Multi-Sensory Portable Information System for Monitoring and Analysis of Cardiac Data

Mitko Valchev Gospodinov[1], Evgeniya Peneva Gospodinova[2], Galya Nikolova Georgieva-Tsaneva[3]

Institute of Robotics, Bulgarian Academy of Sciences, Bulgaria

Abstract

The scientific researches in the recent years in the field of personal cardiology are focused on the creation of a wide variety of portable electronic devices and systems for individual monitoring of the cardiovascular system. This includes: portable electrocardiography (ECG) devices, personal holters and blood pressure recorders, developed as a result of the advances in microelectronics, sensors, wireless communications and advanced software. An important advantage of the portable equipment is the ability to constantly monitoring and record the functioning and parameters of the cardiovascular system of the individual. This article presents the latest hardware and software development of a new portable information system for registration of cardiological data, based on the integration of ECG and photoplethysmography (PPG) sensors, operated in the highly integrated microcontroller system. Among the advantages of the portable system is the registration of the increased set of parameters of a person's cardiac activity in real time - heart rate, RR and PP intervals between the heart beats, the pulse wave velocity in different body parts – arms, legs, etc. This allows for more precise diagnosis of patients in different life situations in normal living, which is based on a subsequent scientific analysis of the registered cardiac information through developed specialized software with implementation of various non-linear mathematical methods applied mainly at Heart Rate Variability analysis.

Keywords: cardiovascular system; ECG sensor; Heart Rate Variability; microcontroller device; PPG sensor.

1. Introduction

In recent years, the application of new information and technological advances in cardiology has grown rapidly. New, inexpensive and non-invasive devices and methods for research and diagnosis of cardiac diseases have been developed. Cardiac analysis is intensively applied in the diagnostic process based on information obtained by electrocardiographic (ECG) and photoplethysmographic (PPG) sensors.

A number of quantitative characteristics evaluating the change in cardiac rhythm parameters in cardiac diseases are determined on the basis of ECG signals that carry information on heart rate variability (HRV) (Acharya et al., 2007). An alternative approach to the application of

HRV assay methods is the recording and processing of signals sensing peripheral arterial pulsation using photoplethysmographic sensors.

From a scientific point of view, it is interesting to study the accuracy ratio in determining cardiac rhythm indicators recorded on the basis of ECG signals taking into account the bioelectric activity of the heart and PPG signals accounting for peripheral arterial pulsation.

The relevance of the study presented in this article is the question of the diagnostic and prognostic values of cardiac data obtained as a result of registration, processing and mathematical analysis of ECG and PPG signals in a multisensory cardiac analysis system.

The article (Allen, 2007) describes the history and current use of PPG as a simple and inexpensive optical technique used to detect changes in blood volume circulating in the peripheral circulatory system and mainly in the microvascular layer of the peripheral organs - fingers, ear and more. This non-invasive technique measures blood circulation below the surface of the skin. The PPG-sensed waveform of the signals includes a pulse wave as a result of cardiac synchronous changes in the volume of blood flow at each heart beat, which is superimposed on a slowly changing base wave at a lower frequency, as a result of breathing, the activity of the sympathetic nervous system and thermoregulation of the human body. „PPG has been applied in many different clinical settings, including clinical physiological monitoring (blood oxygen saturation, heart rate, blood pressure, cardiac output and respiration), vascular assessment (arterial disease, arterial compliance and ageing, endothelial function, venous assessment, vasospastic conditions, e.g.“

The article (Elgendi et al., 2019) presents the measurement of blood pressure (BP), which is crucial for the investigation and treatment different medical conditions. High blood pressure usually is associated with chronic diseases diseases causing fatal outcome. For outpatient care and for the long-term monitoring of patients' health status, it is of great interest to be able to accurately and frequently measure PD outside the clinical setting using mobile or wearable devices. With the advancement of digital sensors, the processing of cardiac signals, through the development of algorithms for mathematical research and the creation of physiological models, pulse wave analysis using PPG for BP evaluation has become significantly more accurate.

The article (Jayadevappa et al., 2016) describes in detail Clinical Physiological Monitoring based on the measurement of PPG signals, including Blood Oxygen Saturation, changing of the Heart Rate (HR) as an important parameter of cardiac measurements, Cardiac Output estimated from PPG derived pulse contour analysis, as well as Respiratory causing variation in the peripheral circulation of the blood.

