Abstract: - The paper deals with an analysis of biosignals for the purpose of non-invasive blood pressure monitoring without the necessity of using a pneumatic cuff. The method of simultaneous recording of electrocardiogram (ECG) and photoplethysmogram (PPG) and evaluations of their mutual time shift, which corresponds to the pulse transit time (PTT), are described in the paper. Results of original and improved methods of blood pressure determination using calibration measurement and subsequent analysis of pulse transit time values are also presented.

Key-Words: - Biosignal Processing, Blood Pressure, Pulse Transit Time, Photoplethysmography, Electrocardiography

1 Introduction
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 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 [1] 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 pulse wave velocity. 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⁻¹.

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 transit time (PTT) in a given position. One from two possibilities is to compare the ECG signal and the signal of photoplethysmograph (PPG) [2]. The R-wave peak of ECG, which corresponds to the systole of ventricles, is sharp and therefore it is a suitable reference point. Moreover, the peak on ECG signal can be easily detected by some automatic method. 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]. Obtaining the PPG signal using the photoplethysmographic sensor is also simple, but this method is very sensitive to any movements of the subject being scanned, which cause motion artifacts in the PPG waveform. In case of need, another method of pulse wave sensing could be used instead of photoplethysmography. For example, the sequential detection of artery sectional area described by Dr. Říha [4] uses ultrasound scanning.
2 Methodology and Arrangement
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. Penaz in 1967 and implemented in Finapres device now, enable non-invasive and continuous blood pressure measurement.

For the measurement of mutual relationship between pulse wave velocity (PWV) and 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 Finapres 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 stored together with the synchronized signal from Finapres using the special data-acquisition device [5] for 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 load in order to continually increase blood pressure. Male and female persons aged about 30, were subjects of measurement.

2.1 Initial measurement
As can be seen in Figs 1 to 3, measuring on the experimental person proved the supposed correlation of beat-to-beat blood pressure values and corresponding pulse wave velocities. But the variance of measured values suggests the impossibility of calculating blood pressure with a sufficient precision using a simple linear function of pulse wave velocity.

3 The First Experiment and Results
In the first phase of the research, the relation between the systolic blood pressure value, which was measured by Finapres, and the reciprocal value of the pulse transit time $\text{PTT}$ between the R-wave of ECG signal and the corresponding peak of PPG signal was sought. The reciprocal value of $\text{PTT}$ 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 load a short section of 3 signals was recorded (see Fig. 7).

Values of systolic ($\text{SBP}$) and diastolic ($\text{DBP}$) blood pressures from Finapres signal were averaged as well as values of the pulse transit time which were read from ECG and PPG signals. The results are given in Table 1. They are processed graphically in Figs 4 to 6.

From the results obtained it is clear that there is an evident correlation between systolic blood pressure and reciprocal value of $\text{PTT}$ only for the experimental person No.1 (compare the progression of blue and green points in Fig. 4). For the other two persons the results are inconsistent (see Fig. 5 and Fig. 6).
Table 1  Results of the first experiment

<table>
<thead>
<tr>
<th>Person</th>
<th>$SBP$ [mmHg]</th>
<th>$DBP$ [mmHg]</th>
<th>$1/PTT$ [s$^{-1}$]</th>
<th>$1/PTT'$ [s$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.1</td>
<td>139.5</td>
<td>93.2</td>
<td>3.094</td>
<td>3.378</td>
</tr>
<tr>
<td></td>
<td>141.4</td>
<td>93.1</td>
<td>3.149</td>
<td>3.463</td>
</tr>
<tr>
<td></td>
<td>141.7</td>
<td>92.9</td>
<td>3.210</td>
<td>3.463</td>
</tr>
<tr>
<td></td>
<td>164.3</td>
<td>100.0</td>
<td>3.420</td>
<td>3.723</td>
</tr>
<tr>
<td></td>
<td>169.5</td>
<td>105.0</td>
<td>3.467</td>
<td>3.816</td>
</tr>
<tr>
<td>No.2</td>
<td>139.5</td>
<td>88.0</td>
<td>2.931</td>
<td>3.482</td>
</tr>
<tr>
<td></td>
<td>147.7</td>
<td>90.3</td>
<td>3.159</td>
<td>3.695</td>
</tr>
<tr>
<td></td>
<td>162.5</td>
<td>100.0</td>
<td>3.138</td>
<td>3.876</td>
</tr>
<tr>
<td></td>
<td>180.0</td>
<td>110.5</td>
<td>3.121</td>
<td>4.322</td>
</tr>
<tr>
<td>No.3</td>
<td>123.5</td>
<td>82.0</td>
<td>2.902</td>
<td>3.035</td>
</tr>
<tr>
<td></td>
<td>128.8</td>
<td>84.5</td>
<td>2.881</td>
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</tr>
<tr>
<td></td>
<td>132.0</td>
<td>87.8</td>
<td>3.002</td>
<td>3.270</td>
</tr>
<tr>
<td></td>
<td>135.0</td>
<td>92.6</td>
<td>3.024</td>
<td>3.321</td>
</tr>
<tr>
<td></td>
<td>135.8</td>
<td>90.3</td>
<td>3.065</td>
<td>3.327</td>
</tr>
</tbody>
</table>

