21. Shcherban, V., Korogod, G., Chaban, V., Kolysko, O., Shcherban', Y., Shchutska, G. (2019). Computer simulation methods of redundant measurements with the nonlinear transformation function. Eastern-European Journal of Enterprise Technologies, 2 (5 (98)), 16–22. doi: https://doi.org/10.15587/1729-4061.2019.160830
22. Soboleva, N. A., Melamid, A. E. (1974). Fotoelektronnye pribory. Moscow: «Vysshaya shkola», 376. Available at: https://lib.convdocs.org/docs/index-20291.html
23. Kondratov, V. T. (2010). Metody izbytochnyh izmereniy: osnovnye opredeleniya i klassifikatsiya. Visnyk Khmelnytskoho natsionalnoho universytetu. Tekhnichni nauky, 3, 220–232. Available at: http://journals.khnu.km.ua/vestnik/pdf/tech/2010_3/47kon.pdf
24. Kondratov, V. T. (2015). The theory redundant and super-redundant measurements: super-redundant measurements of resistance of resistors and resistive sensors. The message 1. Vymiriuvalna ta obchysliuvalna tekhnika v tekhnolohichnykh protsesakh, 4, 7–22. Available at: http://nbuv.gov.ua/UJRN/vott_2015_4_3
25. Kondratov, V. T. (2009). Teoriya izbytochnyh izmereniy: universal'noe uravnenie izmereniy. Visnik Hmel'nits'kogo natsional'nogo universitetu. Tekhnichni nauky, 5, 116–129. Available at: http://journals.khnu.km.ua/vestnik/pdf/tech/2009_5/zmist.files/23kon.pdf

UDC 519.213:612.16:621.383.8
DOI: 10.15587/1729-4061.2021.227001

DEVELOPMENT OF A SIMULATION MODEL OF A PHOTOPLETHYSMOGRAPHIC SIGNAL UNDER PSYCHOEMOTIONAL STRESS

Evhenia Yavorska
PhD, Associate Professor, Head of Department*
E-mail: yavorska_eb@yahoo.com
Oksana Strembitska
Postgraduate Student*
E-mail: oksanaoliinyk93@gmail.com
Michael Strembitskyi
PhD, Associate Professor
Department of Instruments and Control-Measurement Systems**
E-mail: m.strembitskyy@gmail.com
Iryna Pankiv
Postgraduate Student*
E-mail: Ira_Pankiv@ukr.net
*Department of Biotechnical Systems**
**Ternopil Ivan Puluj National Technical University
Ruska str., 56, Ternopil, Ukraine, 46001

A simulation model of a photoplethysmographic signal under psychoemotional stress taking into account the nature of signals of biological origin and stress response stages was developed. The method of constructing the simulation model is based on reconstructing the waveform and coding points of the signal taking into account the stress response curve using harmonic functions at characteristic time intervals. Using the simulation model of the photoplethysmographic signal under psychoemotional stress with previously known parameters allows validation of methods and algorithms for processing such data. It was found that in the process of simulation, it is necessary to take into account the signal frequency, random component and stress response curve. This complicates the simulation algorithm. However, using the simulation model with variable input parameters allows reproducing the signal with an emphasis on stress response stages. One of the features of the proposed model is the ability to reproduce the signal by coding points for amplitude and time intervals using harmonic functions. The relative error for the amplitude variation of the model and experimental data is 3.97 %, and for the period – 3.41 %. Calculation of Student's t-test showed a statistically insignificant difference: p=0.296 for the amplitude and p=0.275 for the period. This indicates that the simulation model takes into account the signal characteristics under stress: frequency, random component and stress response curve. Using the proposed simulation model is an adequate way to assess methods and algorithms for analyzing the state of the cardiovascular system under psychoemotional stress

Keywords: harmonic function, simulation model, periodic signal, psychoemotional stress, photoplethysmographic signal

Received date 23.02.2021
Accepted date 12.04.2021
Published date 19.04.2021

***How to Cite**: Yavorska, E., Strembitska, O., Strembitskyi, M., Pankiv, I. (2021). Development of a simulation model of a photoplethysmographic signal under psychoemotional stress. Eastern-European Journal of Enterprise Technologies, 2 (9 (110)), 36–45. doi: https://doi.org/10.15587/1729-4061.2021.227001*

1. Introduction

The occurrence of psychoemotional stress at the dentist is a factor in the development and progression of diseases of the cardiovascular system (CVS) – hypertensive crisis, myocardial infarction, stroke, arrhythmia, etc. [1]. According to testing data, 80 % of patients who seek help from a dentist suffer from dentophobia [2, 3]. Providing dental care to the population belongs to the mass types of medical care, as 20–25 % appeals are related to oral diseases (345–550 cases per 1,000 inhabitants) [4]. Timely detection of CVS disorders due to psychoemotional stress at the dentist is an urgent medical problem. One of the non-invasive methods to collect data on the state of the CVS, including under psychoemotional stress, is determining pulse signal parameters – photoplethysmography [5, 6]. Since the analysis of the photoplethysmographic signal is based on using data processing algorithms, the reliability of the results can be evaluated using a simulation model with known parameters. Constructing such a simulation model is an urgent task in terms of validating methods and algorithms for assessing the state of the cardiovascular system under psychoemotional stress. In addition, in terms of doctor-patient interaction, using clear markers of the patient's condition is a factor in reducing the risk of emergencies. To some extent, such algorithms are implemented in cardiomonitoring systems, but they are expensive and difficult to use. Therefore, the urgent task is to develop a simulation model of the photoplethysmographic signal under psychoemotional stress with variable input parameters for the validation of algorithms at the stage of developing new and improving existing diagnostic equipment.

2. Literature review and problem statement

The paper [1] presents the results of assessing the psychoemotional state of patients caused by a stressful situation based on the patient and doctor questionnaire. The approach to identifying psychoemotional stress based not only on questionnaires and patient's behavior assessment, but also on cardiomonitoring is proposed in [3]. Evaluation of psychoemotional state requires the use of a large amount of data, so the paper [5], in addition to the above parameters, proposes to assess respiratory movements as an additional diagnostic feature. Calculation of Hildebrandt factor, autonomic index and minute blood volume proposed in [7] is an additional criterion that allows judging the patient's psychoemotional state. Therefore, a number of methods to determine the psychoemotional state of the patient have been proposed in these works: analysis of patient's behavior, questionnaire according to J. Taylor (the name of the method used in [3]), Luscher testing, mechanical – blood pressure measurement, electrocardiographic, plethysmographic, electromyographic, encephalographic, electrodermal, rheographic, printing, joint methods.

It is shown that this approach to determining the patient's condition allows assessing the psychoemotional state based on a significant amount of information obtained by interviewing the patient and assessing physiological parameters. The data obtained in [3] suggest that the psychoemotional state of the patient can be assessed by cardiomonitoring. The work [7] also focuses on the evaluation of measurement indicators – blood pressure, heart rate, respiratory movements, etc. Therefore, it is advisable to exclude factors that affect the reliability of the results from the algorithm for assessing the psychoemotional state. These include those based on the doctor's personal experience and related to the subjective perception and evaluation of the results of analyzing the patient's behavior, testing results and questionnaires. Using different algorithms and methods of data collection, hardware and software, interpretation methods is also a drawback of these studies, since different quantitative and qualitative indicators cause the impracticality of such an approach [3, 7].

