International Journal of Current Advanced Research
ISSN: O: 2319-6475, ISSN: P: 2319-6505, Impact Factor: 6.614
Available Online at www.journalijcar.org
Volume 10; Issue 11 (B); November 2021; Page No.25545-25548
DOI: http://dx.doi.org/10.24327/ijcar.2021. 25548.5099

Research Article

THE MODELS FOR ESTIMATION OF THE ARTERIAL PRESSURE WITH THE USAGE OF THE FINGER PHOTOPLETHYSMOGRAM ON SMARTPHONE

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A R T I C L E I N F O

Article History:
Received 24th August, 2021
Received in revised form 19th September, 2021
Accepted 25th October, 2021
Published online 28th November, 2021

Key words:

Photoplethysmogram, intelligent computational algorithms, systolic blood pressure, diastolic blood pressure.

A B S T R A C T

Arterial pressure - one of the main indicators of functional state of cardiovascular system. The problem of arterial hypertension is one of the most topical issues in modern medicine, because it causes a constant increasement in the number of heart attack, stroke and adrenal insufficiency cases. The constant monitoring of blood pressure is a very important, however, modern cuff methods are inconvenient and impractical in the field survey.
To meet this need, a non-invasive method of non-cuffed estimation of blood pressure by photoplethysmograms has been proposed, which is recorded using a smartphone camera. Photoplethysmogram recordings were obtained from two individuals (a 69-year-old woman and a 22-year-old girl). In total, 78 real records were made. The eight indicators of the averaged photoplethysmogram were used as the potential regressors of statistical models.
The best regression models were selected for the evaluation of systolic and diastolic blood pressure. The systolic blood pressure estimation model provided a coefficient of determination of 0,8 and standard deviation $\pm_{SBP} = 8{,}9$ mmHg and the model for estimating diastolic blood pressure provided a coefficient of determination of 0,3 and standard deviation $\pm_{SBP} = 4{,}2$ mmHg. The models are implemented in a mobile application for a smartphone.

INTRODUCTION

Today, hypertension is one of the main risk factors contributing to the development of cardiovascular disease and patient death rate (***Manci et al., 2013***). Statistics from the World Health Organization (WHO) in September 2019 showed that about 1.13 billion people worldwide suffer from hypertension, and two-thirds of them are from low- and middle-income countries (***World Health Organization, 2019***). Since most patients with arterial hypertension do not experience significant signs of disease and due to the absence of an effective control may drown in the risk zone, daily blood pressure estimation and inexpensive equipment are required.

Several studies have shown that non-invasive continuous blood pressure monitoring is a better detector of death rate than clinical measurements, as clinical measurements have several disadvantages: it is impractical for elderly patients, it is important to perform measurements only at state of rest, any movements should be excluded, cuff should be fixed on the level of the heart (***Frese and Sadowsky, 2011***). Despite their accuracy, it is not convenient to use them in the field.

The optimal method of screening diagnosis is photoplethysmography. It is a simple, non-invasive and reliable quick method that has been used for decades to measure the amount of light absorbed or reflected by blood vessels. This technology is universal and inexpensive, which can be further used not only for estimation of blood pressure, but also other aspects of cardiovascular observation (***Mohamed and Fletcher, 2019***).

Photoplethysmogram Background

The usage of finger photoplethysmography has great diagnostic value in estimation of the permeability of peripheral vessels, rapid and accurate estimation of local capillary blood flow. Finger photoplethysmography provides accurate and objective information about changes in blood flow parameters during a short period of time (***Allen, 2007***). The subject of study during conduction of finger photoplethysmography are pulse waves, the information provided by them reflects the hemodynamics of cardiac blood flow at the peripheral level (***Allen, 2007***).

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The investigated area of the study is highlighted by the light from a smartphone flashlight, which later gets into the photoconverter. The paper (***Fainzilberg, 2020***) proposed the method of finger photoplethysmogram registration and analysis (Fig. 1).