The article (Botman et al., 2015) is devoted to the description of the development of a portable device for individual ambulatory surveillance which may be used to provide timely support for patients with cardiovascular diseases. The prototype consists of an infrared optical TCRT1000 sensor, an analog filter, operational amplifier and a microcontroller Arduino UNO, which is used for analogue-digital conversion and computer communication. Such devices can be used for a multi-parameter sensor system that is connected to a smartphone to allow real-time registration and control of body temperature, electrocardiogram (ear-lead ECG) and oxygenation in outpatients as described in the article (Celik et al., 2015).

Most modern system including wearable wireless multisensor device for real-time computerized biofeedback and data acquisition. The system is based on four built-in sensors: a PPG, electrodermal activity (EDA), triaxial accelerometer, and temperature. The article (Garbarino et al., 2014) describes such system working as in streaming mode using real-time data processing with Bluetooth low energy interface and in recording mode with internal flash memory.

An interesting application of the PPG sensing system is described in the article (Stankevičius et al., 2016), where is presented a scientific development of PPG sensing device provided for studies of the increased risk of atrial fibrillation (PM) in the case of renal replacement therapy, such as hemodialysis.

Methods for the study of heart rate variability (HRV), which is an important tool for analyzing patients' physiological readings, are presented in the article (Moraes et al., 2018). PPG-based multisensor systems have been successfully used in conjunction with ECG sensors to determine cardiac pathologies. This study presents definitions of the PPG technique, the different types of sensors used, and the mathematical methods for examining and analyzing PPG signals (linear and non-linear), as well as the progress in the clinical and practical applicability of the PPG technique in the diagnosis of cardiovascular disease has been evaluated.

In the descriptions of developments presented in a number of articles, some important HRV parameters are calculated using PPG-HRV and ECG-HRV. An important scientific question is the comparison of the two methods of obtaining rhythmic studies. The article (Jeyhani et al., 2015) shows the results of time-domain analysis for signals were recorded using two different sensor nodes on a wireless sensor network with a 16-bit A/D converter resolution.

The comparison of the 5-minute records made in the article (Lu et al., 2019) showed a lot high degree of correlation in time and frequency domain and in nonlinear dynamics analyzes between HRV measurements obtained from GHG and ECG. The results confirm that PPG provides accurate time intervals from which HRV measurements can be accurately extracted at real conditions, suggesting that this technique may prove practical an ECG alternative for HRV analysis.

The purpose of this article is to present a multisensory portable information system for simultaneous real-time recording of ECG and PPG signals in the study of cardiac status of healthy subjects. The simultaneous registration shows the possibility of comparative analysis of physiological data by modeling of RR and PP time intervals by applying linear and non-linear mathematical methods.

2. Multi-Sensory Portatable Information System

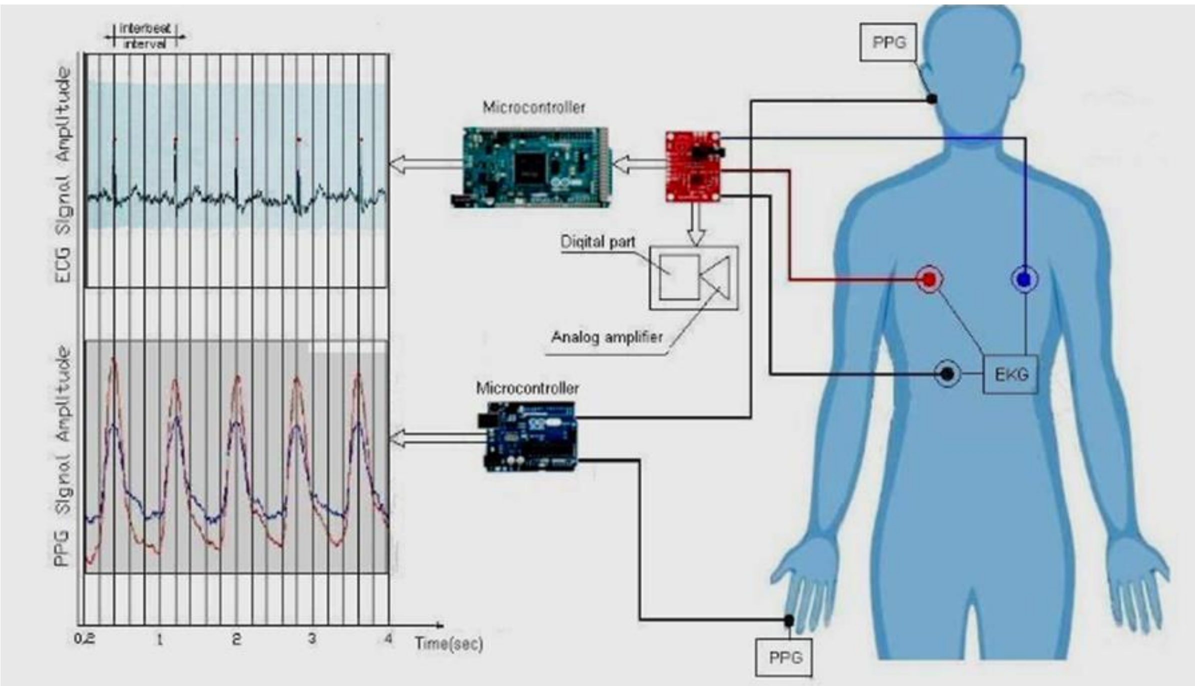
The system is a microcontroller board with touch screen display and integrated power supply. It has 54 digital input/output pins, 16 analog inputs, 4 UARTs (hardware serial ports), a 16 MHz crystal oscillator, a USB connection, a power jack, an ICSP header, and a reset button. It contains everything needed to support the microcontroller; simply connect it to a computer with a USB cable or power it with a AC-to-DC adapter or battery to get started. The microcontroller can be powered via the USB connection or with an external power supply. The power source is selected automatically. External (non-USB) power can come either from an AC-to-DC adapter (wall-wart) or battery (Arduino, 2019).