An option to overcome such difficulties is to use an approach based on the selection and interpretation of data obtained non-invasively and without the intervention of a subjective factor. One method is to assess the activity of the cardiovascular system by analyzing the pulse wave using optical sensors – photoplethysmography [8]. It displays the parameters of peripheral circulation and does not require complex hardware and software. When evaluating algorithms for analyzing the photoplethysmographic signal (PPS), it is advisable to use data that have known parameters. Such data can be obtained using simulation models. The paper [9] proposes the simulation model of a pulse wave in the form of exponentially damped sinusoid, which takes into account signal waveform and coding points, but does not take into account the frequency and random component of signals of biological origin. An additive mixture of deterministic and random components as a simulation model reflecting the state of peripheral circulation is proposed in [10]. This simulation model takes into account signal randomness, but does not provide for the reproduction of all coding points and frequency of the signal. The harmonic three-phase model [11] reflects the waveform of the signal without taking into account its frequency and random component. Another option for pulse signal simulation is adaptive non-harmonic model [12], which does not take into account signal frequency. In addition to these shortcomings, the analysis of simulation models showed that they do not take into account changes in time and amplitude indicators due to the course of periodic medium- and long-term processes. The simulation model taking into account signal frequency, random component and course of long-term processes, namely daily pulse signal, is given in [13]. However, issues remain regarding the consideration of specific features of stress response in the signal structure. Stress is a non-specific response of the body to an unexpected and tense situation; it is a physiological reaction that mobilizes the body's reserves and prepares it for physical activity such as resistance, struggle, escape [14]. Stress leads to changes in the activity of many organs and systems, including the cardiovascular system – changes in heart rate, blood pressure, and so on. Stress is expressed by a general adaptation syndrome, which does not depend on pathogenic factors – chemical, thermal, physical, psychological [1]. According to the classification proposed in [15], stress has three main stages:

1. The first stage – alarm, when the body's resistance first decreases ("shock"), and then protective mechanisms are activated ("anti-shock phase").
2. The second stage – resistance, when due to the stress of functional systems, the body adapts to new conditions. If stress does not stop, the third stage may occur.
3. The third stage – exhaustion, when the failure of protective mechanisms is manifested and the violation of the consistency of vital functions increases.

Formation of the body's stress response has a clear sequence (Fig. 1) [15]. The first phase is the shock phase Ia, which passes into the anti-shock phase Ib. At stage I, the body's resources are mobilized and adaptive mechanisms are activated. When the stress factor reaches the maximum value, the body's resistance decreases, which is characteristic of unstable adaptation phase II. If the stress factor ceases at this stage, the body's activity is restored at the level that was observed before the onset of stress. Exhaustion stage III occurs due to the gradual depletion of human reserves. This leads to a deterioration in the activity of the "weakest" part of the body, which violates the functioning of the already ill organ. The peculiarity of this process is a gradual transition from functional changes in internal organs to destructive processes and organic changes in them.

The stages of stress response can be observed in the activity of the cardiovascular system [16], in particular, changes of amplitude and time characteristics of the pulse wave. The paper [17] shows the basic principle of pulse signal analysis using coding points (Fig. 2) within the signal period. Since the pulse is a signal of biological origin, so, in addition to the periodic component, it also has a random component [18] and abnormal segments of random nature [19], the formation of which depends on internal and external factors.

There are many models of pulse wave simulation, but there is no holistic approach to simulating pulse wave changes under the action of stress factor. The mechanism of validation of photoplethysmographic signal (PPS) processing algorithms requires the use of data having predefined parameters. Such data can be obtained using simulation models only if the basic characteristics of signals taken from biological objects are included in the model. Under psychoemotional stress, it is necessary to consider the frequency, random component of the photoplethysmographic signal and stress response curve on a considerable time interval. This time interval corresponds to the period from the beginning of the stress factor to the restoration of cardiovascular activity. Therefore, there is a problem of lack of data with known parameters, i.e. simulation models that can be used to validate methods for processing PPS under psychoemotional stress.

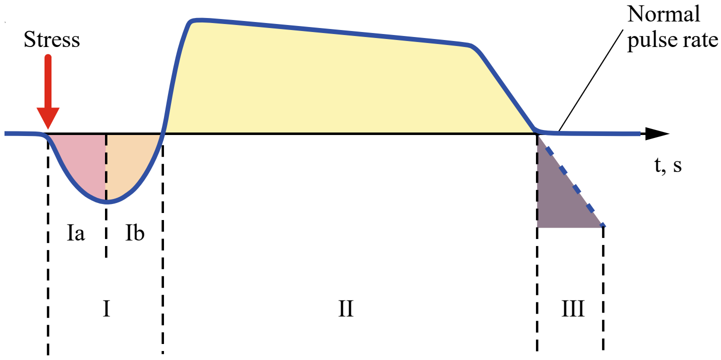

Fig. 1. Stress stages according to H. Selye: I – alarm stage: Ia – shock phase, Ib – anti-shock phase; II – resistance stage; III – exhaustion stage: x–t, s – time in seconds [15]

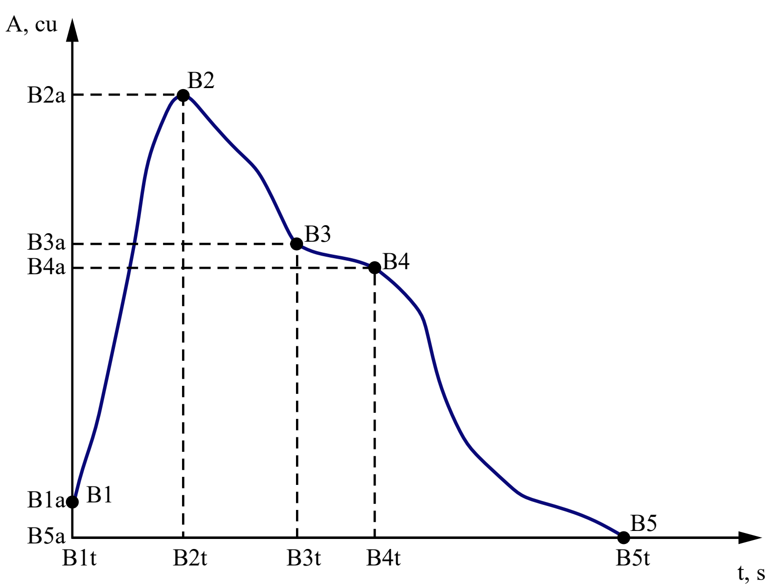

Fig. 2. Main coding points of volume pulse: x – t, s – time in seconds; y – A, cu – amplitude in conventional units [17]

To solve this problem, it is necessary to develop a PPS simulation model taking into account the maximum possible number of signal parameters under psychoemotional stress. The lack of data with predefined parameters that can be obtained using a signal simulation model is one of the reasons for the complexity of validating methods and algorithms for processing PPS under psychoemotional stress. This suggests that the development of a simulation model of PPS under psychoemotional stress is an urgent task to solve the problem of validation of signal processing methods and algorithms when assessing the state of the CVS under the influence of a stress factor.

3. The aim and objectives of the study

The aim of the study is to build a simulation model of PPS under psychoemotional stress taking into account periodic and random components of the signal within the stages of the body's stress response. Such a model will allow validation of algorithms for processing PPS under psychoemotional stress at the stage of software development using data with known parameters.

