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Calibration of the metrological characteristics of photoplethysmographic multispectral device for diagnosis the peripheral blood circulation

Abstract. *This paper presents firstly-engineered photoplethysmographic multispectral device for diagnosis the peripheral blood circulation. The calculation of the main errors as: primary converter error, methodical error of measurement, setting of optical-electronic sensor error was carried out. Moreover the assessment of reliability of diagnosis the engineered device was conducted.*

Streszczenie*. Artykuł prezentuje pierwsze rozwiązanie wielospektralnego urządzenia fotopletyzmograficzego do diagnostyki obwodowego przepływu krwi. Przeprowadzono obliczenia głównych błędów: podstawowego błędu przetwarzania, błędu metodyki pomiaru, ustalonego błędu przetwornika optoelektronicznego. Ponadto przeprowadzono ocenę niezawodności zaprojektowanego urządzenia. (****Kalibracja metrologicznych charakterystyk wielospektralnego urządzenia fotopletyzmograficznego do diagnostyki obwodowego przepływu krwi****).*

Keywords: metrological characteristics, photoplethysmography, peripheral blood circulation, optical electronic device, wavelength.
Słowa kluczowe: charakterystyki metrologiczne, fotopletyzmografia, obwodowy przepływ krwi, urządzenie optoelektroniczne, długość fali.

Introduction

Today, the problem of violations of the peripheral blood circulation is becoming more important. Seeing that under the conditions of modern science and technology progress which is increasingly causing a negative influence on the environment, including human health, the age of many diseases associated with disorders of the peripheral blood circulation began to fall critically [1, 2]. For successful treatment of a disease it is important to conduct timely diagnosis, because identifying of some problems at an early stage greatly increases the probability of the patient's full recovery. Therefore, the development of new diagnostic devices is making great contribution to the development of modern medicine [1, 3, 4].

Perspective methods of early diagnosis of peripheral blood circulation disorders are optical methods that allow conducting painless and non-destructive control of affected areas. There is the photoplethysmographic method which is in illuminating the biological tissue by infrared radiation and registering of reflected or back scattered light from biotissue by photodetector that takes the important place among them. But the results of research are influenced by many factors that must be considered while building devices that implement this method.

That's why the important task thus far is developing of the devices for effective peripheral blood circulation diagnosis. To solve this problem we have engineered a multispectral photoplethysmographic device for diagnosis the peripheral blood circulation.

Results

This engineered device has a control unit, three sources of radiation (infrared, red, green) photodetector, two amplifiers, high-pass filter and a USB controller (Fig. 1).

The source of infrared radiation (wavelength – 905 nm) is used to study the deep layers of the skin. To determine blood oxygen saturation a red light source is used (wavelength – 660 nm). Green radiation source emits luminous flux (wavelength – 532 nm) that penetrates only in corneous and epidermal skin layers (0.3 mm) that allows exploring the surface layers of the skin definitely. The device operates as follows. After switching-on, the zeroing process of block evaluator starts, namely by the discharge of a microcontroller (MC) in zero state and setting the permission of the device work. After that a control unit sets up a consistent choice of the radiation source. Then the selected source of radiation emits light flux that is partially absorbed and partially scattered by biological tissues of researching area and is registered by photodetector (PD). The signal from PD goes to amplifier, then it goes to the high-pass filter (HPF) and it goes to the next amplifier. Amplification coefficient of amplifier is set by MC. The MC has integrated analog to digital converter (ADC), which converts the signal into digital code, and sends data to a PC through the USB-controller [5].

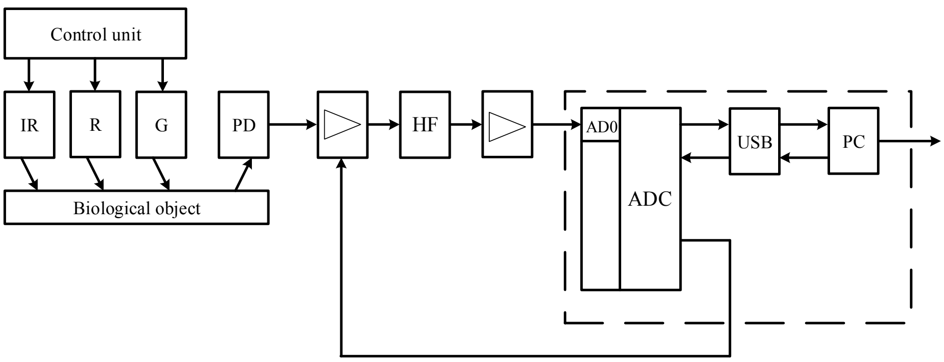

Fig.1. Block diagram of the optical-electronic photoplethysmographic multispectral device for diagnosis of the peripheral blood circulation