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 $PTT$, there are random time shifts between PPG and Finapres signal (see $\Delta T$ differences in Fig. 7). The time shift was nearly constant in all records acquired during measurement with person No.1. Therefore we carried out yet another assessment. We measured the pulse transit time $PTT'$ between the R-wave of ECG signal and the corresponding peak of the Finapres signal. In this case the relation between $PTT'$ and blood pressure values was always in agreement with the assumption that the transit time decreases with increasing blood pressure. The better correlation between blue points (systolic blood pressure) and red points ($1/PTT'$) is clearly proved in Figs 4 to 6.

Fig. 4 Progression of values – person No.1

The problem originates from the location of the photoplethysmographic sensor and the Finapres sensor on the different branches of artery. It disappeared when the place for blood pressure measurement and the place for detection of pulse transit time were the same. We suppose these random time 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 these 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 [6] 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 Finapres and from the photoplethysmographic sensor. In some cases these difference may be very small, as can be seen from results of person No.1.

Fig. 5 Progression of values – person No.2

Fig. 6 Progression of values – person No.3

3 Improvement

During a further phase of our research we did a multiple correlation analysis of the parameters obtained from the signals measured. We were searching for parameters with maximum correlation with blood pressure values measured simultaneously by Finapres. Subsequently obtained coefficients of approximating equation were used for the calculation of systolic and diastolic beat-to-beat blood pressure. Finapres and photoplethysmographic sensors were placed on adjacent fingers of an experimental person during the measurement.
The peak of the R-wave of ECG signal, which was measured at the same time, was used as the reference point for the determination of pulse transit time. Compared to the previous method, it is not the corresponding point of R-wave but the intersection point of the tangent line passing through the inflection point in the rising edge of pulse and the maximum or minimum level of the pulse that was sought in the PPG waveform.

As depicted in Fig. 8, PPG pulses are flatter and the position of their peaks sometimes varies because of motion artifacts. Therefore the Matlab program for the analysis of biosignals calculates the first differences of sampled PPG and then finds simply detectable local maximums among them. The time positions of those maximums correspond to the inflection points of rising edges in PPG and their values equal the difference quotients of the respective tangent lines.
defined pulse transit times were used as input parameters. $PTT_1$ is the difference between the time position of a the intersection point of the tangent line with the maximum level of the PPG pulse while in case of $PTT_2$ the intersection point of the tangent line with the minimum level was used as a point of reference.

One measurement lasted 1 minute. The calculated and real values of beat-to-beat blood pressure were averaged for each measurement (see Fig. 9 and Fig. 10). A comparison of these averaged values showed that the results of the method were accurate enough for the most of experimental persons (see Table 2). Thus the averaging of beat-to-beat blood pressure values during 1 minute measurement minimizes the effect of time deviations caused by the artery branching described in the previous chapter. It also suppresses the influence of deviations in an interval which lasts from the moment of R-wave of ECG signal to the time of real heart ventricle systole.

4 Conclusion

In this paper, the method of measuring the pulse transit time and its using for calculation of blood pressure values have been introduced. During the short-time measurement time shift variations between the PPG and the Finapres signals in the record have been registered. It is supposed that the variations are influenced by artery branching. The wrong position of PPG and Finapres sensors at different branches of the artery may cause deviations in the expected correlation between pulse wave velocity and blood pressure. The pulse wave velocity is also influenced by many other effects [7], 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 propagation delay, although it is very suitable from the technical point of view. However, the finding of the optimal coefficients of approximating equation using the multiple correlation analysis and subsequent averaging of calculated beat-to-beat values enable a more precise determination of blood pressure.

The method described in this paper can be used for non-invasive long-term (up to 42 h) monitoring of blood pressure. The fact that it is not necessary to use a pneumatic cuff is the main advantage of the method. It is because inflating the cuff disturbs the monitored person, especially in their sleep, and it can cause undesirable deviation of blood pressure.

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References:


