Blood Pressure Calculation based on Data Received from Cardiac Monitor Jointly with PPG Sensor

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Abstract—**Blood pressure is one of the key parameters of cardiovascular state assessment. Most methods for blood pressure measurement are either noninvasive and discrete, or invasive and continuous. Moreover, most of the existing methods are required patient staying in the outpatient setting. In this paper, the method of continuous noninvasive measurement of blood pressure is based on the time, during which the pulse wave moves from one artery to another. For applying this method, we should use mobile and wearable gadgets, in particular a portable cardiac monitor and fitness bracelet or an optical heart rate sensor built-in the Android-device. The method assumes the parallel operation of all devices via Bluetooth Low Energy.**

I. Introduction

According to the World Health Organization, cardiovascular diseases are the leading cause of death in the world [1]. This is one of the most actual problems in many countries, including Russia. Russia is on the first place [2] in the list of countries for the percentage of deaths from cardiovascular diseases in the world. Therefore, research and improvement of new methods for cardiovascular system assessment is vital since they can serve as prevention of cardiovascular diseases.

Blood pressure (BP) is the pressure that blood exerts on the walls of blood vessels. Blood pressure is one of the key factors in diagnosing the state of human health. This is an important element of every health monitoring system since BP can provide important knowledge about the patient's condition. BP control can reduce the risk of developing a heart attack, stroke and other complications. For prevention and early diagnosis of hypertension and associated complications, it is necessary to constantly monitor and evaluate blood pressure and its changes over time.

In most cases, the available methods for blood pressure measurement that is used in medical practice either are based on catheterization (invasive method) and are discrete. This means that they strongly impose restrictions on the patients' way of life and cannot provide continuous control around the clock. Obviously, a solution is required for continuous long-term blood pressure monitoring, which can provide more complete and reliable information about the patients' condition. This allows doctors to observe changes in blood pressure of patients under the influence of various factors, for example, such as physical and mental stress.

II. Classification of Methods of Blood Pressure Measurement

There are many methods for blood pressure measurement. One of classification variants is shown at Fig. 1.

Invasive methods [3] for blood pressure measurement are carried out through a catheter or cannula with a pressure sensor introduced into the lumen of the artery. Depending on the location of the sensor the invasive methods are divided into extravascular and intravascular.

1) Extravascular method is the method in which the sensor is located behind the catheter.
2) Intravascular method is the method in which the sensor is located at the tip of the catheter.

With the help of invasive methods, blood pressure can be measured continuously in real time, similar methods provide indications of high accuracy. However, these methods have serious drawbacks, which significantly limit their use. The catheter insertion is painful for the patient and requires the presence of qualified medical personnel, which increases both the procedure time, and its cost. Besides, the discomfort and anxiety of the patient due to placement of the catheter can raise blood pressure, giving false indications.

Noninvasive methods for blood pressure measurement were developed as an alternative to invasive methods. Their goal is to provide accessible and safe BP monitoring in a wide range of applications, including home use. The most famous and widely used method of noninvasive blood pressure measurement is tonometry.

III. Continuous Blood Pressure Monitoring

Doctors daily face the necessity to measure patients' pressure. Another important problem is the continuous blood pressure measurement for a long time. The use of invasive methods imposes a number of limitations, most important of which is the necessity of patient staying in the outpatient setting. Therefore, the work is actively carried out to develop a convenient and accessible method for noninvasive continuous blood pressure monitoring.

There are various methods for continuous blood pressure measurement. For example, the volume-clamp method. This