Assessment errors of primary converter

In different parts of the measuring channel there are errors that affect the result measurement (Fig. 2). Due to GOST 8.009-84 the main errors' characteristics of measuring channel are: systematic error – Δ_c, standard deviation $\sigma(\Delta)$ of random component of the error and the error of measuring channel [6, 10]. On the figure 1 the generalized structure of the measuring channel and its main errors that affects on the measurement result is presented. When measuring optical radiation reflected from biological tissue, there is some error – Δ_Σ, containing the random $\overset{\circ}{\Delta}$ and systematic Δ_c components

(1) $$\Delta_\Sigma = \Delta_c + \Delta^\circ .$$

This error is caused by the influence of environmental factors on measuring channel such as: temperature influence (on the device, on the object of study), random noise, imperfect construction optical sensor and artifacts. As the measurement error is determined by a large number of partial components that are random, it will be the law of distribution that is close to normal with zero expectation. The central limit theorem of probability shows that the distribution of measurement errors will be close to normal, if observation results are influenced by a large number of independently operating random partial errors, each of them is small in value compared to the total measurement error. Normal probability of density law is described by [7, 8]

(2) $$f(\Delta_I) = \frac{1}{\sigma\sqrt{2\pi}} \boldsymbol{exp}\left[-\frac{1}{2}\left(\frac{\Delta_I}{\sigma}\right)^2 \right],$$

where σ – standard deviation of error; Δ_I – error of initial converting the reflected optical radiation on biological tissue.

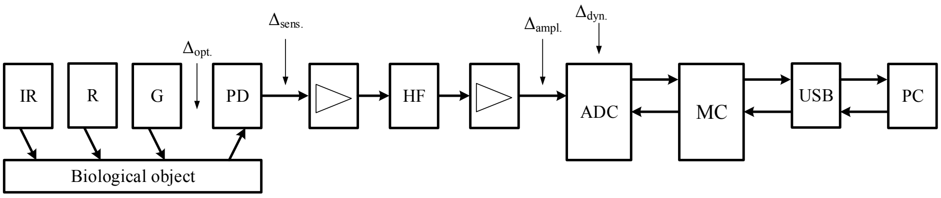

Fig. 2. Generalized structure of measuring channel of optical-electronic device for diagnosis the peripheral blood circulation

Calculation errors of primary converter. Methodological errors of measurement

Methodological error caused by influence of the environmental factors on the measuring channel occurring just at the beginning, i.e. the block of optical-electronic sensor or primary converter. Methodological error is a significant component of the total error for devices that use a relative measurement method. These errors are the results of imperfections computing methods and approximations that admitted when the measuring device is developed.

In optoelectronic devices, the main sources of methodological error are an optical sensor, fiber optic waveguide and actually the sample of researches

(3) $$\sigma_M = f(\sigma_{sens.}, \sigma_{waveg.}, \sigma_{sett.}) .$$

Component $\sigma_{sens.}$ is obligatory in diagnostics optoelectronic devices, as it leads to a significant increase of resulting error. It is caused by design quality and constructive features of the optical sensor.

Component $\sigma_{waveg.}$ is the error caused by the fiber-optical waveguide, which is an important element in the non-invasive researches. This error is caused by signal distortion in the waveguide. It extinction coefficient varies from bends, waveguide material, mechanical damage etc.

Component $\sigma_{sett.}$ is the "sample error". It is random variable, and depends on researches quality, i.e. the human factor. As a result of assessing of methodological errors they can be concluded to make about 2%, 0.17% and 0.15% of total error respectively when comprehensive evaluation of metrological characteristics is conducted [7, 9].

The error of setting of optical-electronic sensor

The error of setting is random error. It is caused by the difference in setting of the object measurement relative to the incident radiation. This error has normal distribution (Gaussian distribution) with zero expectation and has the form [7, 8]

(4) $$p(\delta_{sett.}) = \frac{1}{\sigma_{sett.}\sqrt{2\pi}} \boldsymbol{exp}\left[-\frac{1}{2}\left(\frac{\delta_{sett.}}{\sigma_{sett.}}\right)^2 \right],$$

where $\delta_{sett.}$ – error of the sample setting

$\sigma_{sett.}$ – standard deviation of the setting error.

Information on the measured parameters $x(t)$ enters to the input of the ADC in the form of continuous electrical signals that vary in the range $\pm A$. ADC converts the continuous signal $x(t)$ in a binary code with limited bit. The conversion process infinite set of continuous signal values $x(t)$ in an infinite set of numbers called quantization. Step quantization for level q is determined by the bit of ADC n and is associated with it by the dependence

(5) $$q = A \cdot 2^{-n} .$$

Information from the ADC enters in the discrete moments of time: $t = Tn$, where T – step discretization of time; n – integers: 0, 1…

Thus, continuous signal $x(t)$ before processing is quantized by level and time.

