Novel Method for Recording High Frequency Human Skin Temperature Oscillations

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***Abstract*–Circuitry solution has been developed to create a prototype of the system for the registration of the high frequency human skin temperature oscillations. As they connected with blood circulation, such method allowing in the future to provide the registration of the pulse wave signal, for measuring heart rate in portable devices like smart watches and fitness bracelets. The miniature semiconductor chip diodes sensor has been used. The electronic system for the calibration of the device has been designed. For providing operation of the system in a full voltage range using the automatic set has been used for the maintenance of the operating point and of the necessary slope of the conversion factor (Volts / °C). The structural and circuit diagram has been developed. They consisted of two parts: the remoted preamplifier with the temperature sensor and the main block including all the other digital and analog parts. The developed system has following technical characteristics: the temperature resolution to be 0.01 °C and the thermal time constant of the sensor 0.05 s. The registration system testing has been performed in two ways: in a thermostat and on the human skin surface. Device contains plethysmo- and ECG-channels for obtaining data on the phases of cardiac cycles and synchronous analysis of physiological processes. The cross correlation coefficient between the temperature oscillations and the pulse wave signals laid in the diapason from 0.53 to 0.65.**

I. Introduction

In modern clinical practice, assessment to the state of blood microcirculation (movement of blood in capillaries and adjacent micro vessels) and evaluation of microcirculatory disorders in the diagnosis of a variety of diseases are relevant [1]. It's especially interesting considering the development of portable systems for monitoring human health state, involving the recording of a pulse wave signal. Optical sensors are used in a variety of solutions existing on the market, like sports bracelets and smart watches, working in reflected light (Fig. 1). They allow you to get a sufficiently high-quality signal, good enough to evaluate heart rate, while their main drawback is the increased power consumption associated with the need for a matrix of LED's. Even when operating in pulse mode, they consume a significant amount of current. Sensor for pulse wave monitoring, based on registration of fast temperature octillions, can greatly decrease power consumption.

It remains an unresolved problem for fundamental medicine, to determine the relationship between the blood supply processes at the micro and macrolevels, as well as the metabolic, thermoregulatory and other processes that accompany them [2]. Relating to the foregoing, there is considerable interest in developing and improving tools for reliable and non-invasive monitoring of blood flow in various parts of the body under various conditions and systems capable of recording all vascular elements of the blood stream, i.e. arterial, capillary and venous components.

Fig.1. Example of standard optical sensor for pulse wave registration

In clinical practice, registration of blood microcirculation is especially important for diagnostics of the cardiovascular system diseases. For example, due to impaired vascular endothelial function as consequence of atherosclerosis [2], diabetes, cancer, renal dysfunction, vasospastic (Raynaud's syndrome, vibration disease) and other pathologies, including those associated with inflammatory conditions [3]. The diagnosis of such diseases in the initial stages, when the changes are still reversible is very important. The microcirculatory bed is a part of the vascular system, in which these diseases are manifesting in the initial stages.

Existing methods for recording blood microcirculation can be classified according to the physical principles of measurement (Table I): mechanical (plethysmography), optical (photo-plethysmography, laser Doppler flowmetry (LDF) and laser speckle contrast imaging (LSCI)), acoustic ultrasound) and thermal (thermometry, thermography) [4]. The fundamental feature of microcirculation is its constant variability, which is manifested in spontaneous fluctuations in tissue blood flow.