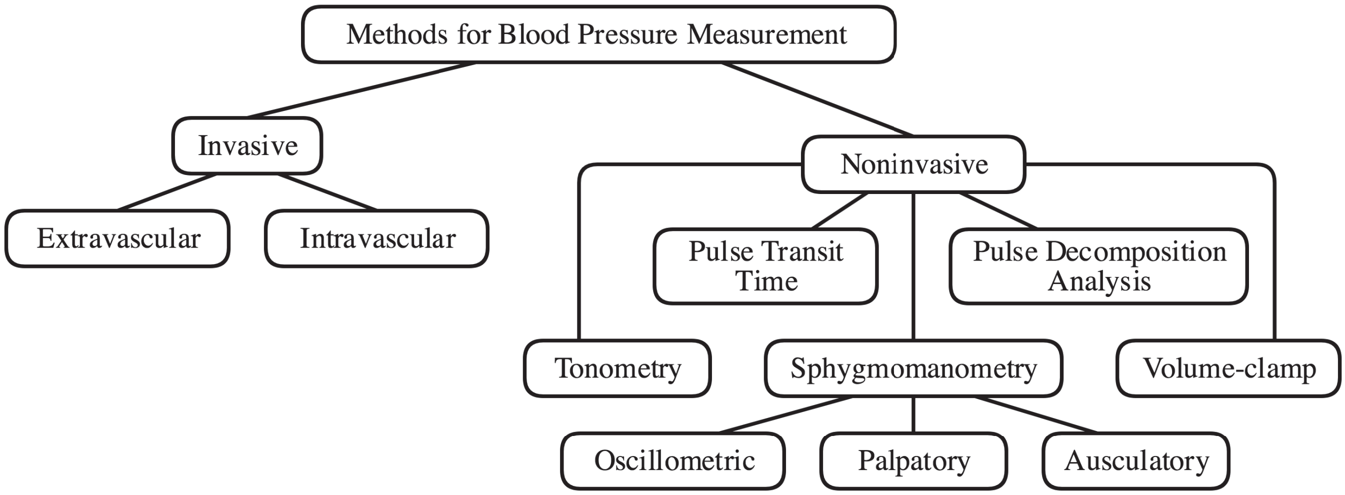

Fig. 1. Classification of methods for blood pressure measurement

method measures the pressure of finger's arteries through the finger cuff with the air pump and the infrared plethysmograph. The plethysmograph (volume measuring device) consists of an infrared light source and a detector: infrared light is absorbed by the blood, and pulsation of the artery during the heart rhythm causes a pulsation in the signal of the light detector. Despite the fact that this method gives sufficiently accurate results, the necessity of outpatient setting makes it difficult to use [4].

The use of other known methods, despite all their advantages, is also difficult outside of ambulatory settings. For example, the auscultative method (according to Nikolai Korotkoff) is sensitive to indoor noise, and the oscillometric method has a low stability to hand movements. Since the accuracy of blood pressure measurement is one of the key characteristics of instruments for blood pressure measurement, the above methods become unsuitable for use in everyday life.

IV. PULSE TRANSIT TIME METHOD

One of the methods for noninvasive continuous blood pressure monitoring is based on the pulse transit time (PTT) [5]. PTT is the time during which the pulse wave moves from one artery to another. Studies have shown that PTT has an inverse linear correlation with blood pressure. Increased blood pressure causes an increase in the vessels' tone, so the walls of the arteries become more rigid, which leads to a shorter PTT [6].

Despite the fact that the method for blood pressure measurement using PTT already exists for a while, it is necessary to use medical devices such as a cardiograph and plethysmograph for its implementation. In this paper, we propose to use the model of continuous noninvasive blood pressure monitoring based on method of joint data analysis of a personal portable digital electrocardiogram and devices such as a smart bracelet. The main advantage of this method is that there is absence of necessity of ambulatory settings. Another advantage of this approach is easily integration of the system consisting of wearable devices into the patient's everyday life. Also, such system monitors patients' indications without changing their way of life. The system is designed within the concept of eHealth [7].

The described system calculates BP based on PTT, which is calculated by electrocardiogram (ECG) and photoplethysmogram (PPG) signals. The key hardware component of the noninvasive monitoring system is the patient's smartphone, and a portable cardiac monitor and "smart bracelet" are used to read heart signals. Such set makes the developed system as simple and accessible to ordinary people as possible. The scenario of using the equipment is that the patient wears a cardiac monitor (not requiring additional wires) and a fitness bracelet on his chest. Both devices are synchronized with the patient's smartphone via Bluetooth and the mobile application starts to read the data. This system presented at Fig. 2.

Since the basis of the system is a smartphone, which in most cases has the ability to access to the Internet, then it is possible easily integrate the developing service with medical information systems. As a result of this integration, the attending doctor will be able to receive up-to-date data on the patient's condition promptly.