The basic microelectronic component of the device is microchip AD8232 – "an integrated signal conditioning block for ECG and other biopotential measurement applications. It is designed to extract, amplify, and filter small biopotential signals in the presence of noisy conditions, such as those created by motion or remote electrode placement. This design allows for an ultralow power analog-to-digital converter (ADC) or an embedded microcontroller to acquire the output signal easily" (Analog Devices, 2012).

The AD8232 can implement a two-pole high-pass filter for eliminating motion artifacts and the electrode half-cell potential. This filter is tightly coupled with the instrumentation architecture of the amplifier to allow both large gain and high-pass filtering in a single stage, thereby saving space and cost. An uncommitted operational amplifier enables the AD8232 to create a three-pole low-pass filter to remove additional noise. The user can select the frequency cutoff of all filters to suit different types of applications (Analog Devices, 2012).

Figure 1 shows a block diagram of a multi-sensor portable system for recording ECG and PPG signals. The system consists of 2 sensors for capturing photoplethysmographic signals from the patient's finger and ear and 3 sensors for electrocardiogram recording. The two types signals are registered simultaneously. The processing and analysis of the received signals is carried out by specialized software, installed on a personal computer, by applying linear and non-linear mathematical methods.

Figure 1: Multi-Sensory device



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3. Data and Methods

3.1 Data

Twenty healthy subjects (10 males and 10 females aged 20.8 ± 1.6) were examined. The recording time is 2 hours. The ECG and PPG signals for the subjects studied are recorded with the multisensor device presented above, and the specialized software developed determines and analyzes the RR time intervals of the ECG signals and PP intervals of the PPG signals. In order to demonstrate the coincidence of the intervals between the two types of signals, the mean square error (MSE) is determined with the following formula:

$$MSE = \sqrt{\sum_{i=1}^{N} (x_i - y_i)^2} \quad (1)$$

Where: x are RR intervals, y are PP intervals, and N is the number of intervals. When the MSE tends to zero, it indicates that the intervals of the two signals are very close, ie they are identical.

3.2 Methods

The analysis of RR and PP interval series is performed by applying linear and nonlinear mathematical methods (Acharya et al., 2006), (Kumar et al., 2013). Linear methods are Time-Domain Analysis and Frequency-Domain Analysis (Smith et al., 2009). From the nonlinear methods, the Poincaré plot was used (Golińska, 2013), (Kamen et al., 1996). Quantitative measurements of parameters determined by linear methods (Time-Domain and Frequency-Domain) have significantly clinical application. There is an active work in this field and the limits of norm-pathology are already known, which makes it possible to introduce this methods into standard clinical practice (Malik, 1996). Nonlinear methods, such as the Poincaré plot, provide additional information about the cardiovascular system of patients (Ernst, 2015), (Khandoker et al., 2013), (Smith et al., 2009).

3.2.1 Time-Domain Analysis

Through this analysis, the following parameters were investigated (Ernst, 2014):

- Mean RR (Mean PP)-средната стойност на RR and PP intervals;
- SDNN-standard deviation of normal RR (PP) intervals;
- RMSSD-square root of the mean squared differeces betwee successive RR (PP) intervals.

3.2.2 Frequency-Domain Analysis

Frequency domain parameters are based on spectral analysis for the following three components: Very Low Frequency (VLF; 0.00-0.04 Hz), Low Frequency (LF; 0.04-0.15 Hz) and High Frequency (HF; 0.15-0.40 Hz). The FFT method was used and the following parameters were investigated (Ernst, 2014):

- Absolute powers of VLF, LF and HF bands in ms^2;
- Relative powers of VLF, LF and HF bands in %;
- Ratio between LF and HF band powers.

3.2.3 Poincaré plot

The Poincaré plot is one of the widely used graphical methods for nonlinear analysis of cardiac data (Khandoker et al., 2013), (Tayel et al., 2015). This method plots each RR (PP) interval against the previous one. To analyze the studied signals, the following two parameters are calculated: Standard deviation 1 (SD1), which represents the short term variability of the data; Standard deviation 2 (SD2), which is the long term variability of the data and the ratio between them (Piskorski & Guzik, 2007). An ellipse with radii is constructed: SD1 and SD2. In healthy subjects, the ellipse is well expressed, whereas in the diseased condition, it may approach a circle when the values of SD1 and SD2 are approximately equal (Khandoker, 2013), (Ernst, 2014) or have a complex shape consisting of several segments. This method enables the entire ECG or PPG recording to be monitored graphically and allows cardiovascular disorders to be detected quickly, if any. When a Poincaré graphic is in the form of a comet, the data refer to a healthy subject. In the various cardiovascular diseases, the graphs have specific images, which allow this method to be used to diagnose cardiovascular diseases.

4. Results and Discussion

Figure 2a and Figure 2b show two 300-second segments corresponding to the RR intervals and the PP intervals recorded by the ECG sensors and the PPG sensor placed in the left ear of the subject. Figure 2c shows their mean square error, which is $1.881 * 10^{-4}$ s. The resulting mean square error when comparing the ECG signal and the PPG signal registrated from the sensor placed on the thumb of the left hand is $2.070 * 10^{-4}$ s.

Based on the results obtained, it follows that the RR intervals and the PP intervals recorded by ECG sensors and PPG sensors placed on the finger and ear are identical due to the small values of the mean square error.

Figure 2: Comparison of the RR and PP intervals registrated from ECG sensors and PPG sensor placed on the ear

