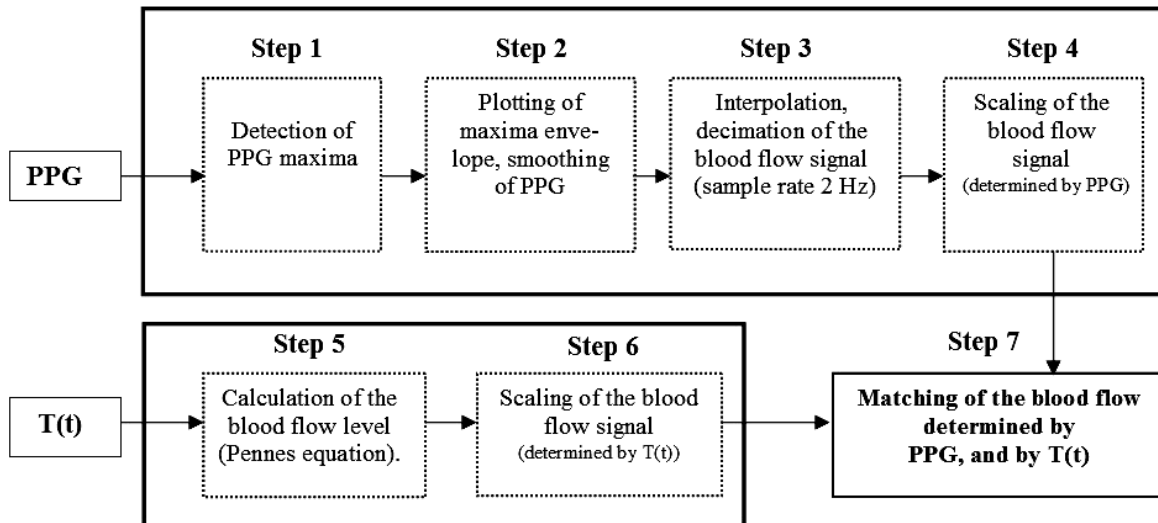


Figure 1. Processing of the photoplethysmography (PPG) and the temperature  $T(t)$  signals.

A maxima envelope of PPG used as characteristics of a finger blood flow (step 1 in Figure 1). Fourier filtering of low-frequency PPG signal may be an alternative method of slow oscillations detecting<sup>5</sup>.

Further, the slowly varying PPG signal smoothed (function ksmooth of MathCad ) and scaled (step 2 in Figure 1). Linear scaling (1) of T(t), and PPG signals represented values in the range of [0;1].

$$Y_{norm}(t) = \frac{Y(t) - Y_{min}}{Y_{max} - Y_{min}}, \quad (1)$$

where  $Y_{min}$  is the minimum value of signal,  $Y_{max}$  is the maximum value of signal,  $Y(t)$  is the value of signal in a time t.

The Pennes bioheat transfer equation is used for restoration of blood flow oscillations by temperature oscillations<sup>6</sup>, represented in the work [7] and in the modified form as equation (2). The Pennes equation is a non-stationary heat transfer equation with heat sources, transferred heat to the skin as a result of blood flow, and source of metabolic heat:

$$\rho \cdot C \cdot V \cdot \frac{dT(t)}{dt} = -H_{air} \cdot S \cdot (T(t) - T_{air}) + \rho_b \cdot C_b \cdot \omega(t) \cdot (T_b - T(t)) + Q_m, \quad (2)$$

where  $S = \frac{\pi \cdot D^2}{2}$  is the surface of the finger,  $V = \frac{\pi \cdot D^3}{12}$  is the volume of the finger, t is the time,  $\rho$  is the tissue density,  $\rho_b$  is the blood density, C is the specific tissue capacity,  $C_b$  is the specific blood capacity, D is the diameter of finger, S is the surface of the finger (surface of hemisphere),  $T_b$  is the blood temperature,  $T_{air}$  is the air temperature, T(t) is the temperature of skin surface, V is the finger volume (hemisphere),  $\omega$  is the volume blood flow,  $Q_m$  is the quantity of metabolic heat,  $H_{air}$  is the convection coefficient of air. Description of parameters and their used values are given in Table 1<sup>7</sup>.