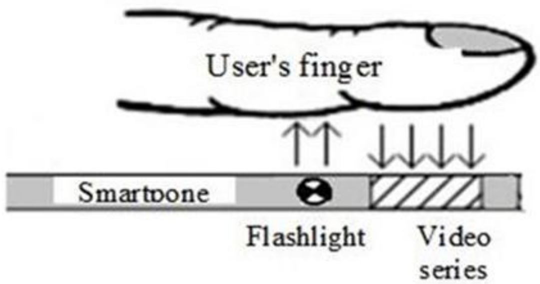

Figure 1 Principle of pulse wave's registration with the usageof smartphone camera

It is known that the observed form of the pulse wave is the sum of two waves: direct and inverse (***Kachuee et al., 2017***). Color change and light absorption by the tissue is regulated by blood circulation in the body, which is determined by heart systole and diastole. The person's arterial pressure increases as a result of the reduction of heart muscle during systole, which pushes blood out into the periphery of the body (***Kachuee et al., 2017***). The same way, the arterial pressure decreases when the heart is relaxing and filling with blood during the diastole (***Kachuee et al., 2017***). This results in a periodic signal with visible and distinct systolic peaks. Each recurring cycle, which periodically repeated, contains one systolic and one diastolic peak.

Based on the original procedures of averaging a pulse wave and estimating its derivatives, it is possible to distinguish automatically characteristic points (hereinafter points *A* and *B*) on the averaged pulse wave, which correspond to the moments of the direct wave generated by a heartbeat and a reversed pulse wave (***Fainzilberg and Muzyka, 2021***). It is considered that the frequency and duration of the pulse wave depend on the heart work, and the size and shape of the peaks - on the condition of the walls of blood vessels.

Blood Pressure Estimation from Photoplethysmogram

Due to the development of modern digital technologies, a personal smartphone can be used to register human physiological parameters. Therefore, the method that can be implemented on a smartphone for registration of photoplethysmograms and used without additional tools draws attention.

Some studies describe different parameters of photoplethysmograms for estimation of blood pressure, in particular (***Baksa, 2017; Elgendi and Fletcher, 2019; Anthony et al., 2015***) regression models to assess systolic blood pressure and diastolic blood pressure are presented in the investigation, which are connected through two parameters: heart rate and pulse wave velocity. To reduce the error in the estimation of arterial pressure based on photosthysmogram, it is proposed to use additional indicators as the arguments of the model (***Fainzilberg and Muzyka, 2021***).

78 real records of photoplethysmograms of two persons aged 22 and 69 years were used to build models to estimate systolic blood pressure and diastolic blood pressure. 8 potential indicators of the averaged photoplethysmogram were used as potential regressors of statistical models of the Group Methods of Data Handling and multiple regression models:

- average heart rate X_1, beats per minute.
- standard deviation of *N-N* intervals X_2, *ms*;
- amplitude of the mode of the array of cardio intervals. X_3, %;
- the ratio of amplitudes on the average photoplethysmogram:

$$X_4 = \frac{AB}{AA}; \quad (1)$$

- pulse wave propagation time, *ms*:

$$X_5 = TB - TA; \quad (2)$$

- relative time of pulse wave propagation:

$$X_6 = \frac{X_5}{Tpw}; \quad (3)$$

- slope of the descending front:

$$X_7 = \frac{X_4}{X_5}; \quad (4)$$

- pulse wave propagation speed, meter per second:

$$X_8 = \frac{L}{X_5}, \quad (5)$$

where *L* – is the path length of the pulse wave over time X_5. This value is determined by user growth using an empirical relationship derived from the standard proportions of the human body.

Figure 2 shows a correlation matrix that provides visual information on the interconnection between indicators.