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TABLE I COMPARISON OF THE FREQUENCY BANDS ALLOCATED FOR HRV, LDF AND TO [4, 5]

Heart Rate Variability		Laser Doppler Flowmetry		Temperature Oscillation	
Range names	Frequency range, Hz	Range names	Frequency range, Hz	Range names	Frequency range, Hz
		Pulse	0.6 – 5	Pulse	0.5 – 5
HF	0.15 – 0.4	Respiratory	0.145 – 0.6	Respiratory	0.14 – 0.5
LF	0.04 – 0.15	Myogenic	0.052 – 0.145	Myogenic	0.05 – 0.14
VLF	0.003 – 0.04	Neurogenic	0.021 – 0.052	Neurogenic	0.02 – 0.05
		Endothelial I	0.0095 – 0.021	Endothelial	0.001 – 0.02
UVLF	< 0.003	Endothelial II	< 0.0095	–	–

II. BLOOD MICROCIRCULATION

The fundamental feature of microcirculation is its constant variability, which is manifested in spontaneous fluctuations in tissue blood flow. This variability of microcirculation is inherently an objective characteristic of the level of vital activity of tissues. Rhythmic fluctuations in the blood flow and their changes make it possible to obtain information about the specific relationships of various mechanisms that determine the state of microcirculation.The nature of the oscillatory processes in the microcirculation system is rather complicated. Today, it has been established that spontaneous fluctuations in blood flow in tissues are largely, though not only, caused by vasomotions.

The physiological activity causes changes of the body surface temperature in a wide amplitude (60 dB) and frequency range (up to 5 Hz, as it's shown in the table I) ranges. This activity is associated with heartbeat pulsations, which have very small amplitude and a maximum frequency of temperature oscillations. For their registration requires high resolution and speed.

The rhythmic structure of flaxemias is the integral result of superposition of various myogenic, neurogenic, respiratory, cardiac and other indirect effects on the state of microcirculation.

Obviously, information on temperature oscillations associated with microcirculation (movement of blood in capillaries and adjacent microvessels) in all frequency ranges is of great interest for medicine and physiology of visceral systems. Regarding this, it is important to develop methods and tools for studying blood flow oscillations based on the results of skin surface thermometry. At this stage of investigation, we consider our device as a unique experimental prototype for conducting research in the field of fundamental physiology, not for implementation in clinical medicine.

Temperature oscillations (TO) of the human's body surface contain some information about physiological processes in frequency ranges from 0.001 to 2 Hz. This information can assist as a source of data on fluctuations of physiological functions (table I). Thus, the relations between micro- and macro- blood circulation are manifested in TO. Study of blood circulation is of interest for the physiology of visceral systems and medicine. The solution of scientific and technical problems of registering a TO with high speed and resolution are relevant.

The most significant frequency ranges of signals obtained by three different methods (Heart Rate Variability, Laser Doppler Flowmetry and Temperature Oscillation) are presented in the Table I for comparison. Each of these frequency ranges are associated with certain mechanisms of active modulation of blood flow in the microcirculation system. The proximity of these ranges is obvious. The analysis of literature data [5], [6] shows that a highly sensitive and fast medical thermometer designed for registration of the fast temperature oscillations of the human body surfaces (skin) should have a resolution of not worse than 0.01°C in a frequency range of temperature variations of 0.02 – 5 Hz.

Existing technical solutions do not meet these requirements [7]. Thus, the goal of the work was to develop technical solutions aimed at achieving maximum resolution and high operational properties for a system, able to register high frequency temperature oscillations on skin surface, caused by blood microcirculation and pulse wave propagation.

III. MATERIALS AND METHODS

Since 1970s, thermograms with additional registrations of the heart rate have been reported. In these thermometers, a thermocouple was used in the temperature measurement mode, and the heart rate was determined from the electrocardiogram. In the invention of S. Epstein (1985) the temperature measurement was first applied, and, in addition, the temperature change caused by the pulsations of the blood flow is determined. Those. In this method, the temperature of the mucosa of the sublingual region determines the heart rate. However, this technical solution did not find wide practical application due to inconvenience of use.

Semiconductor temperature sensors [7-10] are effectively used for recording body surface TO. There are known two types of diode temperature sensors. First of them provide stable direct current of the diode in the static mode, ensuring the steep slope of the conversion voltage to temperature with a temperature coefficient of voltage (TCV) of 2 mV/ºC. Other usage is the pulsed mode. During the measurement, the current through the diode changes in 10 times with the measurement of the forward voltage difference from the current change. However, this method has a reduced value of TCV + 0.2 mV/ºC.