CardiaCare [8] is the first service with which the proposed system will be integrated. CardiaCare is a personalized information service of mobile medicine for management of patients with chronic diseases, which is used in Petrozavodsk State University to organize experiments of Petrozavodsk Medical Institute.

Similar approach allows to provide round-the-clock monitoring of the patient's cardiac activity without necessity of patient staying in the outpatient setting, that is, without interfering with patient's everyday life, while the used algorithm for BP calculation ensures high accuracy of the results.

V. HARDWARE REQUIREMENTS

The used cardiac monitor has many features. One of the features is that the IDT cardiac monitor is wireless. A cardiac monitor can transmit data in real time to a PC, PDA, smartphone or other device for storage and subsequent analysis. Bluetooth Low Energy 4.0 is used for data transfer. The capacity of the cardiac monitor battery is 300mAH, which in turn ensures continuous operation for 12 hours. The capacity and weight of the device,

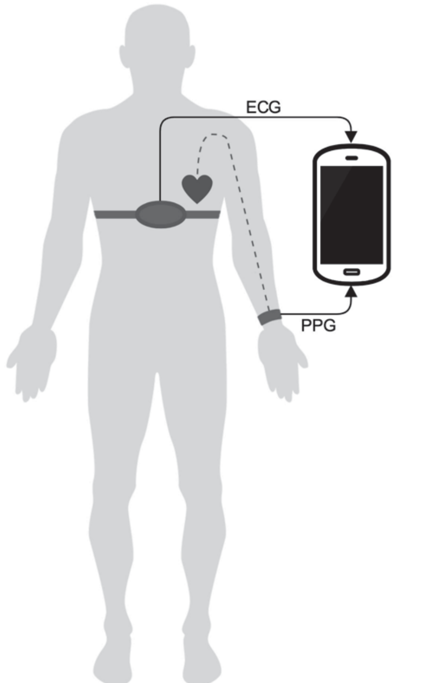

Fig. 2. General scheme of work with noninvasive and continuous blood pressure monitoring system

in combination with the absence of additional wires, allow to use a cardiac monitor without inconvenience during daily activities for a long time.

The used cardiac monitor also has several both common for all BLE-devices and individual disadvantages. Individual drawbacks include the absence of a built-in clock, and general disadvantages comprise the delay of an unknown time during the data transfer (not documented by the manufacturer). On the one hand, the delay in data transmission is a significant drawback. On the other hand, the BLE-device is much more convenient in everyday use, than the device which needs additional wires. The principle of working with a cardiac monitor is described in article [9].

Fitness bracelets are available and convenient devices with the ability of reading pulse and wireless data transfer. Despite the obvious advantages of fitness bracelets, their usage has a number of restrictions:

1) Proprietary software and closed API. Most of fitness bracelets manufacturers limit their use in branded applications, and don't provide any access to the bracelet's API. For these reasons it is impossible to develop own software for working with devices.
2) From our work experience with fitness bracelets, it was found that most of the fitness bracelets don't have the ability to continuously monitor cardiac activity. Although almost all modern fitness bracelets can read the user's pulse with determined interval, they provide only discrete values, while for the assigned task, continuous measurement is required.
3) Sending data in packet mode. The interaction between the fitness bracelet and the patient's smartphone takes place using BLE technology. Fitness bracelets support the packet mode of data transfer, which causes an additional delay in obtaining data on the smartphone and makes it difficult to synchronize the data of the ECG and PPG with each other.

Since the use of fitness bracelets is caused a lot of difficulties, that's why we found another way for obtaining PPG by using smartphone body sensors. A heart rate sensor built-in the Samsung Galaxy series smartphones (see Fig. 3) was used to create a prototype of a continuous noninvasive blood pressure monitoring service. Samsung Sensor Extension SDK provides access to data (PPG) obtained from an optical sensor built-in the smartphone.

The heart rate sensor is an optical sensor. The light-emitting diode / infrared signal in the sensor shines on the skin of the finger or wrist, and the photodetector receives reflected lights from the arteries and capillaries. This reflected light represents a change in the volume of the artery and capillary due to blood flow from the heart.