If a temperature difference between skin and environment increases, the equation (2) shows a slowing of a temperature dynamics, and if blood flow and intensity of metabolic heat sources increases, then it shows accelerating.

Table 1. Values of parameters used in equation (3).

Symbol	Denomination	Value
$\rho$	tissue density	1057 kg/m <sup>3</sup>
$\rho_b$	blood density	1069 kg/m <sup>3</sup>
C	specific heat capacity of a tissue	3780 J·K/kg
$C_b$	specific heat capacity of a blood	3650 J·K/kg
D	diameter of a finger	0.011-0.016 m
$T_b$	blood temperature	37°C
$T_{air}$	air temperature	24°C
V	finger volume (hemisphere)	1.072·10 <sup>-6</sup> m <sup>3</sup>
S	finger surface (hemisphere)	4.02·10 <sup>-4</sup> m <sup>2</sup>
H	convection coefficient of air	6 W·K /m <sup>2</sup>

If there is no muscular work, then metabolic component  $Q_m$  in equation (2) can be considered as a negligible small or a constant dc component. In this case the required temperature level is supported through the balance between heat loss (first item in equation 2) and heat reception from blood (second item in equation 2). In general case, when taking into account the delay between blood flow and temperature signals, it is necessary to input the delay time argument  $\Delta t$ . Thus, neglecting the item  $Q_m$  and applying delay time  $\Delta t$ , volume blood flow  $\omega$  may be expressed from equation 2 as:

$$\omega(t_i - \Delta t) = \frac{\rho \cdot C \cdot V \cdot \frac{dT(t_i)}{dt} + H_{air} \cdot S \cdot (T(t_i) - T_{air})}{\rho_b \cdot C_b \cdot (T_b - T(t_i))} \quad (3)$$

where  $t_i$  is the time, i is the index of time counts.