Thermometers with a resolution of up to 0.001 ºC are also known, but they do not have sufficient speed for recording temperature oscillations. One way to increase the speed of the temperature sensor is to preheat the sensor to the expected temperature. Another way is to use two sensors, separated by thermal insulation material and included in the differential scheme.

The required thermal time constant of temperature (TCT) is achievable using a semiconductor diode sensor in an open-frame design. The reason for choosing such a sensor is given in the reports of A.V. Belov et. al [10].

The need for high resolution in a relatively wide operating temperature range, typical for the surface of the human body (26–34°C), determines one of the basic requirements for the thermometer – the possibility of automatic adjustment of its parameters.

The proposed circuit innovations include:

– Implementation of a packageless (open frame) transistor in a diode connection to ensure operation speed;

– Use of the mixed analog-digital scheme of the operating point (OP) automatic adjustment just in the middle of the supply voltage, to ensure the maximum dynamic range for recording temperature oscillations when the constant level of the body surface temperature changes;

– Automatic gain control to ensure the dynamic range of temperature oscillations registration;

– Use of temperature pulses for testing and calibrating the device.

Thus, according to the medical sources, the recorder should have following capabilities:

– conversion of fast TO (0.02 –5 Hz) by semiconductor miniature silicon diode sensor to an electrical signal;

– automatic selection of the first amplifier operating point position at the middle of the power supply voltage range;

– slope selection of the conversion (V/°C) during temperature registration;

– preliminary calibration of the sensitivity of the sensor (similar to the test signal of the electrocardiograph).

To reduce the effect of artifacts caused by external electromagnetic fields and to achieve high performance of the medical thermometer, the transmission of temperature data and control signals should be performed via a Bluetooth interface. Also, device should use autonomous power supply which has to ensure the duration of the operation up to 5 hours. In addition, it should be possible to connect additional physiological sensors from a photo plethysmograph sensor, a breath sensor, etc. for their synchronous recording.

According to the technical requirements the temperature sensor was developed and constructed. A temperature sensor is an open-frame silicon transistor with weight 2 mg connected in the forward direction base-emitter (the collector does not have any connection).

Proposed device is based on a combination of analog and digital solutions. Fig. 2 shows the block diagram of the temperature channel of device. The conversed signal from the output of temperature sensor goes to the input of an analog-to-digital converter (ADC) through two amplification stages with operating point and gain selection, which carried out by microcontroller (MC).

The main elements of the input part of the thermometer (Fig. 2) include:

– temperature sensor – a Russian silicon chip transistor KT307 (without package, an open-frame version) in diode connection (junction base-emitter).

– stable current source;

– the first stage of voltage amplification;

– operating point selection block of the thermometer, i.e. the source of the compensation voltage of the initial forward diode - voltage at a given temperature;

– the second stage of voltage amplification with selectable gain;

– source of current test impulses.

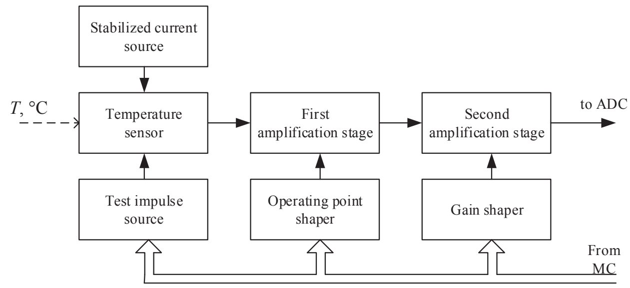

Fig. 2. Structure of the temperature channel of the device

A temperature sensor is an open-frame silicon transistor with weight 2 mg connected in the forward direction base-emitter (the collector does not have any connection).

The maximum dynamic range of temperature recording is provided by automatically setting the position of the operating point of the first amplifying stage. The operating point before the start of the measurement is set at the middle of the supply voltage. The choice of the position of the output voltage for the first amplification stage is carried out by applying the compensation voltage of the initial forward diode voltage at a given temperature. This adjustment is switching on before starting the registration and maintains the indicated voltage during the entire registration period.

