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MODELING AND ANALYSIS OF SYSTOLIC AND DIASTOLIC BLOOD PRESSURE USING ECG AND PPG SIGNALS

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Abstract. *Taking into account the peculiarities of using the MAX86150 evaluation system for measuring ECG and PPG signals, mathematical models were developed for indirect determination of systolic and diastolic pressure using fingers on the hand, which were tested in the MATLAB environment. Received ECG and PPG signals. Based on the proposed mathematical models, ECG and PPG signals were processed in the MATLAB package and the results of indirect measurement of blood pressure were presented.*

Keywords: systolic pressure, diastolic pressure, ECG and PPG signals, measurement, method for determining blood pressure

MODELOWANIE I ANALIZA SKURCZOWEGO I ROZKURCZOWEGO CIŚNIENIA KRWI Z WYKORZYSTANIEM SYGNAŁÓW EKG I PPG

Streszczenie. *Biorąc pod uwagę specyfikę wykorzystania systemu oceny MAX86150 do pomiaru sygnałów EKG i PPG, opracowano modele matematyczne do pośredniego określania ciśnienia skurczowego i rozkurczowego używając palców dłoni, które zostały przetestowane w środowisku MATLAB. Otrzymano sygnały EKG i PPG. W oparciu o zaproponowane modele matematyczne, sygnały EKG i PPG zostały przetworzone w pakiecie MATLAB oraz przedstawiono wyniki pośredniego pomiaru ciśnienia krwi.*

Słowa kluczowe: ciśnienie skurczowe, ciśnienie rozkurczowe, sygnały EKG i PPG, pomiar, metoda określania ciśnienia krwi

Introduction

Determination of human blood pressure both in a static position (standing, sitting, or lying down) and during dynamic movements (when walking, running, or performing other physical exercises) is carried out by many researchers [2, 6, 8, 11, 17, 20, 35]. There are many different methods for determining systolic and diastolic pressure. All of them are implemented using different devices and sensors, as well as different mathematical expressions (formulas) for calculating blood pressure [2, 6, 11, 17]. At the same time, the accuracy of determining blood pressure (BP) values is different.

Therefore, the development and study of a mathematical model for accurate determination of human systolic and diastolic pressure on the fingers of the hand only by ECG and PPG signals for use in an electronic stethoscope [6, 35] with a diameter of 50 mm to expand its functionality is an urgent scientific task.

As a result of the analysis and research of existing methods and algorithms for determining blood pressure, it was found that many of them are difficult to apply in practice and have low accuracy and sensitivity in determining systolic and diastolic pressure for people of different ages with different values of blood pressure (BP). At the same time, the mathematical apparatus for determining blood pressure used by different researchers is interpreted and applied in different ways. In addition, different researchers use different equipment and the resulting waveforms as a result of the experiments are also different. Waveforms sometimes differ from those theoretical (fundamental) information that is described in the literature [2, 8, 17].

Therefore, in order to expand the functionality of the electronic stethoscope [35], we developed and studied in the MATLAB environment an algorithm for indirectly determining systolic and diastolic pressure from ECG and PPG signals received from the fingers, which is based on two different approaches to calculating blood pressure.

1. System for measuring ECG and PPG signals

The MAX86150 Evaluation System equipment was used for the experiments (Fig. 1). The MAX86150 Evaluation System provides a proven platform to evaluate the MAX86150 integrated photoplethysmogram (PPG) and 1-lead electrocardiogram (ECG) sensor module [34]. The Evaluation System consists of two boards that connect through header pins: a MAX32630FTHR microcontroller board and a MAX86150 evaluation kit. The MAX32630FTHR houses a microcontroller with preloaded firmware, Bluetooth communication, and power management. The sensor board contains the MAX86150 module and two stainless steel dry electrodes for ECG measurement. The Evaluation kit is powered by the included lithium ion battery, which is charged with a micro-USB cable [34]. Based on this evaluation system, we obtained the results of measurements of ECG and PPG signals using only fingers. The measurements were carried out on several patients of different ages (42 years old – patient 1 and 66 years old – patient 2). The obtained measurement results were saved in CSV files, and according to the algorithm proposed below, using the MATLAB platform, the values of systolic (SBP) and diastolic (DBP) pressure of these patients were determined.

