Problems of Measuring Pulse Wave Velocity

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Abstract: Problems of measuring pulse wave velocity and its utilization in diagnostics have been examined for many years. Pulse wave velocity is a quantity that can be measured non-invasively, and it may bring much information about the state of circulatory system. The R-wave of electrocardiogram (ECG) is most frequently used as the reference point for measuring the pulse wave velocity but it can also be measured as the phase shift of two pulse waves on one artery. When the pulse wave velocity is brought into correlation with blood pressure, then the method used for long term blood pressure monitoring plays an important role. In many cases, the problem of the artery branching is neglected, although this phenomenon may cause additional mistakes in final results.

Key-Words: Pulse Wave Velocity, Blood Pressure, Electrocardiogram, Photoplethysmogram

1 Introduction

Correct functioning of the circulatory system is a fundamental requirement for correct functioning of the whole organism. The functionality of this system can be assessed by monitoring a number of its parameters. They include blood pressure and, more recently, also pulse pressure. This pressure can be measured using invasive and non-invasive methods. In non-invasive blood pressure measurement, the auscultation method using mercury sphygmomanometer is considered the standard. The blood flow through the circulatory system is also described by other quantities related with blood circulation.

Blood circulation in arteries is of pulsating character, which is given by the heart function. The systole of the left ventricle causes a pulse wave on the inlet into systemic circulation, which propagates through the whole arterial system. The artery wall consists of several layers of different stiffness (see Fig. 1). The velocity and shape of pulse wave depend not only on the pressure in artery but also on the mechanical properties of arterial wall.

2 Dependency of pulse wave velocity

When analyzing the mutual relationship between time-variant pulse wave velocity and blood pressure in arteries, we must realize that blood vessels are not formed by stiff tubes of constant diameter. In practice, the artery is an elastic tube whose diameter varies in dependence on the internal pressure. In an artery, the pressure wave which is formed by the left ventricle systole propagates through the arterial system at a velocity that depends on the quality of arterial wall. It was also proved that this velocity depends on the pressure gradient of pulse wave. When we want to compare the pulse wave velocity in different environments, we can choose two cases. The first concerns the propagation of pulse wave through a stiff tube of constant diameter, and the second the propagation of pulse wave through an elastic tubes such as arteries. In a stiff tube filled with incompressible liquid the pulse wave propagation is infinitely high. When this tube is filled with a common liquid, the velocity may be equal to the sound velocity (c. 1500 m/s in blood). The analysis of the pulse wave velocity in arteries includes many variables such as blood viscosity, elasticity of arterial wall, attenuation of the wave amplitude and the presence of reflected waves due to artery branching. Therefore the real velocity is only 3-12 m/s.

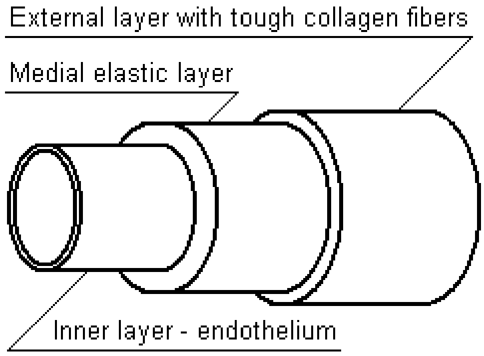

Fig. 1 Anatomy of the arterial wall

The circulatory system is, in principle, a hydraulic system. Using the analogy between electrical and hydraulic circuits, we can draw the equivalent electrical scheme of a part of artery. The serial RLC circuit, which is an equivalent circuit that describes the properties of a part of artery, is a filter. Its parameters depend linearly on the pressure in the corresponding part of the hydraulic system (i.e. artery). With changes in the parameters of this filter its transfer function also change. This entails a change in not only the pulse shape [4] but also in the delay of this pulse. This means that we can monitor changes in the blood pressure in artery in dependence on the shape or delay of the pulse wave.