Due to the value limitation of the output voltage range with increasing gain, the temperature range corresponding to the linear zone.

IV. RESULTS

The structural diagram of the system is shown in Fig. 3. It contains additional plethysmo- and ECG-channels necessary for obtaining data on the phases of cardiac cycles and synchronization of physiological processes.

The remote part of the device is placed in close proximity to the patient’s skin, for example, in the region of the wrist joint of the right hand. The skin temperature is converted by a temperature sensor into a voltage and feed to the two stages of amplifier.

To calibrate and control the correct operation of the thermometer, a test signal is generated by the square-wave current generator. Recorded input signals from sensor come from the microcontroller through Bluetooth to a computing device, for example, a personal computer (PC).

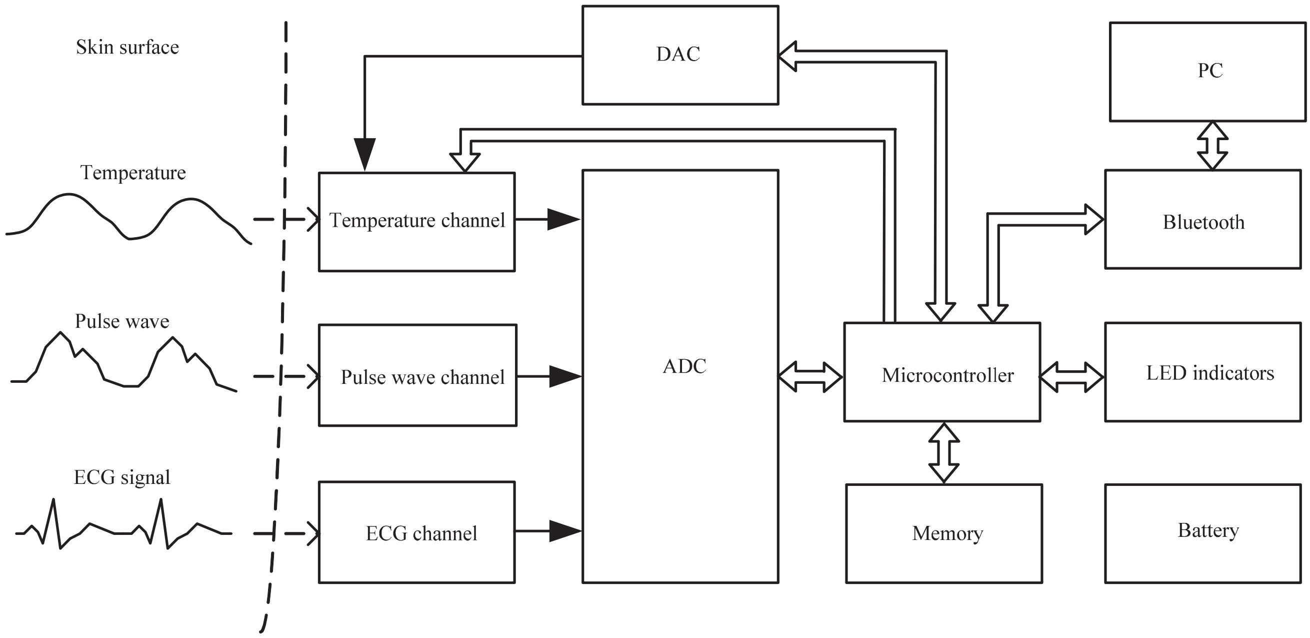

Fig.3. Structure diagram of the device with channels for temperature, pulse wave and ECG synchronous recording

The control signals sent by the PC are transmitted to the microcontroller to adjust the parameters of the thermometer during operation. The microprocessor performs the following actions:

– processing of digital output data from the ADC;

– write the data from the ADC to the memory card;

– transmission of recorded data from the MC to the Bluetooth module;

– transfer of commands for controlling the parameters of the thermometer preamplifier: the test pulse source, the DAC, the digital potentiometer.