The sensor is located on the back of the phone. For measurement the patient should place his finger on the sensor, then the measurement is beginning. Since the sensor is part of the smartphone, the delay in data transfer is minimal.

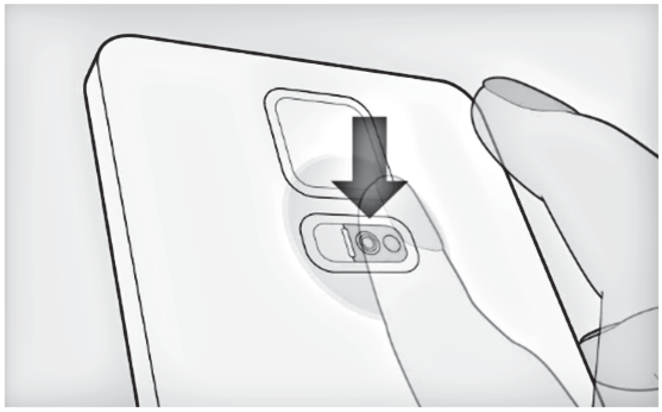

Fig. 3. HRM sensor

Bluetooth Low Energy (BLE) wireless technology is used for the interaction between the Android-device and wearable patient gadgets. BLE is a core specification of Bluetooth wireless technology.

The Android operating system, starting with version 4.3 (API level 18), provides built-in support for Bluetooth Low Energy. Through API applications can use device search and send requests to these devices. In comparison with the classic Bluetooth, BLE has several advantages, one of which is ultra-low energy consumption. BLE is enabled Android-applications to interact with BLE-devices that have low power requirements, including such devices as the mobile cardiac monitor and fitness bracelets in question.

Modern Android-smartphones allow you to organize parallel work with several BLE-devices. Such approach is implemented in the developed prototype.

VI. Calculation of PTT

For calculation the pulse transit time (PTT), it is necessary to determine the exact time of detection of the peak impulse because the impulse peaks are considered as the start and end points of each wave motion impulse [10]. The sensors are located relatively close to each other. Therefore, it is important to achieve the correct accuracy. Besides, reliable detection of an impulse peak is also required for basic clinical applications, such as heart rate monitoring [4], [11].

Fig. 4 shows the result of maximum detection for ECG and PPG signals.

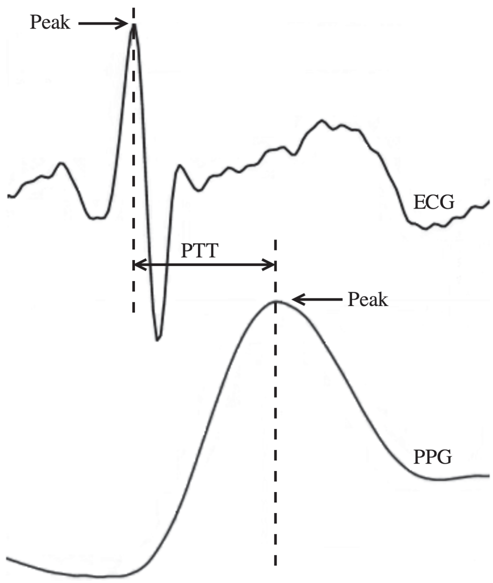

Fig. 4. PTT determined by the ECG and PPG

Exact detection of impulse peaks from the PPG and ECG signals is difficult not only because of the physiological variability of impulse peaks, but also due to breathing, motion artifacts and electrical interferences [4]. Also, excess noise should be suppressed for accurately determination of the impulses peaks. For this a significant number of algorithms have been proposed for noise elimination [12]. In most cases, the algorithm used to suppress noise is a digital bandpass filter. This algorithm doesn't require the detection of any reference points in the PPG signal. However, it usually increases the computational complexity caused by convolution calculations, since in most cases this requires a much larger filter order [13].

Another way for removing interferences is the wavelet-adaptive filter (WAF) [14]. This filter does its job well, but it is computationally heavy, therefore it is not suitable for use with mobile devices.