2 Methodology

In connection with measuring the velocity of pulse wave propagation there is a question of which signals could be used for the determination of pulse delay in a given position. One from two possibilities is to compare the ECG signal and the signal of photoplethysmograph (PPG) [1]. The R-wave peak of ECG, which corresponds to the systole of ventricles, is sharp and therefore it is a suitable reference point. The second possibility is to measure the delay between two corresponding points of two PPG signals obtained by sensors placed on distant positions of the same artery. From the technical point of view, the ECG signal sensing is easy and precise. The problem is, however, that we get exact time of the ventricle systole, but the expulsion of blood from the left ventricle to the artery takes a certain time, which need not be constant. This fact can introduce mistakes in final assessment [3]. Also obtaining of the PPG signal using photoplethysmographic sensor is not difficult, but this method is very sensitive to any movements of the subject scanned.

When we want to relate the pulse wave velocity to changes in blood pressure, we must measure the blood pressure at the same time as the pulse wave velocity. Non-invasive methods for blood pressure measurement are mostly discontinuous so that fast changes in blood pressure cannot be recorded. It is the source of further mistakes in the results of measurement. Only volume-clamp method, invented by Prof. J Peňáz in 1967 and implemented in Finapres device now, enable non-invasive and continuous blood pressure measurement.

3 Measuring arrangement

For the measurement of mutual relationships between pulse wave velocity a blood pressure we have used ECG as reference signal, which was detected by electrodes located on the chest of an experimental person. The blood pressure was measured by Finapress and its sensor was placed on the middle finger of the person. The PPG signal was obtained by reflexive photoplethysmographic sensor on the forefinger. The PPG and ECG signals were amplified and together with the signal from Finapres were plugged to the input of data acquisition card PCI-1712 (Advantech) for A/D conversion and further processing by the MATLAB software.

The experimental person was sitting in an armchair, with the left hand placed (together with the sensors) on the arm rest of the armchair and with a weight held in the right hand. We used this isometric loading in order to continually increase blood pressure. Three male persons aged about 30, were the subject of measurement. The block diagram of the experiment is shown in Fig. 2.

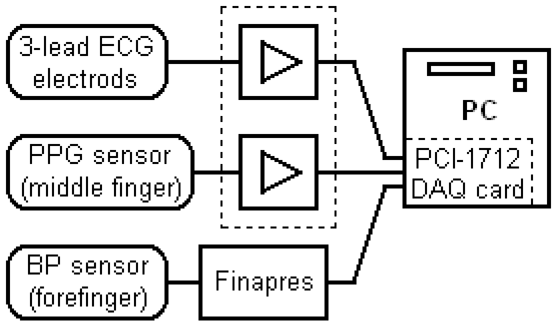

Fig. 2 Arrangement of the measuring equipment

4 Experimental results

In the first phase of the experiment, the relation between the systolic blood pressure value, which was measured by Finapress, and the reciprocal value of the time delay T_1 between the R-wave of ECG signal and the corresponding peak of PPG signal was sought. The reciprocal value of delay could be simply used instead of pulse wave velocity value because the distance between sensors is constant during whole measurement with an experimental person. It also introduced adequate clarity of the depiction of this dependence in following graphs. For each loading a short section of 3 signals was recorded (see Fig. 3).