The usage of a Bluetooth in the thermometer additionally ensures the patient's safety due to the presence of an electrical isolation and reduces the influence of power supply 50 / 60 Hz interference on the amplification stages of the thermometer. To power the device a Li-Pol battery with a capacity of 700 mAh and a nominal voltage of 3.7 V is used. To ensure a stable 3.3 V supply voltage in the digital and analog parts, two low drop out LDO linear voltage converters of the ADP3303 series are used. Due to the low power consumption of the device, the autonomy of its operation reaches 8 hours. The level of battery discharge is carried out by voltage control. The batteries could be charged using a universal USB charger. It is possible to work from an external power source with a voltage of from 3.5 to 12 V. The use of a radio channel for data transmission and an autonomous power supply significantly reduces the level of noise in all analog channels for processing physiological signals (thermo-, plethysmo- and ECG signal). The digital part is described in detail in following paper [12].

Another important elements of the experimental device are the channels for recording the pulse wave and ECG signal. Data on the maximum of the pulse wave and R-wave of the ECG signal serve for two goals. First, they make it possible to detect and verify rapid temperature oscillations (an example of such verification is shown below). The second, temporal relationship between the signals of temperature oscillations, pulse wave and ECG signal have an important physiological significance. The phase relationship between these signals allow us to estimate the propagation time of the pulse wave and temperature time constant of the surface tissues of the body.

For registration of the pulse wave, a plethysmographic sensor is used, which makes it possible to determine the surface blood filling of tissues. The optical reflective channel for recording the pulse wave signal is used. The signal from the optical sensor (Nellcor - Covidien DS100A) is fed to the input differential transimpedance amplifier, to convert the photodetector current into a voltage. The converted signal is filtered (0.05 to 40 Hz) in a given spectral range, amplified (40 – 60 dB) and fed to the matching buffer cascade and further to the input of an analog-to-digital converter (high-resolution sigma-delta ADC, 16 bits).

The ECG signal is recorded with the standard lead I. The signal taken from the disposable gluing electrodes is fed to the input of an instrument amplifier. Also, a driven right leg circuit or DRL circuit is used. It's an electric circuit that is often added to biological signal amplifiers to reduce common-mode interference [13]. The signal is filtered by a bandpass filter in the frequency range from 0.05 to 150 Hz and the notch filter to the network frequency . The gain in the passband is from 60 to 80 dB. There is a built-in quick recovery unit after overload by the input signal.

After filtering, the signal is amplified and fed to the ADC input. The developed modules for recording the electrocardiogram and pulse wave signals, realized on the basis of analog and digital nodes, allow recording signals synchronously with the TO.

The change in the parameters of the temperature oscillations corresponding to the transient processes during occlusive [14] or orthostatic samples [15], can serve as an indicator of various pathological states of microcirculatory channel. These changes allow us to calculate the reserve of capillary blood flow characterizing the adaptive reserves of the microcirculation system. The temperature constant of time characterizes the reactivity of blood vessels microcirculatory bed and is determined by the number of vascular blocks and the degree ischemia of the examined area of the body.

Fig. 4 shows the construction of the temperature sensor. This part of the registration system is structurally remote and consists of a pre-amplifier board (Fig. 4, a, item 1), placed in a special case and connected through a connector (Fig. 4, a, item 2) and a flexible cable to the main parts of the system. The temperature sensor itself is located on the tip of the flexible tab (Fig. 4, b, item 3), which reduces the effect of the temperature of the pre-amplifier board on the sensor readings. To protect the sensor from external mechanical and temperature influences, a special structural element is used - the "protective ring" (Fig. 4, b, item 4).