2. Mathematical models for determining blood pressure from ECG and PPG signals

As a result of long-term measurement of ECG and PPG signals using fingers on the hand, a database of two patients was obtained, signal fragments from which are shown in Fig. 2.

For clarity and a detailed description of the methodology for determining systolic and diastolic pressure, we have identified one period of the ECG and PPG signals, which is shown in Fig. 3.

Fig. 2 and Fig. 3 show that the PPG signals we received using the MAX86150 Evaluation System have a slightly different shape (inverse) and differ from the PPG signal shapes that were obtained in literature sources [2, 17, 34]. This may be due to the use of different equipment and software when measuring ECG and PPG signals.

To determine the pulse transit time interval, which characterizes the systolic pressure ptt, we calculated the difference between the t_2 interval and the t_1 interval

$$ptt = t_2 - t_1 \qquad (1)$$

At the same time, the t_2 interval was defined as the difference between the ECG signal peak and the PPG signal minimum, and the t_1 interval was defined as the difference between the ECG signal peak and the PPG signal maximum (Fig. 3).

Then the number of samples corresponding to the interval ptt between the extrema of the ECG and PPG signals was converted at time ts (ms) taking into account the sampling frequency (which was 200 kHz) according to the formula

$$ts = (ptt/200)*1000 \qquad (2)$$

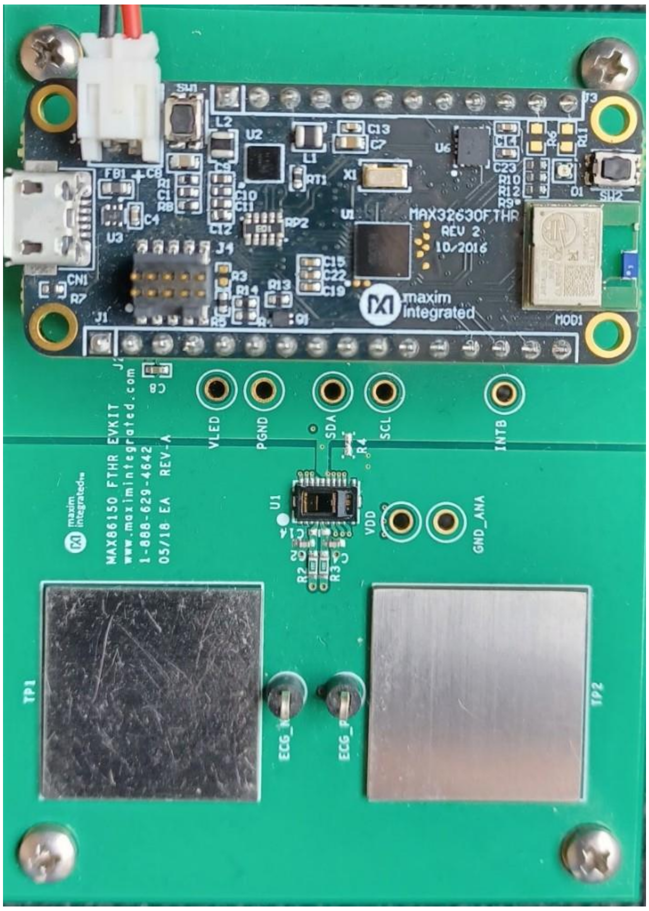


Fig. 1. The MAX86150 Evaluation System equipment was used for the experiments

Taking into account the above formulas (1) and (2), as well as the recommendations of previous studies by other authors [5, 15, 20], we determined the systolic pressure (SBP) using two different formulas

$$SBP_1 = a_1 \cdot ts + b_1 \quad (3)$$

$$SBP_2 = a_2/t_2 + b_2 \quad (4)$$

The diastolic pressure (DSP) of the two patients was also determined using two different formulas

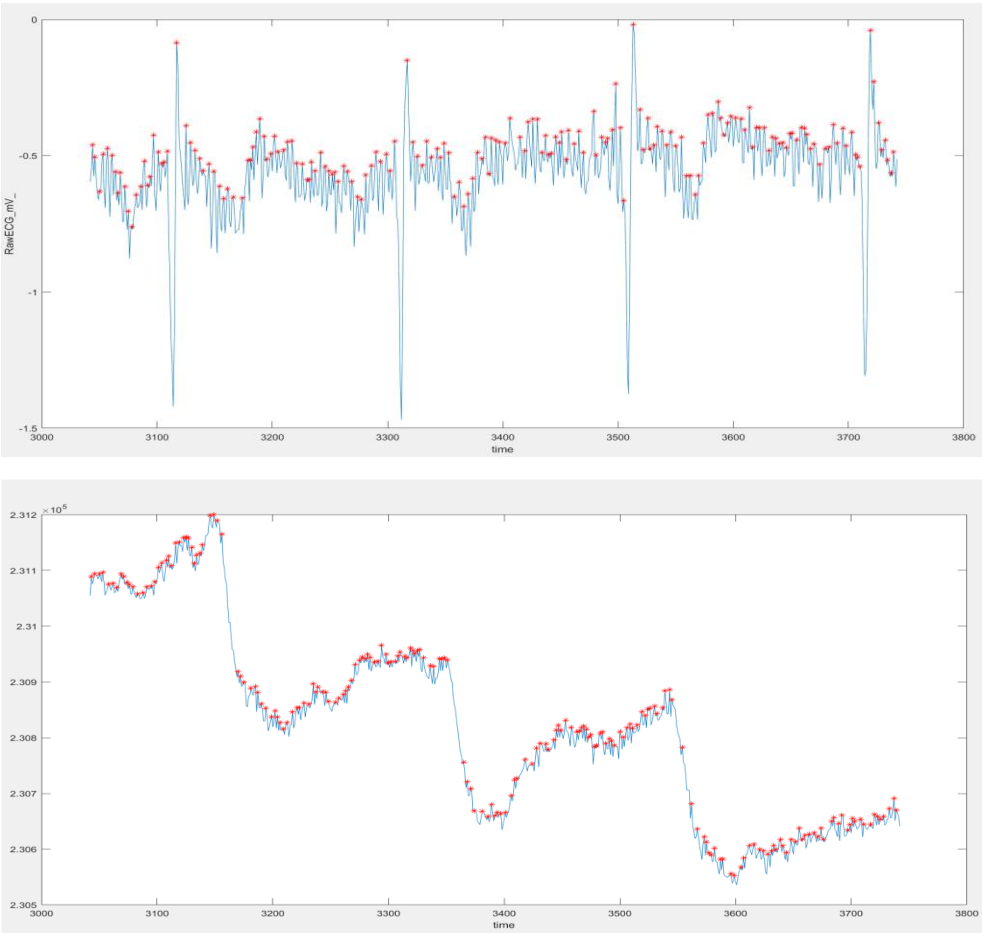
$$DBP_1 = a_1 \cdot t_1 + b_1 \quad (5)$$

$$DBP_2 = a_2/t_1 + b_2 \quad (6)$$

There are a large number of mathematical models for indirectly determining blood pressure from ECG and PPG signals, which are presented in [32]. Various styles of equations are applied, such as linear, quadratic, exponential and others, which are based on different deduction processes. For example, the model (4) reflects the reverse correlation between PTT and SBP shown by large amounts of studies, based on the fact that a high SBP will reduce the time consumed by the pressure pulse to propagate from the proximal to the distal sites, and vice versa [13].

As a result of the analysis and experimental studies of various styles of equations, as well as based on the recommendations of other researchers [13, 15, 20, 32], we have chosen only two models for indirect determination of blood pressure, which are represented by equations (3) – (6). Other styles of equations were either weakly sensitive to changes in blood pressure or did not significantly affect the accuracy of the indirect determination of systolic and diastolic pressure.