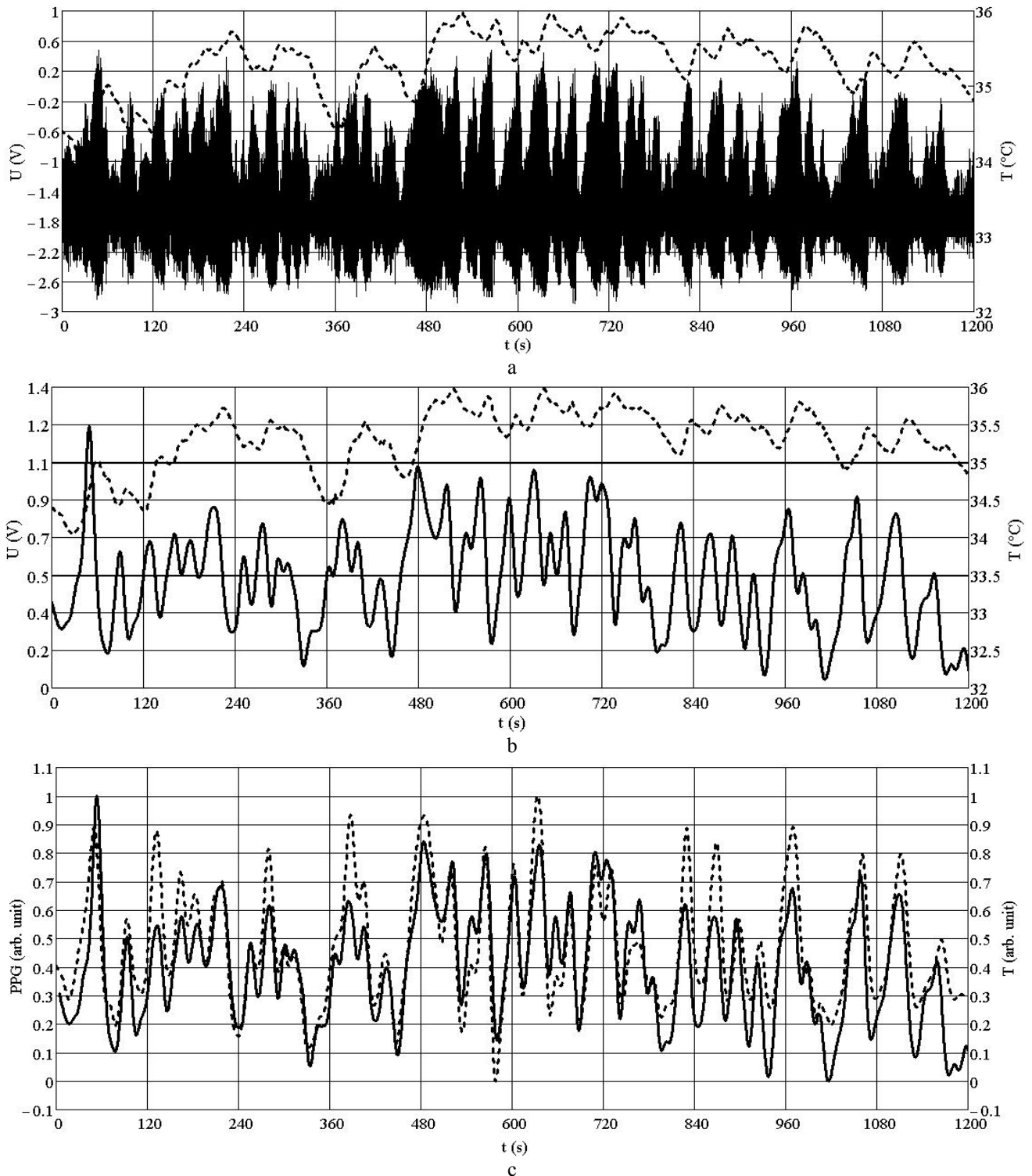


Figure 2. Results of processing of the signals describes temperature variation –  $T(t)$  (dotted line) and photoplethysmogram - PPG (solid line) for the subject №8: a – initial signals of  $T(t)$  and PPG; b – signal of  $T(t)$  and maxima envelope of PPG, c – scaling blood flow signals, calculated from  $T(t)$  and PPG (added time shift (lag)).

To determine the blood flow  $\omega$ , we substituted temperature values  $T(t_i)$  and its derivatives to the right member of equation 3 (step 5 in Figure 1). Calculation of time derivatives of temperature performed by 5 points finite difference method. The resultant signal  $\omega_T(t)$  compared with the experimental signal  $\omega_{PPG}(t)$ , determined by the PPG data (step 7 in Figure 1). Figure 2 shows an example of a signal processing in accordance with the diagram in Figure 1.

Figure 2a shows the initial temperature and PPG signals, Figure 2b shows maxima of pulse waves extracted from the PPG signal, plotting of envelope, and added interpolation (steps 1-3 in Figure 1), Figure 2c shows the temperature signal processed by substitution to the Pennes bioheat equation, and the signal of photoplethysmogram (performed steps 1-6 in Figure 1). Then carried out matching of the blood flow signals determined by temperature and by photoplethysmography (step 7 in Figure 1).

Blood flow oscillations in subcutaneous microvessels results in origination of temperature waves, propagating from blood to the skin surface. Since velocity of a temperature wave propagation in a tissue must have finite magnitude, expected presence of a delay of a skin temperature variation relative in varying of blood flow supply in superficial vessels. Experimentally, it may be evident from presence of the delay  $\Delta t$  between slow temperature and PPG oscillations (see in Figure 2 a, b).

Determination of a delay time  $\Delta t$  of the temperature variation in relation to volume blood flow was performed by means of cross-correlation function (4).

$$F(\Delta t_j) = \sum_i \omega_T(t_i + \Delta t_j) \cdot \omega_{PPG}(t_i) \quad (4)$$

where  $j$  is the index of time shift  $\Delta t$ .

The value of the delay time determined from the maximum of cross-correlation function (4). In Table 2 results of the delay determination for each subject are given. In Figure 2c to the temperature signal  $T(t)$  added time shift, equals of delay time  $\Delta t$  (step 7 in Figure 1).

At calculation of time derivative of temperature by equation (3) additional time shift which equals approximately 8 seconds occurs. The value of the shift added to the values is determined by equation (4) and tabulated in Table 2.