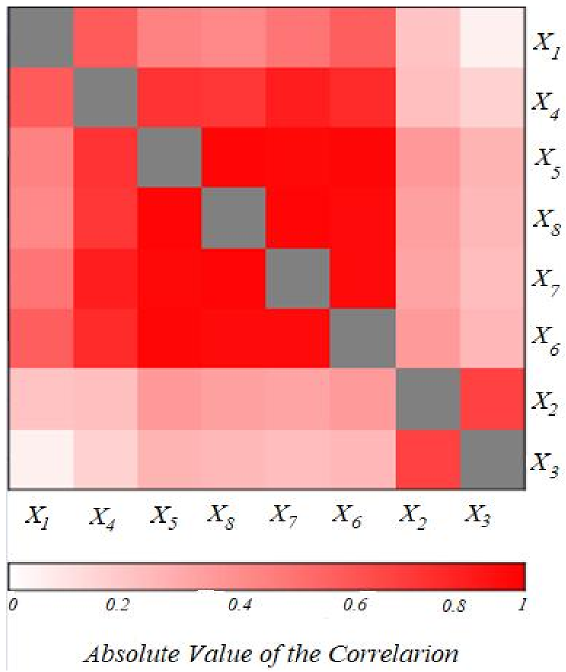

Figure 2 Heat map of the absolute values of the correlation matrix

Using the *GMDH Shell DS* software, which implements the Group Methods of Data Handling (***Madala and Ivakhnenko, 1994***), two models were built for qualitative determination of the systole artery pressure and the diastole arterial pressure, which determine the estimation of two conditions: normal and elevated systolic and diastolic arterial pressure.

For a qualitative assessment of arterial pressure, such restrictions were imposed $SBP \le 140$ millimeters of mercury – normal systolic blood pressure, $SBP > 140$ millimeters of mercury – elevated systolic blood pressure. For the parameter $DBP \le 80$ millimeters of mercury – normal diastolic blood pressure, $DBP > 80$ millimeters of mercury – elevated diastolic blood pressure (***Fainzilberg and Muzyka, 2021***).
These models which were built by using the Group Methods of Data Handling, allowed to formulate such rules:

$$SBP = \begin{cases} \text{normal}, & \text{if } y_{SBP} \le 0{,}5, \\ \text{eleveted}, & \text{if } y_{SBP} > 0{,}5, \end{cases} \quad (6)$$

$$DBP = \begin{cases} \text{normal}, & \text{if } y_{DBP} \le 0{,}5, \\ \text{eleveted}, & \text{if } y_{DBP} > 0{,}5, \end{cases} \quad (7)$$

where

$$y_{SBP} = \frac{1}{1+e^{Z_{SBP}}}, \quad (8)$$

$$y_{DBP} = \frac{1}{1+e^{Z_{DBP}}}, \quad (9)$$

$$Z_{SBP} = -0{,}901895 + 0{,}0902663 X_1 X_6 + 0{,}029065 X_3 - 0{,}000244501\, X_3^2 - 27{,}1281 X_6^2, \quad (10)$$

$$Z_{DBP} = -0{,}203403 + 0{,}181564 X_1 X_5 - 10{,}9753 X_6 + 0{,}603591 X_6 X_7 - 0{,}00411223 X_8^2. \quad (11)$$

The testing of key rules provides the reasonableness for the model *SBP* – 81%, for the model *DBP* – 95%.

In comparison with the received results through the analysis of simple logistic regression (***Fainzilberg and Muzyka, 2021***), where verification of key rules provides accuracy to the model *SBP* – 79%, to model *DBP* – 95%, the models, which are built using the Group Methods of Data Handling to make the qualitative determination of two conditions of arterial pressure, provide greater accuracy and are suitable for the usage in the program application.