In the first method for calculating blood pressure (SBP_1 and DBP_1), the coefficients a1 and b1 of the linear equation (3) were taken equal to a_1 = -0.5 and b_1 = 164 to determine the systolic pressure of SBP_1, as well as a_1 = -0.05 and b_1 = 125 to determine the diastolic pressure DBP_1 (5), based on their numerical values previously presented (calculated) in the literature [3, 14].



a) b)

Fig. 2. Illustration a typical waveform of the PPG and ECG: a) the ECG signal; b) the PPG signal

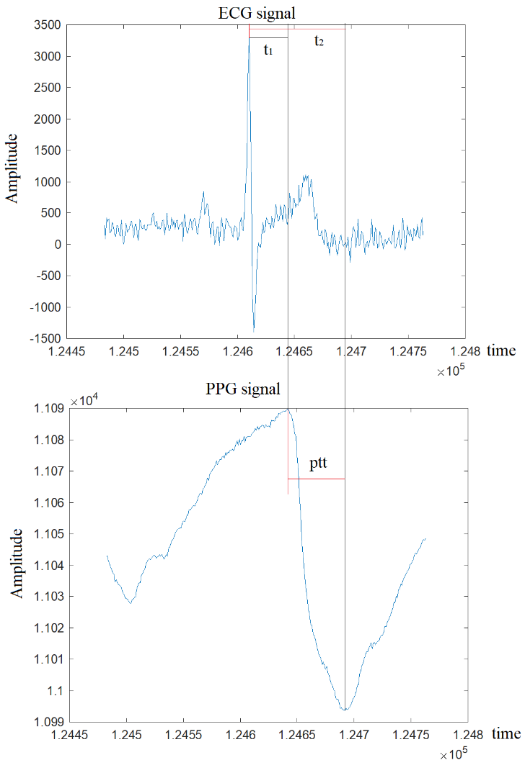


Fig. 3. Calculation of PTT from the time taken for the heart beat pulse to arrive in the finger PPG signal

To calculate blood pressure by the second method (SBP_2 and DBP_2), the values of the coefficients a_2 and b_2 of equations (4) and (6) were calculated based on the experimentally determined values of the signals ptt_S = 640 ms, ptt_D = 140 ms (reference values) and the values of the so-called normal blood pressure SBP_{normal} = 120 mmHg, and DBP_{normal} = 80 mmHg according to the data of the American Heart Association [7, 33] through the solution of the system of equations

$$\begin{cases} SBP_{normal} = \frac{a_2}{ptt_S} + b_2 \\ DBP_{normal} = \frac{a_2}{ptt_D} + b_2 \end{cases} \quad (7)$$

Having solved the system of equations (7) taking into account the known values of normal pressure, the numerical values of the coefficients a_2 = -7170.87 and b_2 = 131.22 were obtained, which were used to process the obtained values of the measured ECG and PPG signals from several healthy people of different ages for determination of blood pressure by formulas (4) and (6) using the MATLAB package.

Based on the principles of dependence of systolic pressure on diastolic pressure, which are detailed in [9, 17, 22, 31] and taking into account the expressions for determining the value of the mean blood pressure (MBP)

$$MBP = SBP/3 + 2 \cdot DBP/3 \quad (8)$$

as well as the aforementioned normal blood pressure values SBP_{normal} = 120 mmHg, and DBP_{normal} = 80 mmHg according to the American Heart Association data [7, 33], which can be used to determine the normal mean blood pressure value: $MBP_{normal} = SBP_{normal}/3+2 \cdot DBP_{normal}/3$ = 93.33 mmHg.

Given the normal mean blood pressure value MBP_{normal} from expression (8), an equation was obtained to determine the diastolic pressure DBP through the values of the systolic pressure SBP

$$DBP = 1.5 \cdot (MBP_{normal} - SBP/3) \quad (9)$$

Measurements of blood pressure were carried out and, according to the experimental data obtained above, the values of systolic pressure were determined in two ways – according to the formula (3) and according to the formula

$$SBP_2 = a_2/ts + b_2 \quad (10)$$

Based on certain values of systolic pressure (3) and (10), taking into account equation (9), the values of diastolic pressure were determined in two ways

$$DBP_1 = 1{,}5(MBP_{normal} - [a_1 \cdot ts + b_1]/3) \quad (11)$$

$$DBP_2 = 1{,}5(MBP_{normal} - [a_2/ts + b_2]/3) \quad (12)$$

Based on the above mathematical models (1) – (12) for determining blood pressure, experimental data were obtained for indirect measurement of systolic and diastolic pressure of two patients aged 42 and 66 years. The calculations were carried out in the MATLAB environment and the results of the studies are presented in the next section.