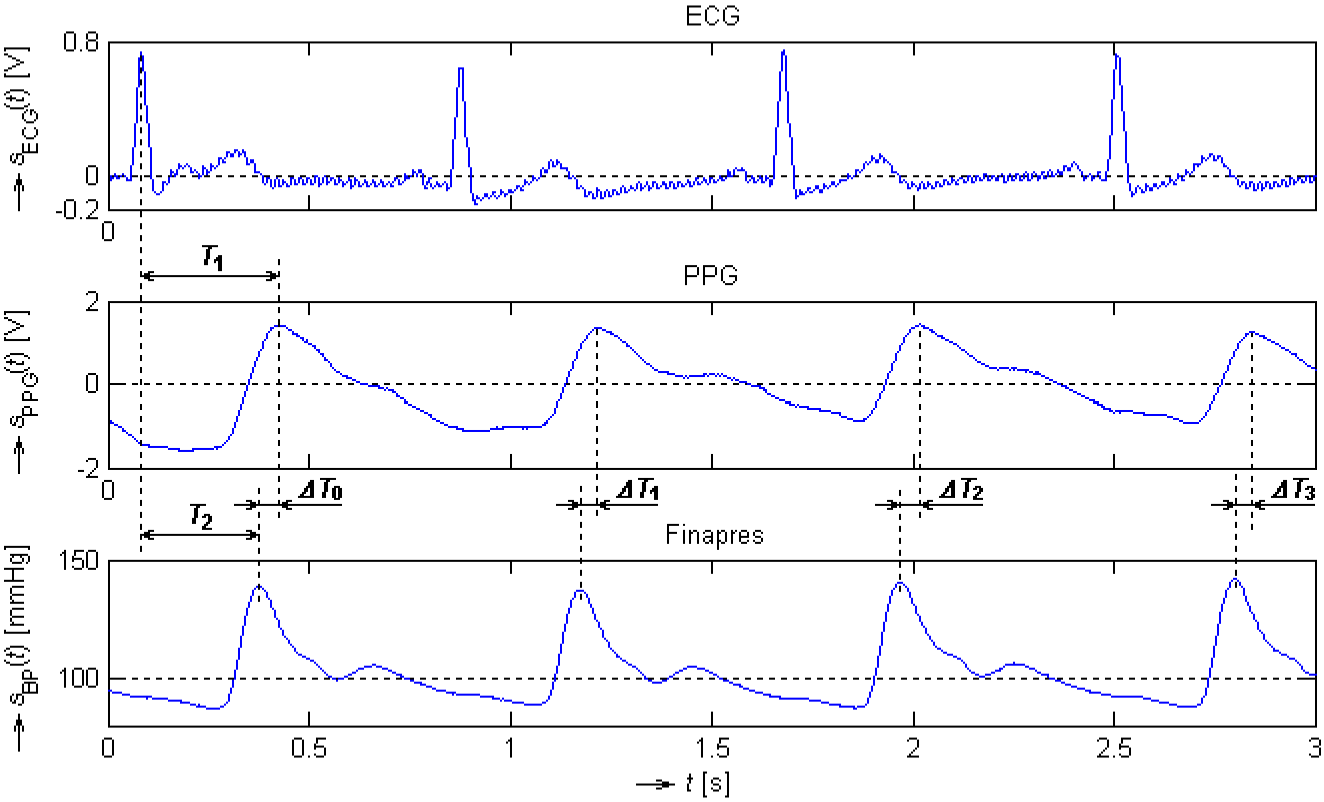

Fig. 3 Recorded signals of person No.2 without loading

Values of systolic (SBP) and diastolic (DBP) blood pressures from Finapres signal were averaged as well as values of T_1 delays which were read from ECG and PPG signals. The results are given in Table 1. They are processed graphically in the next figures.

Table 1 Results

Person	SBP [mmHg]	DBP [mmHg]	$1/T_1$ [s^{-1}]	$1/T_2$ [s^{-1}]
No.1	139,5	93,2	3,094	3,378
	141,4	93,1	3,149	3,463
	141,7	92,9	3,210	3,463
	164,3	100,0	3,420	3,723
	169,5	105,0	3,467	3,816
No.2	139,5	88,0	2,931	3,482
	147,7	90,3	3,159	3,695
	162,5	100,0	3,138	3,876
	180,0	110,5	3,121	4,322
No.3	123,5	82,0	2,902	3,035
	128,8	84,5	2,881	3,166
	132,0	87,8	3,002	3,270
	135,0	92,6	3,024	3,321
	135,8	90,3	3,065	3,327

From the results obtained it is clear that there is an evident correlation between systolic blood pressure and pulse wave velocity only for the experimental person No.1 (compare the blue and the green curve in Fig. 4). For the other two persons the results are inconsistent (see Fig. 5 and Fig. 6).