To achieve the aim, the following objectives must be accomplished:

– to develop a simulation model of a photoplethysmogram within one period;

– to develop a simulation model of a photoplethysmogram within n periods taking into account the random component;

– to develop a simulation model of the curve of changes in physiological parameters under psychoemotional stress;

– to develop a complex simulation model of periodic PPS with the random component and taking into account the curve of changes in physiological parameters under psychoemotional stress.

4. Materials and methods of the study

4. 1. Simulation model of the photoplethysmographic signal within one period

The simulation model of PPS within one period takes into account the waveform and main coding points used to analyze the state of the CVS. The essence of the PPS simulation process is to reproduce the waveform using harmonic functions for n segments for the k-th pulse wave implementation taking into account amplitude and time parameters of the signal (1):

$$\xi_k(t)=\xi_{1k}(t_1)\cup\xi_{2k}(t_2)\cup\xi_{3k}(t_3),...,\xi_{nk}(t_n), \quad (1)$$

where $t_{1,2,3,...,n}\in[0, T_{1,2,3,...,n})$ is the time range of the 1, 2, 3,..., n-th wave, $t\in T_1+T_2+T_3+...+T_n$ is the duration equal to the duration of one cardiac cycle; $\xi_{1k,2k,3k,...,nk}(t)$ is the PPS extended along the time axis of the n-th wave segment, $t\in[0, T_n)$; k is the pulse wave implementation k=1, 2, 3, ..., K, K is the number of pulse wave implementations.

The block diagram of the PPS simulation algorithm within one cardiac cycle is shown in Fig. 3.

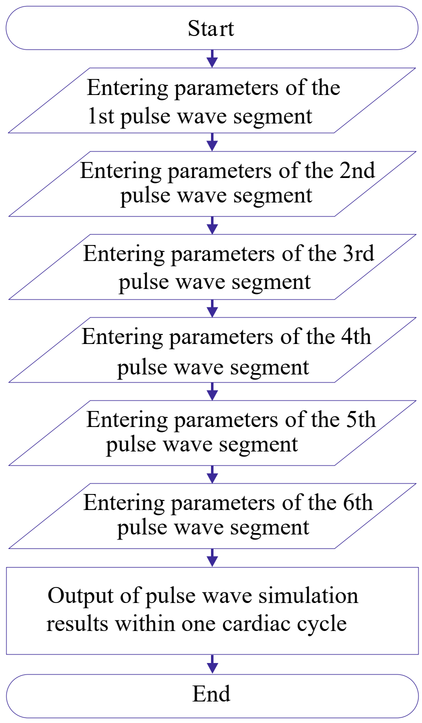

Fig. 3. Block diagram of the PPS simulation algorithm within one period

The model of pulse signal simulation for the period T was constructed taking into account characteristic amplitude and time intervals, which have diagnostic value (2):

$$S_{nk}(t)=A_{nk}\sin\left(2\cdot\pi\cdot t\cdot f_{nk}\right)\cdot e^{-t\cdot K_{nk}}\cdot L_{nk},\ t\in\left[0,T_{nk}\right), \quad (2)$$

where n is the wave number at certain intervals, n=1, 2, ..., N; N is the number of waves; T_{nk} is the duration of the n-th wave in the k-th period, A_{nk} is the amplitude of the nk-th wave, f_{nk} is the sinusoid frequency, K_{nk} is the coefficient of inclination of the nk-th wave, L_{nk} is the scale factors for the nk-th wave.

The process of PPS simulation within one period is shown in Fig. 4.

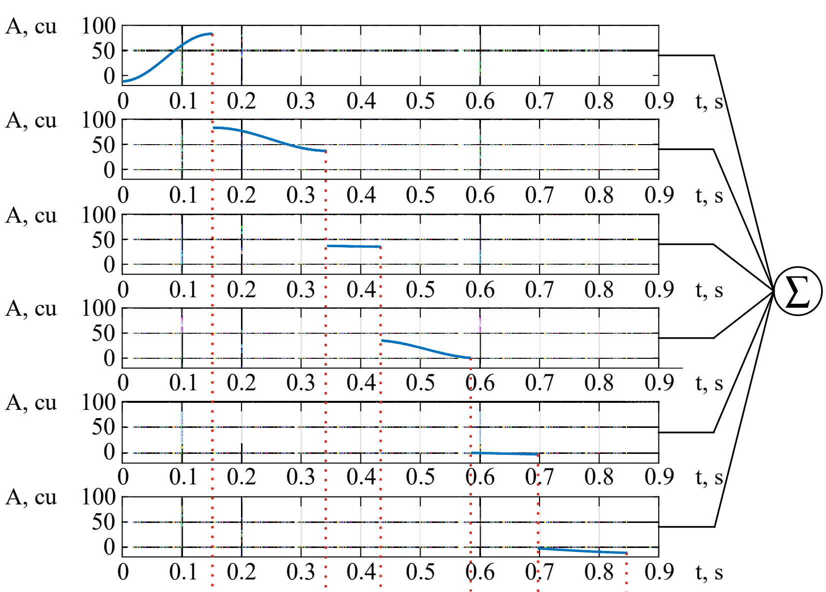

Fig. 4. PPS simulation within one period: x—t, s — time in seconds, y—A, cu — amplitude in conventional units

To simulate PPS within one period, the MATLABR2019b software package (USA) was used.

4. 2. Simulation model of the photoplethysmographic signal within *n* periods taking into account the random component

PPS is a signal of biological origin, so in addition to the periodic component, it contains the random component for time t and amplitude A with mathematical expectation $M\{A\}$, $M\{t\}$ and variance $D\{A\}$, $D\{t\}$. To simulate PPS within n periods, it is necessary to extend it to n cardiac cycles and introduce the random component in formula (2). Expression (2) will take the form (3):

$$S_{nk}(t)=\left(A_{nk}+\psi_A\right)\sin\left(2\cdot\pi\cdot\left(t+\psi_t\right)\cdot f_{nk}\right)\cdot e^{-t\cdot K_{nk}}\cdot L_{nk},$$

$$t\in\left[0,T_{nk}\right), \quad (3)$$

where $\psi_A(M\{A\},D\{A\})$ is the random variable of wave amplitude with mathematical expectation $M\{A\}$ and variance $D\{A\}$; where: $\psi_t(M\{t\},D\{t\})$ is the random variable of wavelength with mathematical expectation $M\{t\}$ and variance $D\{t\}$.

The simulation model of PPS within n periods involves the use of the *rand* function of the MATLABR2019b software package (USA). The numerical value of *rand* varies within the values of mathematical expectation $M\{A\}$, $M\{t\}$ and variance $D\{A\}$, $D\{t\}$ for time t and amplitude A.

4. 3. Simulation model of the curve of changes in physiological parameters under psychoemotional stress

Psychoemotional stress that occurs at the dentist leads to changes in the functional activity of the cardiovascular system, which are manifested in pulse changes. Such changes are observed already when waiting for dental manipulations. The pulse rate reaches its maximum during manipulations, as shown in [6], where quantitative evaluation of indicators was performed by comparing data of control and experimental groups. Tracking these changes using photoplethysmography requires considering the nature of psychoemotional stress. Changes in the CVS activity under psychoemotional stress can be divided into three stages – alarm, resistance and recovery, observed after the stress factor ceases. Prolonged exposure to the stress factor can lead to the exhaustion stage, which causes body disorders.