3. Results of measurements of blood pressure

The experimental blood pressure values of two patients of different ages, which are calculated by formulas (3) and (5) are method 1. They are presented in table 1. And those calculated by formulas (4) and (6) are method 2. They are presented in table 2.

Characteristics of changes in systolic and diastolic pressure in two patients of different ages, obtained based on the use of two different methods for determining blood pressure from ECG and PPG signals, are shown in Fig. 4.

The results of a study of another approach in determining blood pressure using linear (3) and non-linear (10) models for determining systolic pressure, as well as mathematical models (11) and (12) for determining diastolic pressure determined based on the mean arterial pressure (MBP) are presented in table 3 and 4.

Table 1. The experimental data to determine the blood pressure of two people – the first method

Method 1			
Patient 1		Patient 2	
SBP [mmHg]	DBP [mmHg]	SBP [mmHg]	DBP [mmHg]
112.5	84	104.5	84
111.75	89	112.5	84
117	86.5	112.25	91.5
119.5	56.5	112.5	96.5
113	86.5	112	81.5
162.25	84	114.5	76.5
112.75	84	111.5	99
113.25	89	112.5	89
112.5	89	112	89
111.5	99	113.25	89
113.75	76.5	111.75	89
113.25	84	112	81
112.75	94	111.25	81.5
112.25	91.5	111.75	84
113	86.5	112	79
113.25	84	111.5	84
117.5	76.5	112	81.5
118	64	111.75	79
117	66.5	111	86.5
117.75	64	112	81.5
Mean	**Mean**	**Mean**	**Mean**
116.7	81.75	111.73	85.35
u_A(SD)	**u_A(SD)**	**u_A(SD)**	**u_A(SD)**
10.99	11.12	1.86	5.84

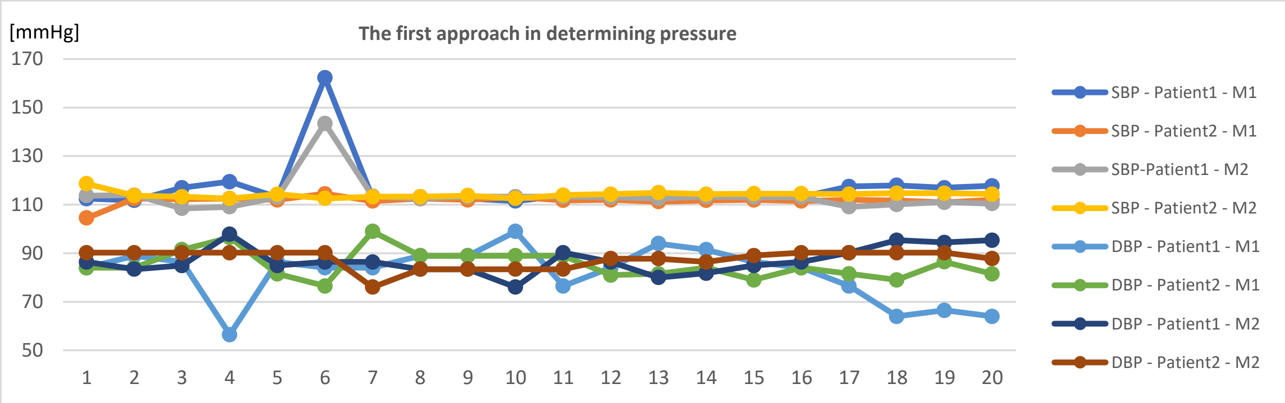


Fig. 4. Characteristics of changes in systolic and diastolic pressure in two patients of different ages

Table 2. The experimental data to determine the blood pressure of two people – the second method