Quantization error is calculated by the formula [7, 10]

(6) $$\Delta x(nT)k = x(nT) - x(nT)k ,$$

where $x(nT) = x(t)$, at $t = nT$; $x(nT)k$ – is quantum values of $x(t)$ for $t = nT$.

The maximum absolute quantization error is calculated as

(7) $$\Delta x(nT)_{kmax} = q/2 = A \cdot 2^{-(n+1)}$$

Error $\Delta x(nT)k$ uniformly distributed in the interval $\pm \Delta x(nT)_{kmax}$, and its expectation and standard deviation is respectively presented:

(8) $$M_D[\Delta x(nT)k] = 0 ;$$

(9) $$\sigma_D[\Delta x(nT)_k] = \frac{\Delta x(nT)_{kmax}}{\sqrt{3}} = \frac{A \cdot 2^{-(n+1)}}{\sqrt{3}} .$$

Absolute error of the integral reflection coefficient is caused by quantization of the output signal and is written as:

(10) $$\delta_D = \frac{A}{2^{n+1}}.$$

Modern ADCs allow, with the number of 16 bits, to reach the time of transformation for 2 microseconds that is sufficient to ensure fair of medical diagnosis. The error of quantization consists of digital representation error and instrumental error of the ADC. Instrumental error is caused by noises and random noises in the input signal and ADC components. This error is caused by many factors, but its distribution law is close to normal. The quantum value is associated with maximum value of output voltage and number of bits ADC [6, 7]

(11) $$q = U_{ex.\,MAX} / 2^n .$$

The law of distribution of such errors is described by [6, 7]

(12) $$p(\delta_D) = \frac{1}{q} = \frac{2^n}{A}, \text{ where } \delta_D \in \left[-\frac{A}{2^{n+1}}, \frac{A}{2^{n+1}}\right].$$

Standard deviation of total measurement error of integral value of reflected light flow is given by [6, 8]

(13) $$\sigma_I = \sqrt{\sigma_D^2 + \sigma_{sett.}^2} .$$

The law of distribution of measuring error of integral luminous flow is the composition of the laws of distribution of quantization error, error that is caused by inaccurate setting of sensor on biological object and random noises. It is defined as the convolution of distribution laws of resulting error components, and its resulting graphs are shown in Fig. 3. The term of the distribution of informative parameter error is represented as [6, 7]

(14) $$p(\delta_I) = p(\delta_I)\cdot p(\delta_D)\cdot p(\delta_{вcm}) = = \frac{2^n}{A\cdot\sqrt{2\pi}\sigma_I}\int_{-\infty}^{\infty}\exp\left(-\frac{(\delta_I - z)^2}{2\sigma_I^2}\right)dz .$$

In example (14) the integral can't be solved analytically and can be found only by numerical methods. In constructing graphs of distribution laws was assumed that the mean square value error that is caused by random interference and inaccurate sample setting is equal to mean square value of quantization error.

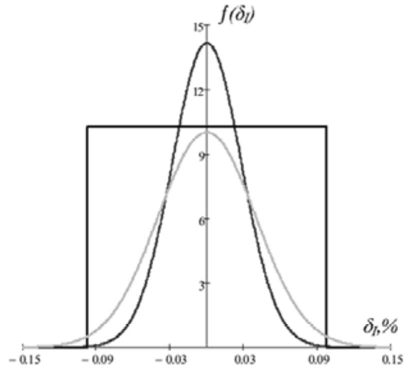

Fig.3. The composition of distribution laws of the total measurement error

Evaluation of reliability of diagnosing optical-electronic device

Probability D_1 of correct operation of diagnostic devices for two possible diagnosis methods (DM) is defined as follows [11]

(15) $$D_1 = C_1 ,$$

where C_1 the probability that at any moment of time DM is workable;

Further reliability of diagnosis D_2 is determined – methodical $C_м$ and instrumental C_5.

Methodical reliability is defined as the multiplication of index C_3 – the accordance of model to diagnosis object (DO) and index C_4 – completeness of diagnosis [11]

(16) $$C_м = C_3 \cdot C_4 ,$$

where $C_3 = \frac{N_1}{N}$; N and N_1 – the total number of indicators that respectively characterize the state of object and parameters that relate to the diagnostic model (DM) and

(17) $$C_4 = \frac{\sum_{i=1}^{N_2} S_i}{\sum_{i=1}^{N_1} S_i} ,$$

where N_2 and S_i – number and importance (informative) of evaluated parameters respectively.

Instrumental reliability is determined by the maximum deviation of each indicator h_i and measurement error ε_i

(18) $$h_i = \sigma_{xi} \cdot \sqrt{3} ;$$

(19) $$\varepsilon_i = \sigma_{\Delta i} \cdot \sqrt{3} ,$$

where σ_{xi} $\sigma_{\Delta i}$ – mean-square deviation of these values.