Given phases of psychoemotional stress, the period change factor B was introduced in the simulation, which provides PPS simulation in form by multiplying by the value of the k-th period $T_k{\cdot}B$. The period change factor consists of n harmonic functions (4):

$$B_{nk}=A_{T_{nk}}\sin\left(2\cdot\pi\cdot t\cdot f_{T_{nk}}\right)\cdot L_{nk},$$

$$n=\overline{1,5},\ k=\left(1,B_{\max}\right),\ k\in l_n, \quad (4)$$

where B_{nk} is the n-th wave of the period change factor for the k-th period, l_n is the n-th area in which the period changes its value $L\in[l_1,...,l_n]$; L is the range of values for the period change factor B_n; $B_{\max}$ is the maximum period change value.

The principle of formation of the factor that defines the change of the period under psychoemotional stress is shown in Fig. 5, where l_1, l_2, l_3, l_4, l_5, l_6 denote the areas in which the period changes the value according to the course of the body's stress response. Area l_1, l_6 represents the state of rest; l_2 – alarm stage; l_3 – l_5 – resistance stage.

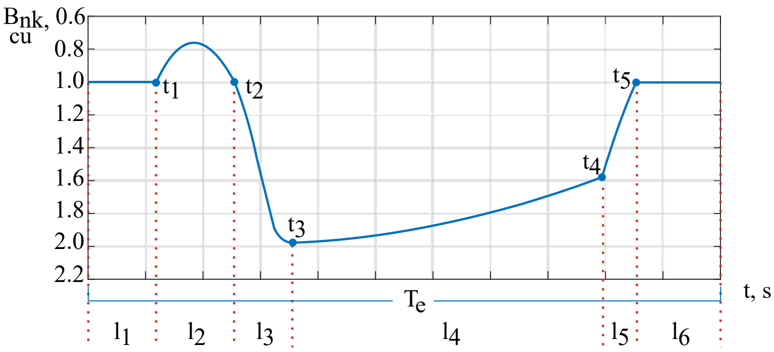

Fig. 5. Curve of changes in physiological parameters under psychoemotional stress: x–t, s – time in seconds; y – B_{nk}, cu – period change factor in conventional units

In Fig. 5, the simulation time T_e is divided into characteristic time intervals. In this case, $T_e \in [t_n,...,t_{n+1}]$, where $n \in 1, 2, ..., N$; N is the number of counts of the period change factor B_{nk} over time. In the period $t<t_1$, the pulse rate corresponds to the state of rest. Waiting for dental manipulations (or another known stress factor) leads to the alarm stage that corresponds to the time interval $t_2<t<t_1$. The resistance stage in the simulation was divided into 3 time intervals. The growth of PPS to the maximum value corresponds to the time interval $t_3<t<t_2$. The sharp increase in pulse rate at the first step of the resistance stage ends with the formation of an unstable equilibrium $t_4<t<t_3$. After the stress factor ceases, the pulse rate is restored in the time interval $t_4<t<t_5$ to the values observed at rest. This statement reflects the time interval $t>t_5$. To simulate the period change curve, the MATLABR2019b software package (USA) was used.

4. 4. Complex simulation model of periodic PPS with the random component and taking into account the curve of changes in physiological parameters under psychoemotional stress

Simulation of PPS under psychoemotional stress using the MATLABR2019b software package (USA) was built according to the following algorithm:

1. Introduction of the parameters of a single PPS.

2. Introduction of time intervals of changes in PPS under psychoemotional stress: T_e – experiment time; t_1 – onset of the stress factor; t_2 – beginning of mobilization of body resources; t_3 – reaching the maximum pulse rate; t_4 – beginning of pulse rate recovery; t_5 – pulse rate recovery to a value at rest.

3. Introduction of mathematical expectation $M\{A\}$, $M\{t\}$ and variance $D\{A\}$, $D\{t\}$ to form the random component.

4. Simulation of PPS for the period T_e taking into account the period change factor B_{nk}.

5. Output of PPS simulation results taking into account the period change factor B_{nk}, mathematical expectation $M\{A\}$, $M\{t\}$ and variance $D\{A\}$, $D\{t\}$.

The block diagram of PPS formation under psychoemotional stress is shown in Fig. 6.

Validation of simulation results requires evaluation of simulation data. The method of validation of the simulation model is to calculate the relative error and Student's t-test for the simulated and experimentally obtained signals. Experimental PPS was obtained using SamsungGalaxy Note8 (South Korea). Evaluation of its metrological characteristics was performed using NeXus-10 MKII (Netherlands) [21].

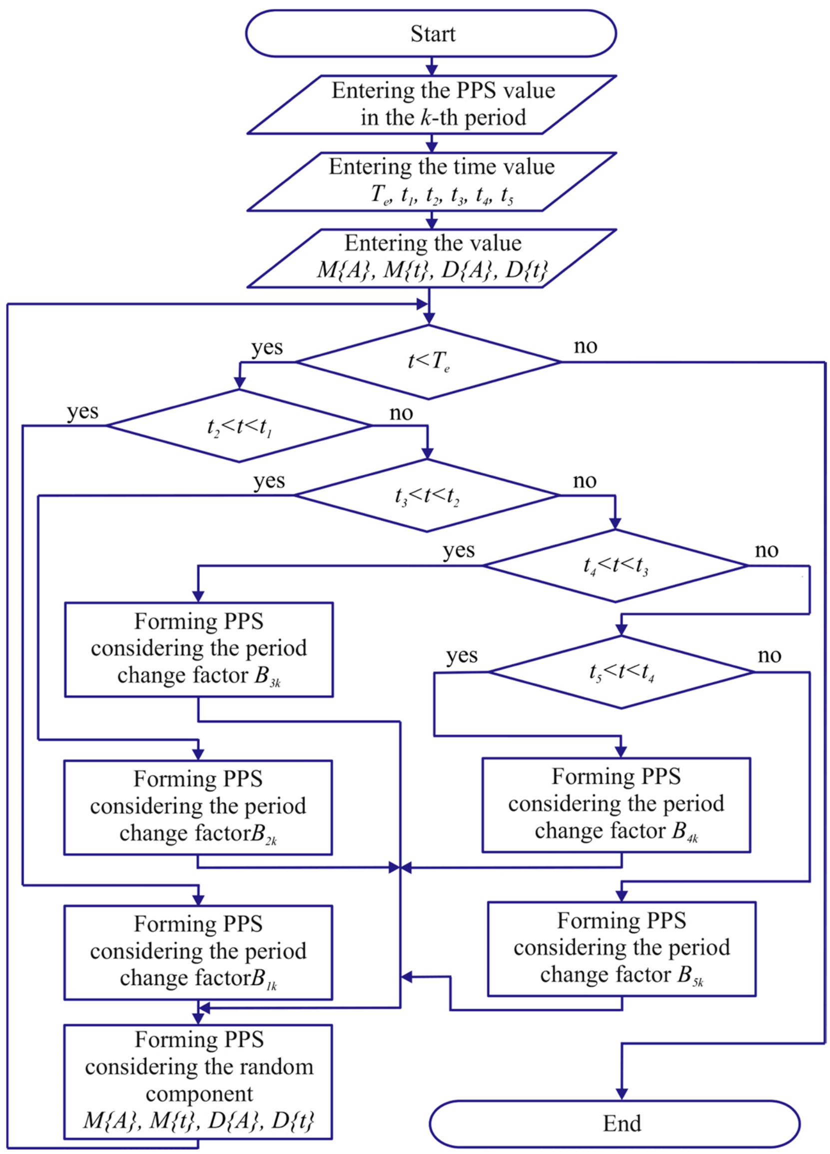

Fig. 6. Block diagram of PPS simulation under psychoemotional stress

5. Results of the development of a simulation model of PPS under psychoemotional stress

5. 1. Development of a simulation model of the photoplethysmographic signal within one period

The result of PPS simulation within one period using the MATLABR2019b software package (USA) is shown in Fig. 7.