Smoothed z-score algorithm is used for detection real-time impulse peaks. This algorithm removes noise and, at the same time, doesn't require high processing power and can be easily implemented on a mobile device. After filtering the heart rate signal is smoother, so we can find the peak locations in a simple way. On the filtered signal, the peak will be determined by the condition: if (signal [i] > signal [i-1] and signal [i] > signal [i + 1]), then the signal [i] is the peak. This algorithm is presented at Fig. 5.

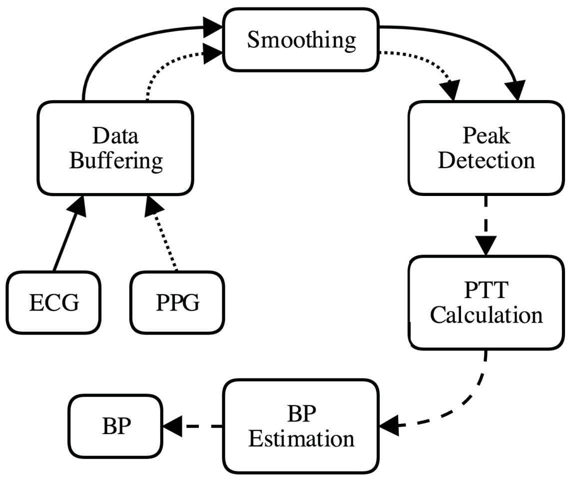

Fig. 5. Analysis flow overview

ECG and PPG data are sent to the smartphone in real time. This greatly complicates the data processing and the search of peaks. For solving this problem data from the sensors is accumulated in the buffer for 1 second. Then the search of peaks algorithm is applied to the accumulated data. Thus, the delay for calculating the PTT amount to 1 second. The result of algorithm work is shown at Fig. 6.

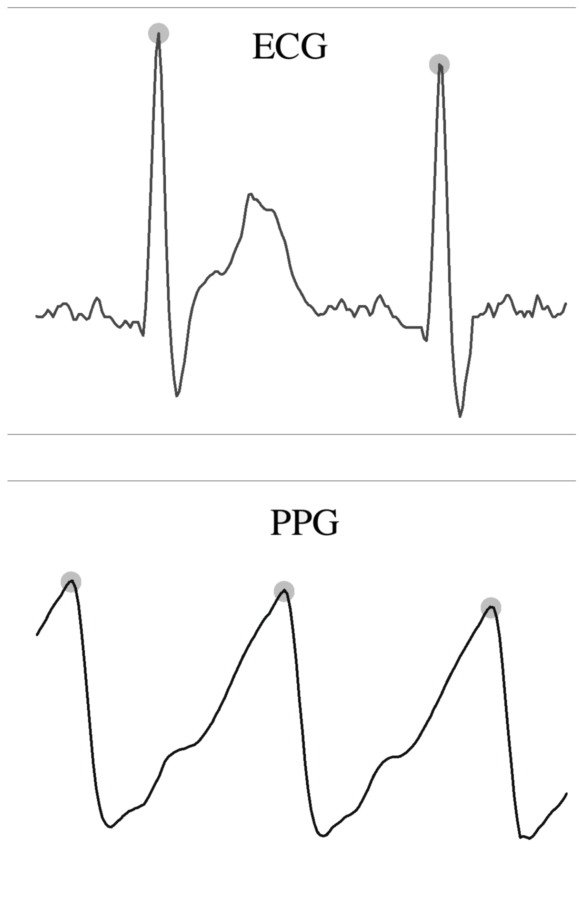

Fig. 6. ECG and PPG signals

VII. Conclusion

The use of information technology in medicine is a very perspective direction. Using described approach can significantly speed up and simplify the procedure of blood pressure measuring for both patients and doctors. Moreover, the method allows to diagnose the disease at an early stage and prevent its further development.

At the moment, a prototype of the system has been designed and implemented, including the organization of parallel interaction of a portable cardiac monitor and an optical heart rate sensor with an Android-smartphone, processing of the obtained data and detection peaks on ECG and PPG obtained in real time, as well as calculating PTT.

Since PTT is calculated using ECG and PPG signals collected on different devices, the synchronization between these two signal sources is important for achieving accuracy. The next stage of the work will be the development of an algorithm for synchronizing devices and increasing the accuracy of the PTT calculation. After the devices are synchronized, blood pressure will calculate based on the received PTT.

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