Accordance to the correlation between h_i and ε_i, and bounds of permissible changes of indicators δ_i is determined the probability of erroneous conclusion for each indicator [11]

(20) $$d_{e.c.\ p} = d_{f.f.\ p.} + d_{d.f\ p} ,$$

where $d_{f.f\ p}$ and $d_{d.f\ p}$ – probability of false and not determined failure respectively.

The ration between the values δ_i, ε_i and h_i, and the probabilities $d_{f.f\ p}$ and $d_{d.f\ p}$, that are used in practice are given in table 1.

For dependent diagnostic indicators (DI) the instrumental reliability of diagnosing of the object C_5 is determined by errors of the first kind [11]

(21) $$C_5 = D_{f.o} = 1 - \prod_{i=1}^{N_1}(1 - d_{f.f\ p}) .$$

Based on the correlations the diagnosing reliability is expressed by multiplying

(22) $$D_2 = C_3 \cdot C_4 \cdot C_5 .$$

Then the security of operator performance D_3 is determined. It is characterized by the multiplying of the probability of operator efficiency C_6 to start of diagnosis and the probability C_7 of preservation of efficiency during the time of diagnosis

(23) $$D_3 = C_6 \cdot C_7 .$$

Then the efficiency of diagnosis is determined as [11]

(24) $$E = D_1 \cdot D_2 \cdot D_3 .$$

Condition of the object diagnosis is characterized by 12 indicators. In the process of diagnosing is estimated 10 parameters and the selected diagnostics tools have the following quantitative parameters $C_1 = 0.95$; $C_2 = 0.99$.

Table 1. Correlations between variables δ_i , ε_i i h_i

Correlations between δ_i , ε_i i h_i	$d_{f.f\ p}$	$d_{d.f\ p}$
$\delta \geq h$, $\varepsilon \leq \delta - h$	0	0
$\delta \geq h$, $\varepsilon > \delta - h$	$\frac{[\varepsilon - (\delta - h)]^2}{4h\varepsilon}$	0
$\delta < h$, $\varepsilon > h - \delta$	$\frac{\varepsilon}{4h}$	$\frac{[2\varepsilon - (h - \delta)](h - \delta)}{4h\varepsilon}$
$\delta < h$, $\varepsilon < h - \delta$	$\frac{\varepsilon}{4h}$	$\frac{\varepsilon}{4h}$

According to (15)

(25) $$D_1 = C_1 = 0.95 .$$

and according to (15) and (16)

(26) $$C_3 = \frac{10}{12} = 0.84 .$$

(27) $$C_4 = \frac{\sum_{i=1}^{10} S_i}{\sum_{i=1}^{10} S_i} = 1 .$$

From (16) the methodological validity $C_M = 0.84$.

Considering to (18) – (21) and table 1 we determine the values ε_i , h_i and $d_{x.в\ i}$.

Table 2. The value of the main diagnostic indicators

σ_{fi}	$\sigma_{\Delta i}$	h_i	ε_i	$d_{f.f\ p}$
2.46	0.0900	4.2521	0.1559	0.1657
0.44	0.1100	0.7706	0.1905	0.0367
1.31	0.1130	2.2627	0.1957	0.1107
1.79	0.0860	3.0934	0.1490	0.1152
0.00	0.1020	0.0000	0.1767	0.0000
1.34	0.1120	2.3173	0.1940	0.1124
1.31	0.1500	2.2627	0.2598	0.1470
0.89	0.0796	1.5467	0.1379	0.0533
2.23	0.0800	3.8641	0.1386	0.1339
0.67	0.1000	1.1587	0.1732	0.0502

From the expression (21) the probability of false conclusion

(28) $$C_5 = D_{f.o} = 1 - \prod_{i=1}^{N_1} (1 - d_{f.f\ p}) = 0.08 .$$

The instrumental authenticity is in accordance with (21)

(29) $$C_5 = 0.92 .$$

The reliability of diagnosis [6]

(30) $$D_2 = 0.84 \cdot 0.92 = 0.78 .$$

Conclusion

Engineered optoelectronic multispectral photoplethysmographic device to determine the state of the peripheral blood circulation allows us to research biological tissue on several wavelengths (infrared, red and green radiation). The combination of these wavelengths allows not only effectively investigate the blood supply vessels and determine oxygen saturation, but also it allows to investigate the superficial layers of the skin, by using the green light, that is very important in diagnosis skin cancers [12].

The calculation of the main errors as: primary converter error, methodical error of measurement, setting of optical-electronic sensor error was carried out. As a result of calculations, the reliability of optoelectronic multispectral photoplethysmographic device to determine the state of the peripheral blood circulation is 78%.

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