The simulation model of PPS within one period takes into account the main coding points and waveform of the signal. The period of the simulated signal corresponds to a heart rate of 70 beats per minute. Signal reproduction using harmonic functions for 6 segments allows changing time intervals between control points and changing the amplitude of the signal segments, which allows reproducing the signal waveform in the normal functioning of the CVS and in the presence of pathologies. Changing the vascular lumen leads to an increase or decrease in reflected wave amplitude [20], which is a sign of pathological changes in vascular elasticity. Since the simulation model was built of individual segments using a harmonic function, the change of amplitude parameters and shift of segments 3 and 4 (Fig. 4) allows reproducing the waveform taking into account such deviations from the norm. The simulation model of PPS within one period is a basic element for building a simulation model at any time, both at rest and under psychoemotional stress.

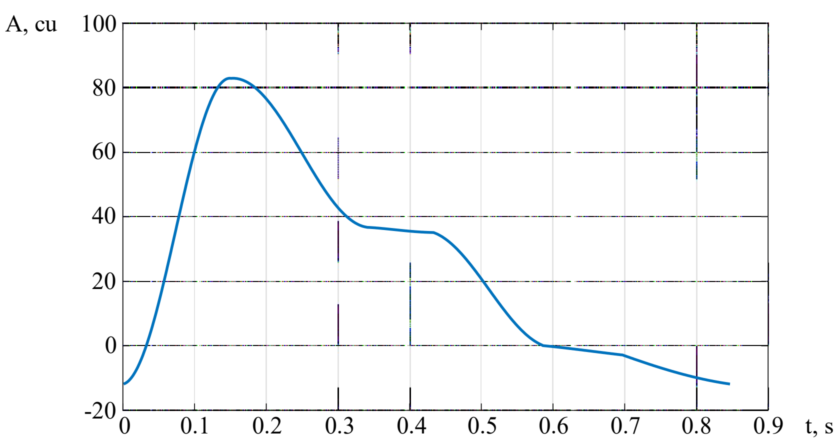

Fig. 7. Simulation model of PPS within one period: x – t, s – time in seconds; y – A, cu – amplitude in conventional units

5. 2. Development of a simulation model of the photoplethysmographic signal within *n* periods taking into account the random component

The result of PPS simulation taking into account mathematical expectation $M\{A\}$, $M\{t\}$ and variance $D\{A\}$, $D\{t\}$ within 10 periods is shown in Fig. 8.

The simulation model of PPS within 10 periods reflects the signal frequency and random component with *rand*=2 for amplitude A and *rand*=1 for period t. Reproduction of the signal in this way allows taking into account the presence of random variables for amplitude $M\{A\}$, $D\{A\}$ and time $M\{t\}$, $D\{t\}$, as shown in Fig. 8. Signal deviations are due to external and internal factors: motion artifacts, optical interference, etc. Using this approach to build a PPS simulation model allows taking into account the random component of signals of biological origin.

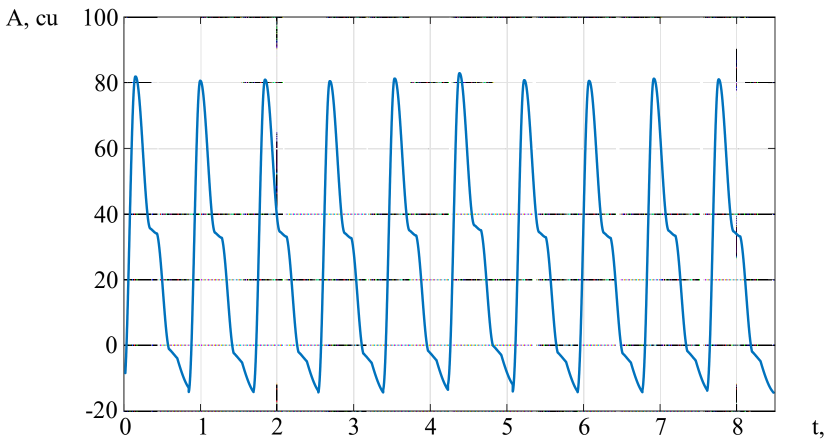

Fig. 8. Simulation model of PPS within 10 periods taking into account the random component: x – t, s – time in seconds; y – A, cu – amplitude in conventional units

5. 3. Development of a simulation model of the curve of changes in physiological parameters under psychoemotional stress

The result of the period change curve simulation is shown in Fig. 9. The simulation was performed in the period T_e=220 s.

In Fig. 9, the simulation time T_e is divided into characteristic time intervals. In the period $t<t_1$, the pulse rate corresponds to the state of rest. Waiting for a known stress factor leads to a decrease in pulse rate by 20 % (time interval $t_2<t<t_1$). A 2 times increase in pulse rate occurs in the time interval $t_3<t<t_2$. After that, an unstable equilibrium $t_4<t<t_3$ is formed. During this period, the pulse changes insignificantly until the stress factor ceases. After that, the pulse rate is restored in the time interval $t_4<t<t_5$ to the values observed at rest.

The simulated stress response curve reflects characteristic changes in the CVS activity observed under psychoemotional stress. Using it to develop a simulation model of PPS under psychoemotional stress allows taking into account changes in the CVS activity, which are subject to certain stress response stages. This makes it possible to predict the patient's condition during the period of action of the stress factor and after it ceases. The proposed simulation model allows changing the duration of stress response stages for the reproduction of various scenarios of changes in the patient's condition under psychoemotional stress.

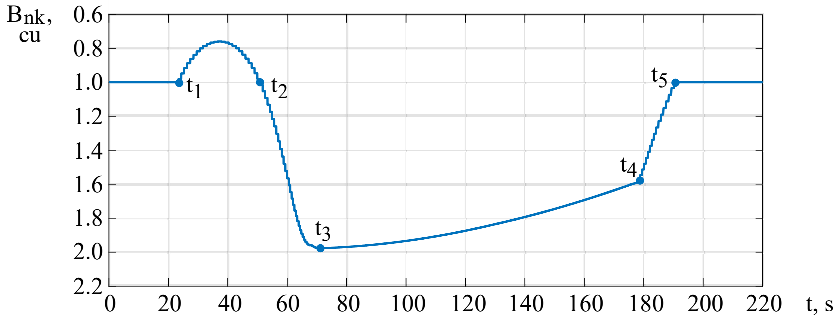

Fig. 9. Simulation model of the curve of changes in physiological parameters under psychoemotional stress (T_e=220 s): x – t, s – time in seconds; y – B_{nk}, cu – period change factor in conventional units

Calculation of the relative error for the amplitude variation of the simulated and experimental signals is 3.97 %. The relative error between the values of the simulated and experimental signal (maximum amplitude) periods is 3.41 %. The results show high accuracy of the PPS simulation method. Calculation of Student's t-test for two samples of amplitude and period variation for the simulated and experimental signals indicates a statistically insignificant difference between the data – p=0.296 and p=0.275, respectively.