Method 2			
atient 1		Patient 2	
SBP [mmHg]	DBP [mmHg]	SBP [mmHg]	DBP [mmHg]
113.73	86.4	118.64	90.24
113.94	83.41	113.73	90.24
108.46	84.96	113.29	90.24
109.16	97.87	112.59	90.24
113.07	84.96	114.35	90.24
143.48	86.4	112.59	90.24
113.51	86.4	113.29	76.06
112.59	83.41	113.29	83.41
113.29	83.41	113.73	83.41
113.29	76.06	112.59	83.41
113.29	90.24	113.94	83.41
113.07	86.4	114.35	87.76
112.59	80	114.92	87.76
113.29	81.77	114.35	86.4
113.07	84.96	114.54	89.04
113.07	86.4	114.54	90.24
109.16	90.24	114.35	90.24
110.13	95.37	114.74	90.24
111.02	94.45	114.74	90.24
110.43	95.37	114.35	87.76
Mean	**Mean**	**Mean**	**Mean**
113.68	86.92	114.15	87.54
u_A(SD)	**u_A(SD)**	**u_A(SD)**	**u_A(SD)**
7.22	5.54	1.29	3.82

Characteristics of changes in systolic and diastolic pressure in two patients of different ages, obtained on the basis of using a different method for determining blood pressure using the mean arterial pressure (MBP) are shown in Fig. 5.

Based on the results of experimental studies of systolic and diastolic pressure, the uncertainty of type A measurements [1, 4, 10, 12, 16, 18, 19, 21, 23–30] was calculated using the formula

$$u_A = \left[\frac{\sum_i^n (BP_i - \overline{BP})^2}{n(n-1)}\right]^{0.5} \quad (13)$$

Table 3. The experimental data to determine the blood pressure of two people another approach – models (3) and (10)

Method 1			
Patient 1		Patient 2	
SBP [mmHg]	DBP [mmHg]	SBP [mmHg]	DBP [mmHg]
112.5	83.75	112	84
111.75	84.12	111.25	84.37
110	85	111.75	84.12
113	83.5	112	84
112.5	81.5	112.25	83.88
113.25	83.37	112	84
112.75	83.62	112	84
113.25	83.37	112.5	83.75
111.25	84.37	111.75	84.12
112.5	83.75	110	85
111.5	84.25	112.25	83.88
113.75	83.13	112	84
115.25	82.38	111.5	84.25
113.25	83.37	113	83.5
112.5	83.75	112.5	83.75
112.75	83.62	113.75	83.13
112.25	83.88	112.75	83.62
113	83.5	113.25	83.37
113.25	83.37	112	84
112.25	83.88	113.25	83.37
114	83	111.25	84.37
114.75	82.62	112.25	83.75
117.75	81.12	111.5	84.25
Mean	**Mean**	**Mean**	**Mean**
113	83.4	112.12	83.93
u_A (SD)	**u_A(SD)**	**u_A(SD)**	**u_A(SD)**
1.52	0.86	0.79	0.4

Comparing the obtained values of type A measurement uncertainties (standard deviations SD in table 1 – 4), which are obtained using two different approaches to determine systolic and diastolic pressures (table 1 – 4), it can be seen that the deviations are much smaller when using the second approach to determine systolic and diastolic pressures (table 3 and 4).

That is, when determining the systolic pressure SBP through the values of *ts* (the number of readings between the maxima of the ECG and PPG signals) and determining the value of the diastolic pressure DBP based on it, taking into account the normal mean blood pressure value MBP_{normal}.

As the research results showed, when using the first approach to determine blood pressure (Table 1 and 2) according to formulas (3) and (5), (4) and (6), the second method of calculating blood pressure was more accurate - when using formulas (4) and (6). The type A measurement uncertainty in the first patient was 7.22 mmHg for SBP and 5.54 mmHg for DBP. In the second patient, this measurement uncertainty was 1.29 mmHg for SBP and 3.82 mmHg for DBP.

And as the research results showed, when using the second approach to determine blood pressure (Table 3 and 4) using formulas (3) and (11), (10) and (12), the first method for calculating blood pressure was more accurate - when using formulas (3) and (11). The type A measurement uncertainty in the first patient was 1.52 mmHg for SBP and 0.86 mmHg for DBP. In the second patient, this measurement uncertainty was 0.79 mmHg for SBP and 0.4 mmHg for DBP.