At presence of high intensity non-stationary processes of heat exchange the group velocity of temperature wave  $V$  may be estimated with the use of delay time value  $\Delta t$  by expression<sup>8</sup>:

$$V = \sqrt{\frac{\lambda}{\rho \cdot c \cdot \Delta t}} \quad (5)$$

where  $\lambda = 0.3 \text{ J}\cdot\text{K}/(\text{m}\cdot\text{s})$  is the heat conductivity of tissue;  $\rho = 1057 \text{ kg}/\text{m}^3$  is the tissue density;  $c = 3780 \text{ J}\cdot\text{K}/\text{kg}$  is the specific heat capacity of tissue. By value of velocity  $V$  and delay time  $\Delta t$  estimates the thickness of tissue -  $d$  for each subject.

While temperature wave propagates to the skin surface, it passes through layers with different thermal constants. If instead of multilayer model one-layer model with effectiveness thermal constants is used, than value of thickness -  $d$  estimated by equation (5) can be considered as an effectiveness or averaged thickness (calculated values of thickness  $d$  for each subject see in Table 2).

Than carrying out comparison of the blood flow variation, determined by temperature data -  $\omega_T(t)$  and by photoplethysmogram  $\omega_{PPG}(t)$  with the aim of calculation of correlation coefficient (6):

$$r = \frac{\sum_i (\omega_T(t_i) - \overline{\omega_T}) \cdot (\omega_{PPG}(t_i) - \overline{\omega_{PPG}})}{\sqrt{\sum_i (\omega_T(t_i) - \overline{\omega_T})^2 \cdot \sum_i (\omega_{PPG}(t_i) - \overline{\omega_{PPG}})^2}} \quad (6)$$

where  $\overline{\omega_T}$ ,  $\overline{\omega_{PPG}}$  are the average values of volume blood flow, determined by temperature data and by photoplethysmography, respectively (see  $r$  values in Table 2).

### 3. RESULTS

Thus, temperature variation and photoplethysmogram for 11 subjects has been processed according to the diagram in Figure 1. Table 2 contains results of determination of delay time between the signals, values of the temperature wave velocity, effective thickness, correlation coefficient for each subject, and for different combinations of cases with substitution to the equation (3) and calculation of signal delay time, as well as without those operations.

Table 2. Results of determination of delay time between blood flow and temperature signals, velocity of temperature wave propagation, effective thickness of tissue layer, correlation coefficient of blood flow, calculated by temperature signal and by photoplethysmogram.

Subject Parameter		1	2	3	4	5	6	7	8	9	10	11	Avg. value
		<b>Delay <math>\Delta t</math>, s</b>	7.5	8.5	10	10.5	12	15	16	15	16	17	21
<b>Velocity V, mm/s</b>	0.1	0.094	0.09	0.085	0.08	0.07	0.07	0.07	0.07	0.07	0.06	0.08	
<b>Thickness d, mm</b>	0.75	0.8	0.87	0.89	0.95	1.06	1.1	1.06	1.1	1.13	1.26	1	
<b>Correlation T(t) and PPG</b>													
<b>1</b>	without delay without (3)	0.8	0.32	0.52	0.25	0.29	0.18	0.41	0.27	0.19	0.3	0.35	0.35
<b>2</b>	with delay without (3)	0.82	0.42	0.61	0.42	0.34	0.34	0.61	0.53	0.26	0.42	0.54	0.48
<b>3</b>	Without delay with (3)	0.53	0.73	0.46	0.64	0.5	0.27	0.34	0.47	0.18	0.68	0.62	0.49
<b>4</b>	with delay with (3)	0.53	0.73	0.58	0.65	0.52	0.7	0.68	0.84	0.27	0.72	0.71	0.63

### 4. DISCUSSION

Data in Table 2 shows that average delay times of the temperature signal in relation to low frequency signal of photoplethysmogram amplitude amounts 13.5 seconds and take values in a range of 8-21 seconds. Delay time is an individual parameter of each subject, mainly connected with the thickness of the subject's bloodless superficial tissue.