5. 4. Development of a complex simulation model of periodic PPS with the random component and taking into account the curve of changes in physiological parameters under psychoemotional stress

The result of simulation of PPS under psychoemotional stress using the MATLABR2019b software package (USA) taking into account the signal frequency, random component and stress response curve is presented in Fig. 10.

The result of the simulation was confirmed by the experimental signal obtained using SamsungGalaxy Note8 (South Korea) [21]. Evaluation of its metrological characteristics was performed using NeXus-10 MKII (Netherlands), which is the FDA's gold standard for such measurements. Fig. 11 shows that the implementation of PPS within 3 s reflects the waveform of the signal and its main parameters within the specified period.

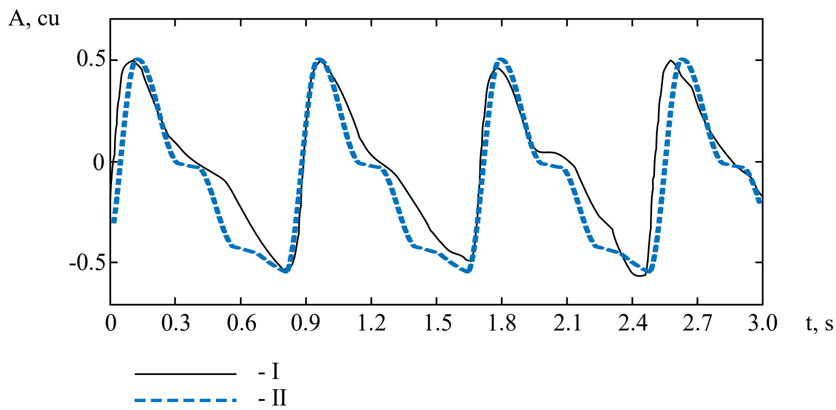

Fig. 11. Implementation of the simulated and experimentally recorded PPS in the period T_e=3 s: I – experimentally recorded PPS [21]; II – simulated PPS: x – t, s – time in seconds; y – A, cu – amplitude in conventional units

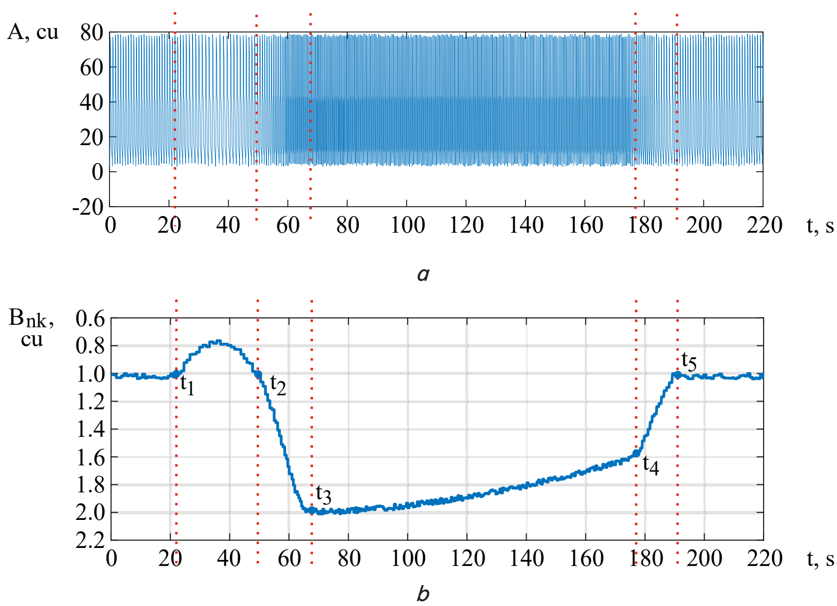

Fig. 10. Simulation model of PPS under psychoemotional stress (T_e=220 s) taking into account the random component: *a* – simulated PPS: x – t, s – time in seconds; y – A, cu – amplitude in conventional units; *b* – curve of the period change factor B_{nk} for the simulated PPS: x – t, s – time in seconds; y – B_{nk}, cu – period change factor in conventional units

6. Discussion of the results of developing a simulation model of the photoplethysmographic signal under psychoemotional stress

The developed simulation model of PPS under psychoemotional stress (Fig. 10) illustrates the basic patterns of simulating signals of biological origin – frequency, random component and stress response patterns. PPS has a number of characteristic coding points reflecting the state of the cardiovascular system as a whole, as shown in Fig. 2. Under psychoemotional stress it is also important to consider the process of body's stress response, which has a number of characteristic time intervals shown in Fig. 1. Therefore, the simulation of PPS was carried out taking into account three starting points: PPS is a periodic signal; PPS contains the random component; PPS should reflect stress response stages. Simulation of the signal using formula (2) allows taking into account only frequency, because changes in signal characteristics are subject to the law that does not provide for random processes in signals of biological origin. Signal frequency in the simulation of peripheral circulation was taken into account in [9, 13]. Using formula (2) allows reproducing the waveform, which is also provided in the harmonic three-phase model [11] and simulation model of the daily pulse signal [13]. However, reproduction of the waveform and coding points is not provided in the additive mixture of deterministic and random components [10]. The simulation model of PPS within one period is based on 6 harmonic functions taking into account the amplitude and time characteristics of the CVS, as well as the frequency of signals of biological origin .

The introduction of the random component, namely mathematical expectation $M\{A\}$, $M\{t\}$ and variance $D\{A\}$, $D\{t\}$ for amplitude and frequency (3), allows taking into account the signal characteristics that occur when taking a signal from a real biological object. Deviations in PPS, which are random, can be due to both body peculiarities and obstacles, motion artifacts, etc. The simulation model of PPS within 10 periods reflects the signal frequency and random component with the value $rand$=2 for amplitude A and $rand$=1 for period t. Reproduction of the signal in this way allows taking into account the presence of random variables for amplitude $M\{A\}$, $D\{A\}$ and time $M\{t\}$, $D\{t\}$. The random component in signals of biological origin is not taken into account in the simulation model of the pulse wave in the form of exponentially damped sinusoid [9] and harmonic three-phase model [11].

Since the stress response has stages that can be traced by changes in the cardiovascular system, PPS must also change according to a certain law that allows judging the patient's condition. Fig. 9 shows the simulation model of the stress response curve using formula (4), reflecting the long-term process of stress response. Such a simulation model is based on 4 harmonic functions. Only in the simulation model of the daily pulse signal [13], the course of long-term processes is taken into account, which do not reflect stress response peculiarities. Using a comprehensive approach for simulating PPS under psychoemotional stress allows taking into account the state of the CVS not only at the moment, but also predicting changes in the body over a certain period of time. That is, based on the data on stress factor cessation time, it is possible to determine the period required to restore the CVS activity. However, signal simulation taking into account the stress response curve complicates pulse signal simulation algorithms and increases the number of input parameters.

To confirm the adequacy of the simulation results, the experimental and simulated signals were evaluated by calculating the relative error and comparing the signals by Student's t-test. Calculation of the relative error for the simulated and experimental signals shows high accuracy of the method of simulating PPS under psychoemotional stress. The relative error for the amplitude variation of such a model and experimental data is 3.97 %, and for the period – 3.41 %. Calculation of Student's t-test for the experimental and simulated signals showed a statistically insignificant difference – p=0.296 for the amplitude and p=0.275 for the period.

