

MEASUREMENT OF ARTERIAL BLOOD PRESSURE BY ANALYZING THE PULSE WAVE TRANSIT TIME AT A SELECTED PERIPHERAL POINT

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Abstract

Arterial blood pressure is one of the most important vital parameters of warm-blooded organisms, which is connected directly to their existence. This paper presents a method and apparatus for continuous blood pressure monitoring in extreme conditions by measuring pulse wave transit time. An approach is developed to determine the individual coefficients of the subject, allowing for the calculation of systolic and diastolic arterial pressures.

Key words: non-invasive continuous blood pressure measurement, blood pressure monitoring, personal body coefficients

Introduction. Non-invasive continuous monitoring of arterial blood pressure (BP) is gaining increasing application in modern practice. With the development of electronic technologies, it has become possible to develop various algorithms and devices that measure this vital human parameter in real-time in critically ill patients or those in high-risk environments. Measuring BP using Korotkoff sounds and the oscillometric principle are the most commonly applied methods for automatic or semi-automatic blood pressure measurement in patient monitoring and are widely used in work and home settings. The requirements for such devices are very high [1] and are subject to strict and prolonged checks [2]. There are also other alternative approaches for determining BP, based on ultrasonic Doppler meters or tonometers. All the listed methods require the subject to be still, a

quiet environment, and highly qualified personnel. Another disadvantage is the inability to continuously measuring the pressure due to time limitations related to the specifics of the applied methods. In an extreme environment, such as a combat flight in a fighter jet, the subject is under dynamic overload within wide limits from 0 G to 10 G (in some cases even up to 15 G), high levels of vibration, and loud noise. This makes it impossible to apply the methods mentioned above. For continuous BP monitoring in extreme conditions, the method of analyzing the delay of the pulse wave passing between two points of the human arterial system, also known as pulse transit time (PTT), can be applied with a high degree of reliability. The time it takes for the pulse wave to travel the distance between two points in the arterial system is inversely proportional to blood pressure. Although PTT is effective for tracking changes in blood pressure, there are many challenges in constructing such a measuring device.

To determine BP, PTT is usually measured by calculating the time difference between the peak of the R-wave on the ECG and a characteristic point of the pulse wave at a peripheral point of the human body, such as the fingertip, wrist, ear, and other points on the human body, which is recorded by photoplethysmography (PPG).

When blood pressure increases, arteries become stiffer, which causes the pulse wave to travel faster, thus decreasing PTT. Conversely, when blood pressure decreases, arteries become less stiff and the pulse wave travels slower, increasing PTT.

The application of the PTT method for blood pressure measurement is accompanied by many difficulties, which can be summarized into two groups [3]:

- The parameter correlating with blood pressure is the delay of the recognized pulse wave. It should be measured from the moment the wave is generated at the output of the left atrium, but due to variations in the mechanical delay of contraction, this is not synchronized with the appearance of the QRS complex, which depicts the electrical stimulus for the onset of systole.
- The relationship between blood pressures measured by the pulse oximetry method and some of the more objective methods (oscillometric, Korotkoff) is often non-linear and strictly individual.

Some researchers try to overcome the first difficulty by measuring the time between pulse waves at two distant body surfaces. MCCOMBIE [3] uses two sensors, one placed on the ulnar or brachial artery, and the other around the finger, where the measurement of the delay between the sensors allows for real-time adaptive individual calibration of PTT against results obtained by a reference method.

The speed of the pulse wave depends on the elasticity and rigidity of the blood vessel walls [4]. Studies on a wide range of subjects prove the influence of age, gender, and the presence of risk factors for the cardiovascular system [5–7].

JEONG et al. [10] state that in many cases the relationship between PTT and conventional blood pressure measurement is almost linear, making it possi-

ble to continuously monitor pressure changes after individual calibration. The photoplethysmographic sensor is placed on the lower part of the ear, where it is assumed that the vertical movement of the head relative to the heart is minimal. The R wave is recognized after wavelet transformation of the ECG signal. Before recognition, the pulse wave is passed through three filters: a high-pass filter with a cutoff frequency of 0.5 Hz, a notch filter with a centre frequency of 60 Hz, and a low-pass filter with a cutoff frequency of 10 Hz. There are also other approaches for determining individual correlation coefficients, based on dependence (1)

$$(1) \quad P = aT_p + b.$$

Here P is the measured pressure, T_p is the pulse wave propagation time to point M , and a and b are individual coefficients of the examined person, depending on their anatomical features. With known coefficients a and b , the individual's pressure P can be determined by the time T_p .