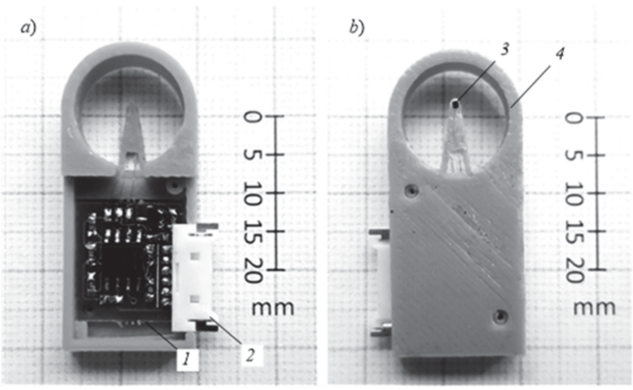

Fig. 4 Appearance of the input part of the thermometer: top view (a), bottom view (b), 1 - pre-amplifier board with control of the operating point of the first amplifying stage and the gain of the second amplifying stage, 2 - connector, 3 - temperature sensor — Russian silicon chip transistor KT307 (D1), 4 - "protective ring"

V. Discussion

To verify the right operation of the device groups of experiments were carried out. In the second group of studies, the subjects simultaneously recorded a signal of temperature and pulse wave (plethysmogram) from young healthy people with a clean skin surface. The sensor was attached to the arm with an elastic band.

Fig. 5a shows a fragment of the recording of these signals of test A. The temperature signal registered in the region of the wrist joint of the right hand of subject A is shown by a thick line (curve 1), its plethysmogram from the finger of the right hand is thin (curve 2). Since the amplitudes of these signals differ by more than a hundred times (the plethysmographic signal is much larger), then for their comparison they were normalized. The coefficient of cross-correlation of the fragments of two recording signals was 0.53 (criterion of significance $p < 0.05$).

Fig. 5b shows the fragment of the recording of the subject B. The coefficient of cross-correlation is 0.65 (criterion of significance $p < 0.05$).

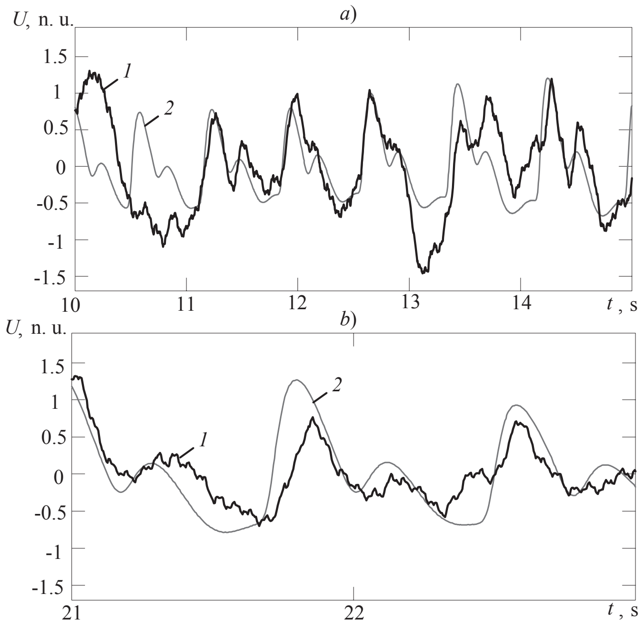

Fig. 5. Fragments of recording temperature signals (curve 1) and pulse wave (curve 2) of subjects A (*a*) and B (*b*). The correlation coefficient is 0.53 (*a*) and 0.65 (*b*), ($p < 0.05$). Signal amplitude values are normalized, n.u. – normalized units

The result of the spectral analysis of these signals is shown in Fig. 6: a) the spectrum of the plethysmographic signal, b) the temperature signal spectrum. In both cases, the fundamental harmonic has a frequency of 1.25 Hz, which corresponds to a heart rate of 75 bpm.

In this case, the spectrum of the temperature signal has large components in the low-frequency region of the spectrum ($f<1$ Hz) in comparison with the plethysmographic signal. This is due, on the one hand, to the inertia of heat exchange processes that occur due to changes in the intensity of the blood flow seen by the plethysmogram, and on the other hand to slow physiological processes, for example, breathing (see Table I).