Using the proposed simulation model of PPS under psychoemotional stress makes it possible to obtain data with known parameters. An important advantage of this PPS simulation method is that the structure of the models allows changing the input parameters of the signal both in amplitude and time, which provides a set of different data. The use of such data is one of the important criteria for validating algorithms for processing signals under psychoemotional stress. Modern equipment for PPS takeout has a high signal discreteness and is ergonomic, which allows it to be used for a long time. One way to improve existing equipment and create a new one is to use PPS processing algorithms that can interpret data within a specific problem. Therefore, validation of processing algorithms is an important step in obtaining reliable data that help reduce the risk of emergencies in dental practice caused by psychoemotional stress. Since ergonomics and hardware allow long-term monitoring, software improvement and validation are an important step in production processes and creation of competitive equipment. The developed simulation model of PPS under psychoemotional stress can be used to test PPS processing algorithms at the stage of equipment design.

Using the proposed simulation model, unlike existing ones, helps to take into account most factors arising in response to the stress factor. Therefore, the developed simulation model of PPS under psychoemotional stress can be used not only in dental practice, but also in other stress-related areas. These, in addition to medicine, include the service sector, as workers of certain professions are exposed to stress, which negatively affects the state of the CVS. The proposed principle of simulation can also be used to reproduce other signals that have a similar nature, i.e. are periodic, contain a random component and are subject to long-term processes. An example of a process that can be simulated using this approach is simulating the efficiency of solar panels during daylight hours. The constant component is the minimum level of diffused light, the random component is the presence of cloud cover during the day, and the long-term process is a change in efficiency depending on the angle of sunlight incidence. That is, using the proposed simulation principle is promising in various fields.

Limitations of the simulation model of PPS under psychoemotional stress include the fact that the model does not take into account changes in PPS due to respiratory movements. That is, the model provides for signal conditioning relative to zero for one of signal coding points. This, in turn, requires additional computing power for signal conditioning, only then it can be compared with the simulated signal. Improving the existing simulation model taking into account changes in the signal caused by respiratory movements will improve the process of validating algorithms for processing signals under psychoemotional stress without using additional signal preparation steps.

The development of this study can be carried out in the direction of eliminating this shortcoming of the simulation model of PPS under psychoemotional stress.

7. Conclusions

1. The simulation model of PPS taking into account the waveform and main coding points was developed. This model is based on 6 harmonic functions that allow simulating the signal by amplitude and at certain time intervals. This simulation makes it possible to reproduce the waveform and the main time and amplitude parameters that reflect the activity of the CVS.

2. The simulation model of PPS within 10 periods considering the random component was developed. This simulation model allows taking into account the random component of signals of biological origin by introducing mathematical expectation and variance for amplitude $M\{A\}$, $D\{A\}$ and time $M\{t\}$, $D\{t\}$.

3. The simulation model of the curve of changes in physiological indicators under psychoemotional stress using 4 harmonic functions was developed. This model is based on the reproduction of characteristic stress response stages. The proposed simulation model allows changing the duration of stress response stages for the reproduction of various scenar-

ios of changes in the patient's condition under psychoemotional stress.

4. The complex simulation model of periodic PPS with the random component and taking into account the curve of changes in physiological parameters under psychoemotional stress was developed. The simulation model is based on the reproduction of signal characteristics and stress response curve using harmonic functions for individual parts of the model. The main purpose of the proposed model is to obtain data with known parameters to solve the problem of validating algorithms for processing PPS under psychoemotional stress. The relative error for the amplitude variation of such a model and experimental data is 3.97 %, and for the period – 3.41 %. The calculation of Student's t-test showed that a statistically insignificant difference: p=0.296 for the amplitude and p=0.275 for the period. The developed simulation model is characterized by high accuracy and reproducibility, which contributes to using it to solve the problems of validating algorithms for processing PPS under psychoemotional stress.

References

1. Burgonskyi, V., Burgonskaya, S. (2014). Changes in stress as a prerequisite for psychosomatic disorders dental patients. Sovremennaya stomatologiya, 4, 13–20.
2. Dem'yanenko, C. A., Avdonina, L. I., Boyko, V. V. (2004). Kardiomonitoring pri razlichenii boyazni i straha i prinyatii resheniya o premedikatsii na stomatologicheskom prieme. Institut ctomatologii, 3 (24), 8–12. Available at: https://instom.spb.ru/catalog/article/8594/?view=pdf
3. Demyanenko, S. A. (2014). Psycho-emotional stress of hypertensive reaction to dental reception. Vyatskiy meditsinskiy vestnik, 3-4, 53–56. Available at: https://cyberleninka.ru/article/n/psihoemotsionalnoe-napryazhenie-v-razvitii-gipertenzivnyh-reaktsiy-na-stomatologicheskom-prieme/viewer
4. Vagner, V. D., Nimaev, B. Ts. (2005). Kontseptual'nye osnovy dal'neyshego razvitiya obschey (semeynoy) praktiki v stomatologii. Institut stomatologii, 4, 20–21. Available at: https://instom.spb.ru/catalog/article/8762/?view=pdf
5. Mintser, O. P. (Ed.) (2011). Suchasni metody i zasoby dlia vyznachennia i diahnostuvannia emotsiynoho stresu. Vinnytsia: VNTU, 228. Available at: http://dspace.wunu.edu.ua/jspui/bitstream/316497/2138/1/Monografiya_Syergyeyeva.pdf
6. Moraes, J., Rocha, M., Vasconcelos, G., Vasconcelos Filho, J., de Albuquerque, V., Alexandria, A. (2018). Advances in Photopletysmography Signal Analysis for Biomedical Applications. Sensors, 18 (6), 1894. doi: https://doi.org/10.3390/s18061894
7. Tkachenko, P. I., Lokhmatova, N. M., Byelokon, S. A., Dobroskok, V. A. (2017). The intensity of emotional tension in children with cleft palate in response to situational stress. Ukrainskyi stomatolohichnyi almanakh, 1, 75–78. Available at: http://elib.umsa.edu.ua/jspui/bitstream/umsa/10292/1/Vyrazhenist_psykhoemotsiinoho_napruzhennia.pdf
8. Moshkevich, V. S. (1970). Fotopletizmografiya (Apparatura i metody issledovaniya). Moscow: Meditsina, 208. Available at: https://www.twirpx.com/file/1537026
9. Akulov, V. A. (2006). Model' pul'sovoy volny i ee realizatsiya v srede Excel. Proceedings of the Third All-Russian Scientific Conference. P. 4, Matem. Mod. Kraev. Zadachi. Samara, 13–16. Available at: http://www.mathnet.ru/links/7fb61787446959c52d59306ab30dee10/mmkz693.pdf
10. Samkov, C. B., Chernenko, A. I. (2006). Sverhshirokopolosnyy radar dlya izmereniya parametrov serdechno-sosudistoy sistemy cheloveka pri fizicheskih nagruzkah. II Vseros. nauchnaya konf.-seminar. Murom, 475–479.
11. Gnilitskyy, V. V., Muzhitska, N. V. (2010). Refinement of the harmonic model of pulse wave for the express-diagnosis of pulsogram. Visnyk ZhDTU. Seriya "Tekhnichni nauky", 4 (55), 28–38.
12. Wu, H.-T., Wu, H.-K., Wang, C.-L., Yang, Y.-L., Wu, W.-H., Tsai, T.-H., Chang, H.-H. (2016). Modeling the Pulse Signal by Wave-Shape Function and Analyzing by Synchrosqueezing Transform. PLOS ONE, 11 (6), e0157135. doi: https://doi.org/10.1371/journal.pone.0157135
13. Hvostivska, L. V., Oksukhivska, H. M., Hvostivskyy, M. O., Shadrina, H. M. (2019). Imitation Modeling of the Daily Pulse Signal for Long-Term Monitoring Systems. Visnyk NTUU KPI Seriia - Radiotekhnika Radioaparatobuduvannia, 77, 66–73. doi: https://doi.org/10.20535/radap.2019.77.66-73
14. Trigranyan, R. A. (1988). Stress i ego znachenie dlya organizma. Moscow: Nauka, 175.
15. Kokun, O. M., Ahaiev, N. A., Pishko, I. O., Lozinska, N. S. (2015). Osnovy psykholohichnoi dopomohy viyskovosluzhbovtsiam v umovakh boiovykh diy. Kyiv: NDTs HP ZSU, 170. Available at: https://lib.iitta.gov.ua/11222/1/%D0%9F%D0%BE%D1%81%D1%96%D0%B1%D0%BD%D0%B8%D0%BA_2015.pdf
16. Wawrzyniak, A. J., Dilsizian, V., Krantz, D. S., Harris, K. M., Smith, M. F., Shankovich, A. et. al. (2015). High Concordance Between Mental Stress-Induced and Adenosine-Induced Myocardial Ischemia Assessed Using SPECT in Heart Failure Patients: Hemodynamic and Biomarker Correlates. Journal of Nuclear Medicine, 56 (10), 1527–1533. doi: https://doi.org/10.2967/jnumed.115.157990
17. Shevchenko, V. V., Osadchiy, A. V., Esipenko, E. S. (2012). Sposob vydeleniya informativnyh parametrov fotopletizmosignala dlya opredeleniya sistemnyh reaktsiy na MLT. Sovremennye nauchnye issledovaniya i innovatsii, 5. Available at: http://web.snauka.ru/issues/2012/05/12640
18. Hvostivska, L. V. (2016). The human vascular pulse signal imitation model. Herald of Khmelnytskyi national university. Technical sciences, 2, 94–100. Available at: http://nbuv.gov.ua/UJRN/Vchnu_tekh_2016_2_18
19. Teng, Y., Ge, L., Chou, Y. (2018). A Novel Abnormal Segments Detection Method for Photopletysmography Signal. 2018 37th Chinese Control Conference (CCC). doi: https://doi.org/10.23919/chicc.2018.8483815