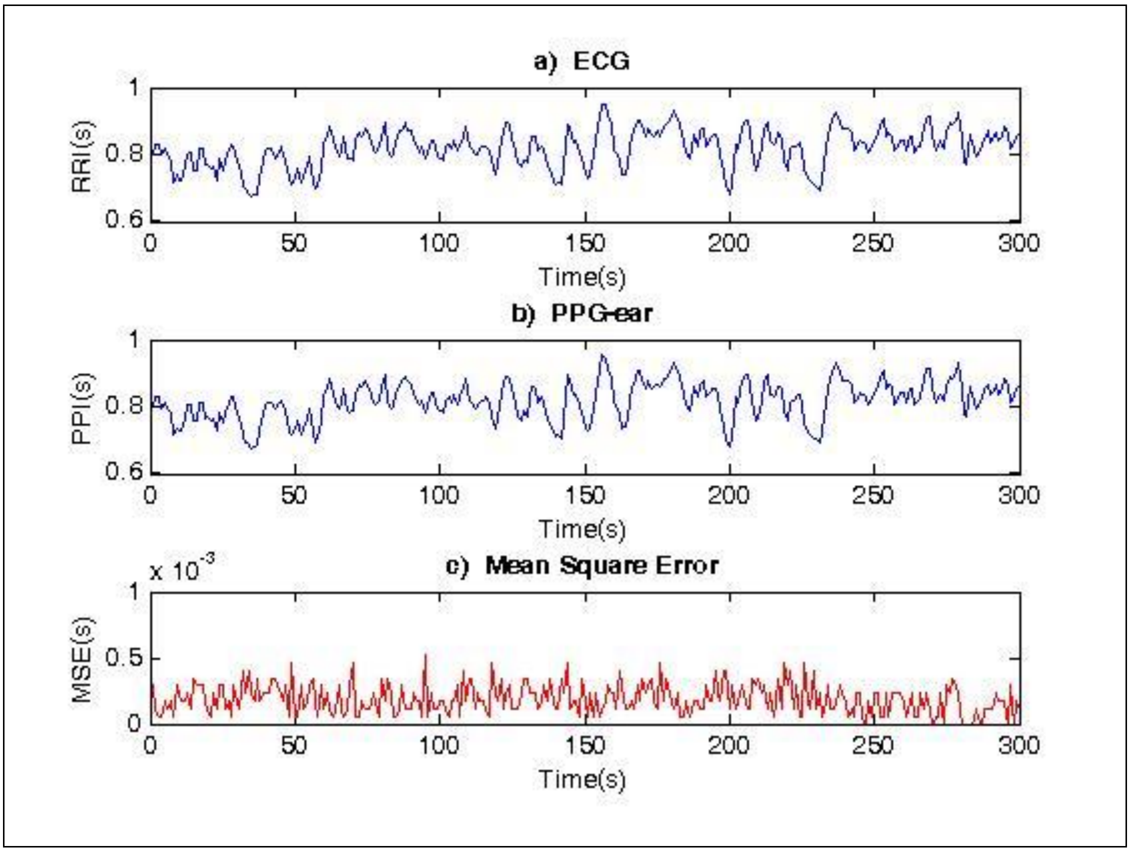

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Figure 3 shows the graphs of the RR and PP interval series of the two studied signals obtained by the non-linear mathematical method-Poincaré plots. The values of the calculated parameters are identical and the graphs of the constructed ellipses are well expressed, which is evidence that the studied data corresponding to the ECG and PPG-ear signals refer to a healthy subject. The shape of the graphs looks like a comet, which is further proof that the recorded signals through the multi-sensor system presented above belong to a healthy subject. Similar results are reported in (Ernst, 2014).