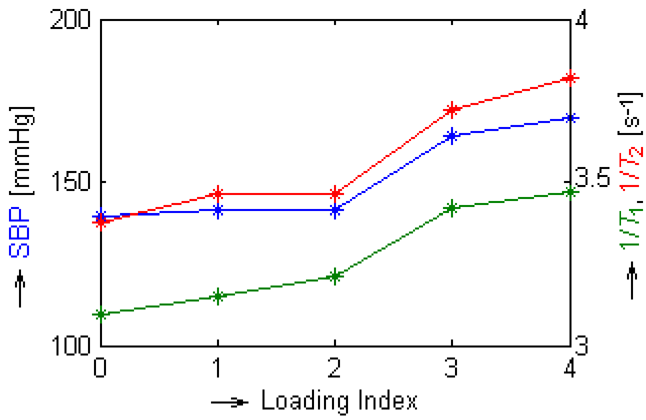

Fig. 4 Progression of values for person No. 1

In an analysis of the obtained results it was discovered that in cases of persons without evident correlation between the blood pressure values and reciprocal values of T_1 delays, there are random phase shifts between PPG and Finapres signal (see ΔT differences in Fig. 3). The phase shift was nearly constant in all records acquired during measurement with person No.1. Therefore we carried out yet another assessment. We measured the time delay T_2 between the R-wave of ECG signal and the corresponding peak of the Finapress signal. In this case the relation between T_2 delays and blood pressure values was always in agreement with the assumption that the delay decreases with increasing blood pressure. The better correlation between blue curve (systolic blood pressure) and red curve ($1/T_2$) is clearly proved in Fig. 4 to 6.

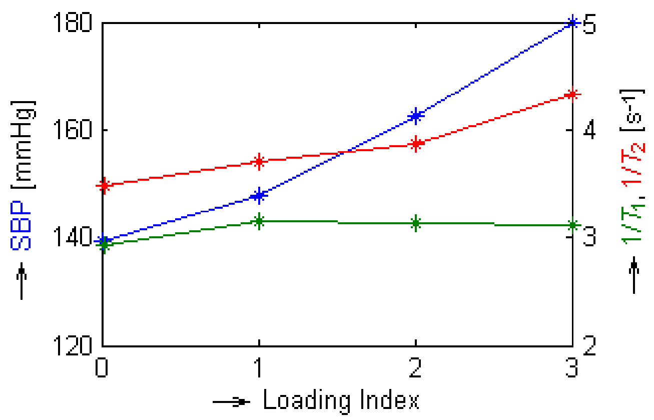

Fig. 5 Progression of values for person No. 2

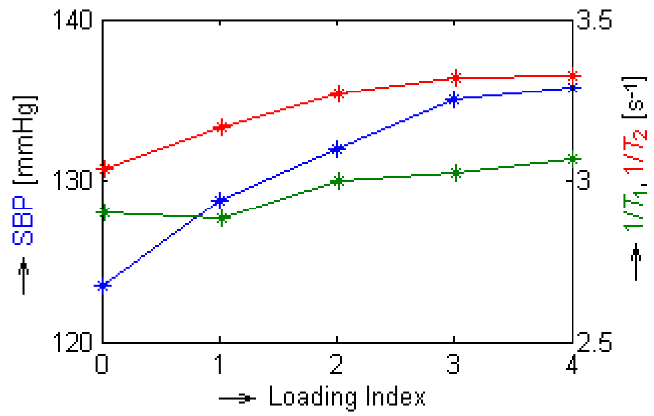

Fig. 6 Progression of values for person No. 3

The problem originates from the location of the photoplethysmographic sensor and the Finapress sensor on the different branches of artery. It disappeared when the place for blood pressure measurement and the place for detection of pulse wave delay were the same. We suppose these random phase shifts between PPG and Finapres signal are caused by phenomena that occur at points where the artery becomes branched. Blood flowing to the place of branching strikes against the wall between the branches, and this results in turbulence. The turbulence quantity depends on the Reynolds number at the point of artery branching. This turbulence causes a random instability in the distribution of the blood flow into branches [5] and this is reflected in the velocities of pulse wave propagation. In addition, this phenomenon depends on the anatomy of the arterial system of the given person. This may cause significant deviations between signals from Finapress and from the photoplethysmographic sensor. In some cases these difference may be very small, as can be seen from our results for person No.1.

5 Conclusion

In this article, the method of measuring the pulse wave velocity and its correlation with blood pressure values has been introduced. The phase shift variation between PPG and Finapres signals in the short-time record has been registered. It is supposed, that the variations are influenced by artery branching. The wrong placing of PPG and Finapres sensors at the different branches of the artery may cause deviations in expected correlation between pulse wave velocity and blood pressure.

The pulse wave velocity is also influenced by many other quantities [2], which cannot be totally suppressed at the time of measurement. Another question is the reliability of using the ECG as a reference signal. According to some authors [3], the peak of the R-wave is not a reliable reference point for the measurement of pulse wave delay, while it is very good from technical point of view.

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