The developments reviewed so far do not discuss the measurement of systolic pressure using PTT. CHEN et al. [12] believe that this pressure can be determined with acceptable accuracy through individual calibration. An estimation of both pressures is proposed by YE et al. [13] using the following formulas, obtained by the authors after statistical processing of experimental data:

$$(2) \quad SPTT_{SYS} = 190.2 + 0.2157 \cdot (PPT_{PPG}) - 0.5981 (PPT_{pressure})$$

$$(3) \quad DPTT_{DIAS} = 96.41 + 0.2419 (PPT_{PPG}) - 0.3897 (PPT_{pressure}).$$

Here PPT_{PPG} is the measured time in the photoplethysmogram, and $PPT_{pressure}$ is measured by a conventional sphygmomanometer.

Measurement methodology. The purpose of this work is to present a method for continuous monitoring of blood pressure in extreme conditions, by measuring the pulse wave transit time from the heart to the peripheral point of the human body M_1 and to create an approach for determining the individual coefficients of the subject, allowing the calculation of systolic and diastolic arterial pressures.

The principle of measuring BP by the pulse wave transit time (PW) method at two peripheral points is shown in Fig. 1. The pulse wave at both points M_1 and M_2 is registered with photoplethysmographs with adjustable gain. The gain correlates with the degree of tissue perfusion with blood at the measurement point.

Two delay times T_{d1} at point M_1 and T_{d2} at point M_2 are measured. The main parameter in the measurement is the delay time T_{d1} of PW – relative to the R peak of the ECG. The delay T_{d2} measured at point M_2 is a reference parameter and is used to assess the reliability of the measured time T_{d1} . The correct measurement of T_{d1} is extremely important, as it directly participates in the measurement of BP. Since it depends on the correct registration of the pulse wave, T_{d1} can be



Fig. 1. Principle of BP measurement by the PTT method

compromised by various factors of electrical, optical, or mechanical origin. The absolute value of the differences of the two measured times T_s (4) is recorded in a shift register of N elements using the first-in, first-out method.

$$(4) \quad T_s = |T_{d1} - T_{d2}|.$$

The reliability criterion for the n -th delay T_{d1n} will be, if T_{sn} satisfies condition (5):

$$(5) \quad \sum_{i=0}^N \frac{T_{s_i}}{N} - 2T_{discr} > T_{sn} < \sum_{i=0}^N \frac{T_{s_i}}{N} + 2T_{discr},$$

where N is the dimension of the shift register, and T_{discr} is the sampling period of the pulse wave.

Upon satisfying condition (5), the reliability of T_{d1n} is confirmed, and the data in the shift register is shifted one position to the left, after which the value of T_{sn} is written into the freed rightmost cell. Otherwise, the current T_{d1n} and T_{sn} are ignored, and the next measurement of the delay time is proceeded with.

To determine the systolic pressure, dependence (1) is applied, from which the two coefficients a and b must be determined. For this purpose, a specially developed device for measuring blood pressure, operating on the principle of the oscillometric method, is used once for each individual. The determination of coefficients a and b is carried out after solving the system of equations (6).

$$(6) \quad \begin{cases} P_1 = T_{d1_1}a + b \\ P_2 = T_{d1_2}a + b \end{cases}.$$

For this purpose, two reference measurements are required with guaranteed differing systolic pressures P_1 and P_2 , respectively, as well as their associated pulse wave propagation times, T_{d1_1} and T_{d1_2} , respectively. This condition is easily achieved by taking one measurement of the subject's blood pressure in a relaxed state and a second with simulated climbing of 20 steps (step test – climbing up and down a cube with a side of 30 cm).

Each reference measurement is allowed after N reliable T_d values are recorded. After determining a and b , the systolic pressure is calculated by expression (7):

$$(7) \quad P_{sys} = aT_{d1} + b.$$

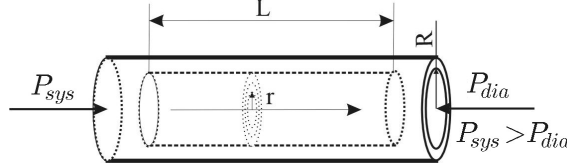


Fig. 2. Determination of the volume of liquid passing through a pipe with a given cross-section and velocity

To determine the diastolic pressure P_{dia} , the well-known Hagen–Poiseuille law is used to calculate the volume of fluid passing through a tube with a given cross-section and pressure (Fig. 2).

$$(8) \quad Q = \int_{r=0}^{r=R} dQ = \frac{\pi(P_{sys} - P_{dia})}{2\eta L} \cdot R^4,$$

where R is the inner radius of the vessel, L is the length of the vessel, η is the viscosity of the blood, and Q is the volumetric flow rate or flow.