Tissue thickness, which characterizes occurrence depth of blood vessels, serves as a source of temperature wave, has values around 1 mm. Correlation coefficient of the temperature and the blood flow significantly change, depending on whether or not blood flow estimation is used by equation (3) and takes into account the delay time between signals of temperature and photoplethysmogram. Earlier<sup>9</sup> it was pointed out a presence of correlation between pulse waves of the photoplethysmogram and temperature with correlation coefficient  $r=0.55$ . At the same time before the correlation calculation of the temperature signal is not mathematically processed.

Results of the described technique shows that maximum of the correlation coefficient (see in Table 2) corresponds to the case, when the temperature signal preliminary shifts on the delay time and the blood flow is calculated on the base of temperature signal by expression (3). Thus, the correlation coefficient of the blood flow and the temperature signal must be greater if we substitute temperature variations to the equation (3), and then the signal shifts to some delay time. Using this technique allows to increase correlation coefficient, for example, correlation rises from 0.27 to 0.84 in Figure 2 and

for the group of subjects from 0.35 to 0.63 on average (see Table 2).

Results shows that in investigations of the correlation of blood flow and temperature variation Pennes bioheat transfer equation is more correctly represented as equation (3) with retarded argument ( $t-\Delta t$ ). In other words, under normal environment conditions the finger temperature variation at the time  $t$  is a consequence of the blood flow changing at the previous time  $t - \Delta t$ , i.e. the temperature variation depends on the prehistory of the blood flow variation.

According to the described technique, value of the delay time may be used in determination of the effective thickness of tissue layers that separate the blood vessels, as sources of temperature wave, and the surface of the skin. This technique may find practical application in skin and superficial tissue thermal damage investigations, or in the description of physical and chemical impacts on the skin blood flow. Using of bioheat transfer equation in the form of equation (3) allows to perform restoration of the blood flow of superficial tissue by means of non-contact thermal imaging measurements of temperature. It might be especially useful for prevention of contact influence on the measured subject or at high complexity of contact measurements of a blood flow. In addition, during the execution of various exercise tolerance tests, e.g. cold test, the temperature measurements gives statistically significant differences of extremity state before, during and after cooling. At the same time, varying of the blood flow might be statistically non-significant<sup>10</sup>. The [11] given details, describes the pronounced temperature reaction of fingers to another exercise tolerance test – occlusion test. After the cuff deflation and opening of blood flow, the temperature changing of fingers occurs not immediately, but with some delay time.

Analysis of equation (3) shows high significant determination of the waveform of blood flow signal by the temperature time derivative. Other parameters that include environmental temperature, thermal constants of blood and tissue, finger geometry and convection coefficient change values of the finger temperature, but not the temperature signal waveform. It follows, that for the determination of delay time of temperature variation its necessary at least to estimate temperature time derivative.

As shown in Table 2, determination of the delay time of the temperature signal in relation to blood flow signal and utilization of equation (3) increased the correlation coefficient of the signals in time domain, which must also lead to increasing of the correlation coefficient in time-frequency domain. Consequently, phase synchronism of the blood flow and the temperature oscillations analyzed in [10] and the correlation of their spectrum, investigated in [12], should increase. Stated high degree of the interrelation between the blood flow and the temperature allows using thermal imaging technique as the non-contact method of a blood flow investigation at exercise tolerance tests as well as at rest.

## 5. CONCLUSIONS

Thus, presented findings described the method of the blood flow restoration by temperature oscillations with using Pennes bioheat transfer equation in the form of equation (3) and a determination of the temperature signal delay time in relation to the blood flow signal. It is established that the temperature oscillations lags from the blood flow oscillations of 13.5 seconds on average due to the finite time of temperature stabilization under volume blood flow variation in superficial tissue. Delay time and velocity of temperature signal propagation might be used in determination of the thickness of the tissue, which separates a blood vessels and a skin surface.

Application of the described technique of matching of the blood flow and the temperature oscillations allows to increase correlation coefficient from 0.35 to 0.63 on average, that testifies high degree conditionality of the temperature oscillations by the blood flow oscillations.

The considered method of the non-contact determination of blood flow oscillations by the temperature measurements might find practical application in thermal skin damage investigations, investigation of influence of physical and chemical factors on the circulatory dynamics in the peripheral vessels and skin microcirculation.

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