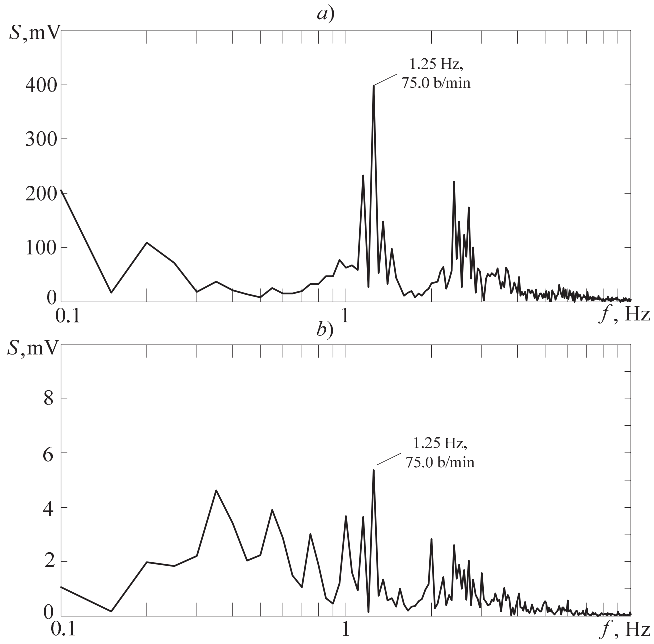

Fig. 6. Spectrum of plethismographic signal (a) and temperature signal (b), in both cases the fundamental harmonic has a frequency of 1.25 Hz, which corresponds to a heart rate of 75 bpm

As in the study of electrocardiographic or plethysmographic signals, the results of recording temperature oscillations strongly depend on the location of the temperature sensors. A thermal signal has a large amplitude if the temperature sensor is located near large arteries, for example, a carotid. However, temperature oscillations can be recorded at various sites of the skin surface of the body.

Thus, the tests carried out with the help of a thermostat confirmed the technical characteristics of the developed thermometer, and the tests associated with synchronous recording of TO and registered with standard optical sensor pulse wave confirmed the possibility of its use for the evaluation of blood microcirculation and pulse wave registration.

TABLE II CHARACTERISTICS OF THE TEMPERATURE RECORDER

Parameter	Value	Unit
Temperature range	From +20 to + 45	°C
Temperature resolution	0.01	°C
Thermal time constant	50	ms
Thermal resistance	3	°C/mW
Sensor type	p-n junction	
Sensor weight	2	mg
Sensor dimensions	0.7x0.7x0.8	mm
Sampling frequency	0.01-1000	Hz
The value of test pulse	1	°C
Data transfer interface	Bluetooth 2.0	
Battery capacity	700	mAh
Battery life	5	h

VI. CONCLUSION

The developed system has the following features:

– High sensitivity, high speed, auto-calibration, selection of the temperature measuring range, work in contact with a controlled surface, manual or automatic change of the slope transformation temperature to voltage, self-test, autonomous

– Power supply, wireless data transmission, sample rate adjustment, indication of operation;

– Using the developed system for registration high frequency temperature oscillations, it is possible to provide a study on the previously unavailable level of interrelation between micro- and macrocirculation of blood;

– Manifested in temperature oscillations of the surface of the human skin. Such method allowing in the future to provide the registration of the pulse wave signal, for measuring heart rate in portable devices like smart watches and fitness bracelets. This is also of interest for physiologists and physicians working in the field of visceral systems researches.

These features of the developed thermometer provide the following areas of its application:

– diagnostic techniques in medicine and physiology,

– laboratory equipment,

– a technique for exo- and endothermic reactions,

– non-stationary thermometry.

–registration of pulse waves for heart rate evaluation in portable devices

As a result of work, the system for registration of high frequency temperature oscillations was built, tested and implemented in various experiments. The developed device has technical characteristics presented in Table II.

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