On the other hand, there is a dependence for the flow Q as a function of the velocity and direction of the flow.

$$(9) \quad Q = Av \cos(\theta),$$

where A is the cross-section of the vessel, v is the blood flow velocity, and θ is the angle enclosed between the perpendicular to the cross-section and the direction of blood flow. When $\theta = 0^\circ$, expression (9) simplifies:

$$(10) \quad Q = Av.$$

The dependence is known:

$$(11) \quad v = \frac{S}{t},$$

where S is the path travelled by the wave, i.e., the length of the vessel, and t is the time it takes for the wave to appear at measurement point M_1 . After substituting v into (10), the dependence takes the form (12):

$$(12) \quad Q = A \frac{S}{t} = A \frac{L}{T_{d1}}.$$

From (8) and (12), the following equality is obtained:

$$(13) \quad A \frac{L}{T_{d1}} = \frac{\pi(P_{sys} - P_{dia})}{2\eta L} R^4,$$

where expression (14) is obtained for P_{dia} .

$$(14) \quad P_{dia} = P_{sys} - A \frac{L}{R^4 \pi T_{d1}} 2\eta L.$$

If the location of the measurement point M_1 does not change, $A \frac{L}{R^4 \pi} 2\eta L$ remains a constant value, in which case, after transforming (14), the diastolic coefficient D can obtain the expression:

$$(15) \quad D = (P_{sys} - P_{dia}) T_{d1}.$$

The value of diastolic pressure P_{dia} is calculated from the expression:

$$(16) \quad P_{dia} = \left(P_{sys} - \frac{D}{T_p} \right).$$

Discussion of the results. Using (7) and (16), the systolic and diastolic arterial blood pressure values are determined for each reliably measured interval T_{d1} . The described method has been applied in the Beon 1B, Diver Body Monitor device and a bilateral stimulation system for the treatment of post-traumatic stress. Figure 3 shows a five-minute recording of BP registered by the method described above with the Beon 1B device for assessing the psychophysiological status of operators.

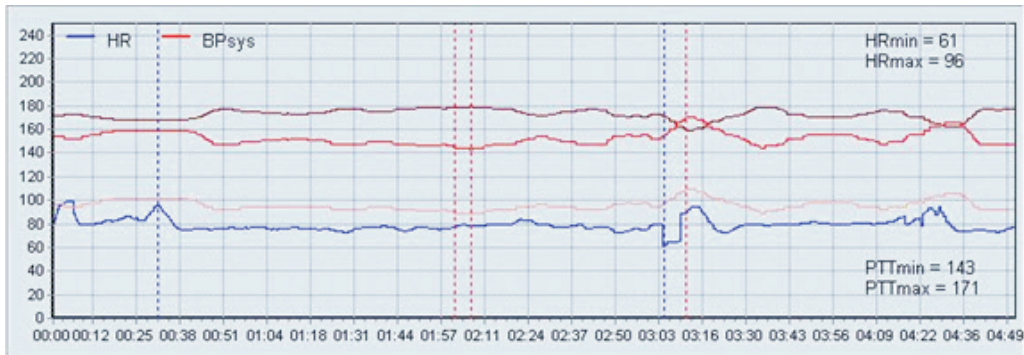


Fig. 3. Five-minute recording of T_{d1} , systolic, diastolic pressures, and heart rate

In Fig. 3, the curve of T_{d1} change in ms is shown in brown, the systolic pressure curve in mm/Hg in red, the diastolic pressure curve in mm/Hg in pink, and the heart rate change curve in bpm in blue.

Conclusion. The non-invasive method described above can be applied in continuous blood pressure monitoring systems. The absence of a cuff and pump allows its application in BP measurement systems for operators in extreme environments, such as fighter pilots and astronauts. It is a useful indicator for tracking sudden changes in blood pressure and cardiovascular activity during work, sleep, or physical exercise, as the measurement is carried out without disturbing the subject.

A known limitation is the need for calibration, but this process is not so significant, as it is done once before each measurement and does not require complex devices and equipment. With minor modifications, the method can also be successfully applied to divers using dry or wet suits at depths of up to 100 m.

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