Figure 3: Poincaré plot for the RR and PP intervals

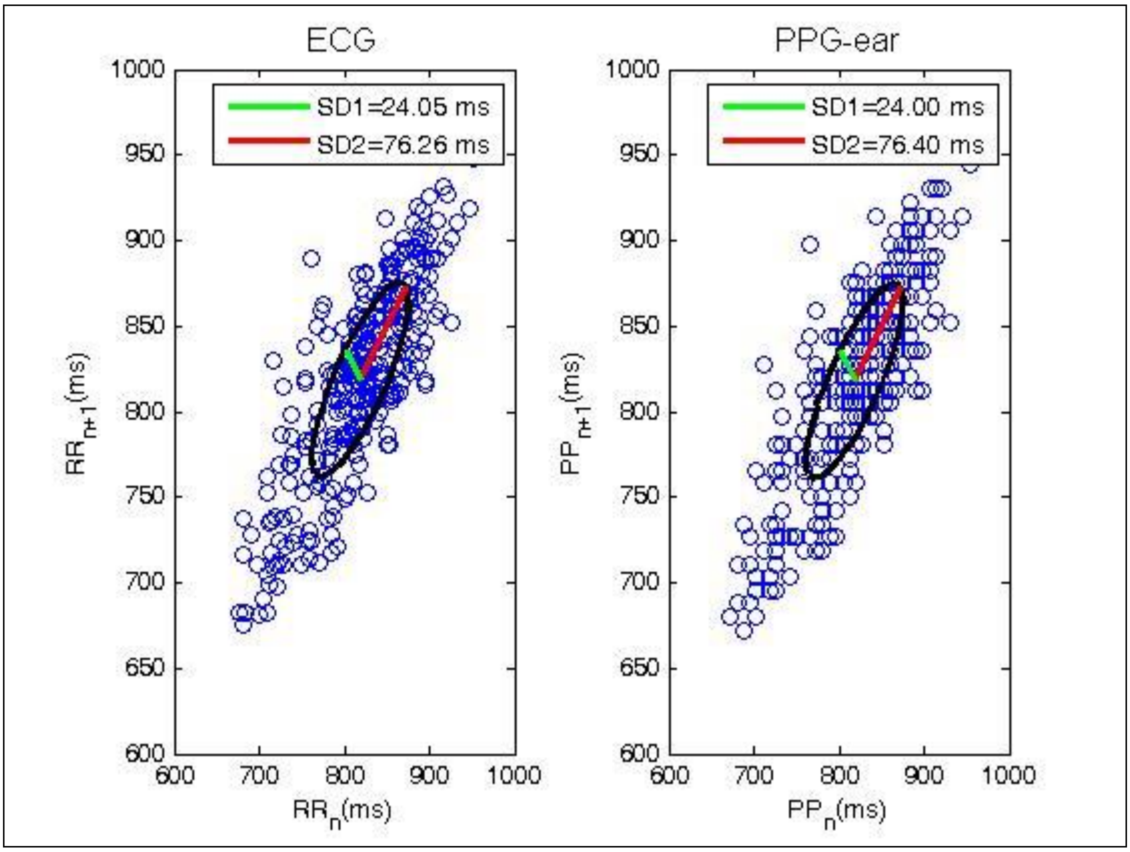

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Table 1 shows the values of the parameters calculated by the linear and the nonlinear methods of analysis of the registered ECG and PPG signals with a duration of 2 hours per 20 healthy control subjects. The results are shown as mean values. The studied signal groups are: Group1 signals captured by ECG sensors; Group2 signals captured by a PPG sensor placed on the left ear of the subject; and Group3 signals captured by a PPG sensor placed on the left thumb of the subject's arm. The relative errors between the following pairs of signals: ECG-PPG_f and ECG-PPG_e are shown also in Table 1.

From the comparative analysis of the studied data pairs, it follows that the relative errors for all the parameters studied are less than 2.3% for the ECG-PPG_{ear} pair and less than 5.6% for the ECG-PPG_{finger} pair. The reason for the larger errors in the ECG-PPG_{finger} pair is due to the following physiological features:

- the muscle of the ear is smaller than the finger of the hand;
- the ear has no cartilage tissue;

- the pulse wave reaches the ear sensor faster than it reaches the finger sensor. This is due to the fact that the sensor placed on the ear is located closer to the heart.

Table 1: Comparative analysis between ECG, PPG_{finger}, PPG_{ear}, $ECG\text{-}PPG_{ear}$ and $ECG\text{-}PPG_{finger}$

Parameters		Group 1 ECG	Group 2 PPG_e	Group 3 PPG_f	Relative Error[%] $ECG\text{-}PPG_e$	Relative Error[%] $ECG\text{-}PPG_f$
Time Domain Analysis	MeanRR(PP)[ms]	1122	1100	1089	2.0%	3.03%
	SDNN [ms]	95.1	94.2	93	0.9%	2.3%
	RMSSD [ms]	20	19.8	19	1.0%	5.2%
Frequency-Domain Analysis	Power VLF [ms^2]	3628	3626	3622	0.5%	1.6%
	Power LF [ms^2]	1844	1813	1800	1.7%	2.4%
	Power HF [ms^2]	1129	1128	1125	0.8%	3.5%
	Power VLF [%]	47	46.2	45.5	1.7%	3.3%
	Power LF [%]	30	29.3	28.7	2.3%	4.5%
	Power HF [%]	22.5	22	21.3	2.2%	5.6%
	LF/HF ratio	1.81	1.8	1.79	0.5%	1.1%
Poincaré plot	SD1 [ms]	28.3	28	27.3	1.0%	3.7%
	SD2 [ms]	111	109	107	1.8%	3.8%
	SD1/SD2	0,254	0.257	0.256	1.1%	0.7%

Source: Authors

The all results in this article were obtained on Matlab.

Conclusion

The development of new models of portable biomedical devices is an important trend in the modern automation of diagnostic activity in medicine. The portable medical devices for computer diagnostics of biosignals are intended for autonomous examination of the health status of a wide range of users. Portable cardiovascular diagnostics are among the most sought after medical devices. The application of innovations in this field will lead to the widespread use of these devices in order to reduce mortality from cardiovascular diseases.

The subject of this article is to investigate a multi-sensory portable information system for registration of ECG signal and two types of PPG signals: the finger and the ear. From the experimental studies, based on mathematical processing and linear and nonlinear analysis of the cardiac data obtained, corresponding to the RR and PP interval series, it follows that the registrated signals from the two types of sensors are identical.

The importance of the created software for linear and nonlinear analysis of the registered signals through ECG and PPG sensors consists in the formation of parametric and graphical assessment of the patients' health status.

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