20. Takazawa, K., Tanaka, N., Fujita, M., Matsuoka, O., Saiki, T., Aikawa, M. et. al. (1998). Assessment of Vasoactive Agents and Vascular Aging by the Second Derivative of Photoplethysmogram Waveform. Hypertension, 32 (2), 365–370. doi: https://doi.org/10.1161/01.hyp.32.2.365
21. Askarian, B., Jung, K., Chong, J. W. (2019). Monitoring of Heart Rate from Photoplethysmographic Signals Using a Samsung Galaxy Note8 in Underwater Environments. Sensors, 19 (13), 2846. doi: https://doi.org/10.3390/s19132846

UDC 004.35: 004.9
DOI: 10.15587/1729-4061.2021.230042

INFORMATION PROCESSING PSYCHODIAGNOSTIC SYSTEM: DESIGNING AND IMPLEMENTATION

Valentine Lazurik
Doctor of Physical and Mathematical Sciences, Professor
Department of Systems and Technologies Modeling**
E-mail: mst@karazin.ua

Nicolay Styervoyedov
Doctor of Technical Sciences, Associate Professor, Head of Department*
E-mail: keus@karazin.ua

Natalia Varlamova
Lecturer*
E-mail: natess123@gmail.com

*Department of Electronics and Control Systems**
**V. N. Karazin Kharkiv National University
Svobody sq., 4, Kharkiv, Ukraine, 61022

The reasons for the creation of a modern psychodiagnostic system are considered. The design and implementation of an information processing system using the structure of the reference model of the Internet of Things is proposed. The existing psychodiagnostic tools and a number of disadvantages are described. In the process of developing the system design, requirements were formed: three-dimensional representation of signals, remote control of the diagnostic process, data collection, transmission and storage on a remote server, processing of results, expert assessment. The main two tasks of the study are formed. The structure of an information processing system containing four blocks interacting with each other is presented. The principle of operation of the system provides for the transfer of data for testing and saving the results on a cloud server using WiFi or GPRS connection. The Thingspeak cloud service used provides guaranteed access to research data "anytime and from anywhere in the world." Data exchange occurs every 15 seconds when using the free version and with a cycle of up to 1 second when using the cloud on a commercial basis. The models of LED-cube, LED-ball, LED panels diagnosed using addressable digital RGB LEDs with built-in WS2812B microcontrollers (PRC) have been developed. A method for assessing the influence of various types of load on the functional state of a person is proposed. Scenarios of data processing for the formation of a subject's profile in the case of unclear classes are considered. The importance of developing such a system lies in the possibility of using various types of communication for data transmission and the ability to adapt it to non-standard research requirements

Keywords: Internet of Things, microcontroller, WiFi module, GSM module, information processing system, psychodiagnostic research, fuzzy sets

Received date 09.02.2021
Accepted date 19.04.2021
Published date 30.04.2021

***How to Cite**: Lazurik, V., Styervoyedov, N., Varlamova, N. (2021). Information processing psychodiagnostic system: designing and implementation. EasternEuropean Journal of Enterprise Technologies, 2 (9 (110)), 45–54. doi: https://doi.org/10.15587/1729-4061.2021.230042*

1. Introduction

The problems of the relationship between the psychological and psychophysical characteristics of a person and its effective work activity still require careful study. These interrelationships are relevant in all professional activities, but they are especially important in the operation of critical systems, in which the human factor can lead to a malfunction of the system, and, as a consequence, large losses [1, 2]. Accordingly, there is a requirement for fast and reliable hardware data collection, which, in turn, gives rise to the need to develop a modern psychodiagnostic and psychophysical information processing system.

Despite the development in recent years of the concept of the Internet of Things, which makes it possible to remotely control technical means [3–5], mainly hardware and software methods and means for local collection, storage and processing of data are used. These psychodiagnostic tools allow using a fairly large volume of tests, storing data on a local drive, but they are not very useful for remote collection of information, work in "field" conditions or in the absence of an expert at the research site. In addition, diagnostic systems often have a narrowly focused principle without the possibility of integrating new testing tools and the same specialized scenario for creating an expert conclusion.

For professional selection, it becomes necessary to form a professional profile of a person, based on its psychological and psychophysical indicators. The definition of such a profile is possible based on the objective requirements for a particular profession, as well as the requirements of the employer (including non-standard ones). Therefore, to form a profile, a variety of psychodiagnostic techniques can be used, the purpose of which is to determine the specific, both qualitative and quantitative characteristics of a person. This approach presupposes considering the profiles of the subjects as classes or collections of sets that have given common features. Taking into account the variability of the requirements for the profile, the obtained human indicators, the introduction of new diagnostic methods and subjective expert assessment, it is assumed that there is a problem of fuzzy classes. Therefore, it becomes necessary to determine the belonging of the object (subject) to a certain class and the optimal solution to this problem was to use the theory of fuzzy sets using membership functions.