Also, for the quantitative determination of systolic blood pressure and diastolic blood pressure based on primary signs two regression models were constructed using the group accounting method of arguments, that had the form:

$$SBP = 154{,}323 + 1084410\frac{X_4}{X_7^2} + 2249{,}99\frac{1}{X_4 X_8} + 881490\frac{1}{X_4 X_8^2} + 1{,}77494\frac{1}{X_4^2 X_6} + 100{,}857 X_5 X_8 - 0{,}419473\frac{1}{X_5 X_6^2} + 0{,}637922\frac{X_8^2}{X_5} - 19{,}3368\frac{X_8}{X_6} + 14{,}8961\frac{1}{X_6^2} - 1982870\frac{1}{X_7 X_8} + 67154{,}8\frac{1}{X_7 X_8^2} + 956{,}744\frac{1}{X_8 X_7^2} \quad (12)$$

This model provides the coefficient of determination 0,81.

$$DBP = 118{,}908 - 34128{,}1\frac{1}{X_1 X_3} - 10916{,}9\frac{X_6}{X_1} + 23{,}7105\frac{X_2}{X_3} - 0{,}100545 X_2 X_7 - 227{,}518\frac{X_4}{X_2} + 0{,}649044\frac{X_3}{X_7} + 456{,}778\frac{1}{X_4 X_8} + 278{,}899\frac{X_6}{X_8} - 608{,}963\frac{1}{X_7}. \quad (13)$$

This model provides the coefficient of determination 0,3.

The model (12) allowed a mean square deviation $\pm_{SPB} = 8{,}9$ mmHg and the model (13) $\pm_{DPB} = 4{,}2$ mmHg, which is much better than the results obtained in the analysis of linear regression models based on the primary features $X_1 \ldots X_8$.

An application for predicting blood pressure has been developed (Fig. 3)

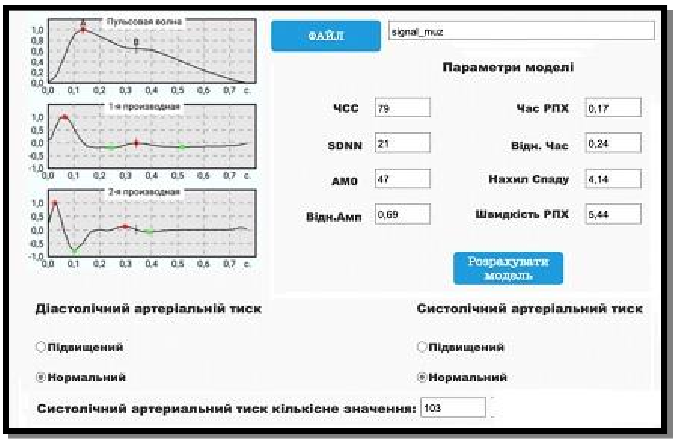

Figure 3 Software application for blood pressure estimation

The application uses data from real photoplethysmograms obtained from the smartphone, processes and predicts quantitative and qualitative determination of systolic and diastolic blood pressure according to the above-mentioned models.

DISCUSSION

Thus, it is demonstrated that the Group Methods of Data Handling provides sufficient accuracy for the usage of models in the software application for qualitative estimation of two states of systolic blood pressure and diastolic blood pressure - normal and elevated.
The regression models built using secondary indicators provide better accuracy than models based on primary indicators of the averaged photoplethysmogram, and they are suitable for usage in software applications for predicting the quantitative value of systolic pressure (Fig. 3).

CONCLUSION

In the above considered case, a method of cuffless measurement of blood pressure is proposed. Multiple regression models that provided the best accuracy of data were used in the software application. With the help of the software application, it became possible to assess blood pressure in the field survey using a smartphone.

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How to cite this article:

Fainzilberg Leonid and MuzykaYaryna (2021) ‘The Models For Estimation Of The Arterial Pressure With The Usage Of The Finger Photoplethysmogram On Smartphone ', *International Journal of Current Advanced Research*, 10(11), pp. 25545-25548. DOI: http://dx.doi.org/10.24327/ijcar.2021. 25548.5099

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