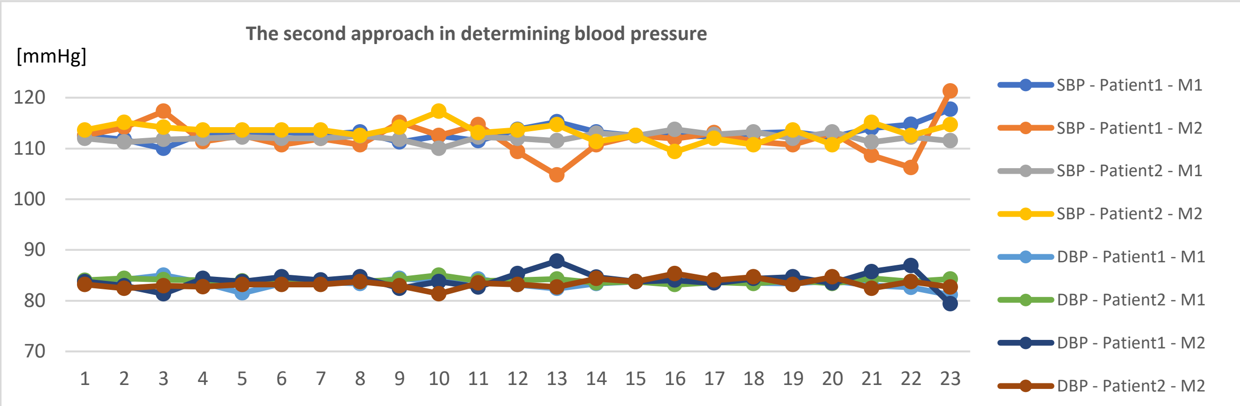


Fig. 5. Characteristics of changes in systolic and diastolic pressure in two patients of different ages using the mean arterial pressure (MBP)

Table 4. The experimental data to determine the blood pressure of two people another approach - models (11) and (12)

Method 2			
Patient 1		Patient 2	
SBP [mmHg]	DBP [mmHg]	SBP [mmHg]	DBP [mmHg]
112.54	83.73	113.64	83.18
114.16	82.92	115.14	82.43
117.32	81.34	114.16	82.92
111.34	84.33	113.64	82.73
112.54	83.73	113.64	83.18
110.71	84.65	113.64	83.18
111.95	84.02	113.64	83.18
110.71	84.65	112.54	83.73
115.14	82.43	114.16	82.92
112.54	83.73	117.32	81.34
114.66	82.67	113.1	83.45
109.35	85.33	113.64	83.18
104.75	87.78	114.66	82.67
110.71	84.64	111.34	84.33
112.54	83.73	112.54	83.73
111.95	84.02	109.35	85.33
113.1	83.45	111.95	84.02
111.34	84.33	110.71	84.65
110.71	84.65	113.64	83.18
113.1	83.45	110.71	84.65
108.63	85.69	115.14	82.43
106.24	86.88	112.54	83.73
121.33	79.34	114.66	82.67
Mean	**Mean**	**Mean**	**Mean**
112.06	83.98	113.28	83.34
u_A(SD)	**u_A(SD)**	**u_A(SD)**	**u_A(SD)**
3.39	1.71	1.72	0.87

4. Conclusions

Studies of indirect determination of systolic and diastolic blood pressure from ECG and PPG signals using the MAX86150 Evaluation System were carried out. The proposed algorithms for determining blood pressure can be used to expand the functionality of an electronic stethoscope. The studies were carried out in the laboratory on two patients of different ages using two different methods for determining blood pressure using the MATLAB pack-age.

Considering the peculiarities of using the MAX86150 Evaluation System for measuring ECG and PPG signals, our group developed mathematical models for indirect determination of systolic and diastolic pressure using fingers on the hand, which were tested in the MATLAB environment. A database of ECG and PPG signals was obtained from two patients aged 42 and 66 years. Based on the proposed mathematical models, ECG and PPG signals were processed in the MATLAB package and the results of indirect measurement of blood pressure were presented (table 1 and 2). The algorithm for determining blood pressure using mathematical models (3) and (11) gives the highest accuracy. In this case, diastolic pressure was determined based on the mean blood pressure.

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