Biosignal Data Acquisition and its Post-processing

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Abstract: The paper describes an experimental device for recording biological signals, such as electrocardiogram (ECG) and photoplethysmogram (PPG), and their use in a new non-invasive method of blood pressure measurement without a cuff. The purpose of the data acquisition device is to record one ECG and two PPG signals from sensors placed at different places on patient’s artery in order to determine their mutual time shifts and pulse wave velocity using digital signal processing. These parameters and data obtained during the first calibration measurement enable us to calculate subsequent values of patient’s blood pressure.

Key Words: Data Acquisition, Blood Pressure Measurement, Electrocardiography, Photoplethysmography, Pulse Wave Velocity

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 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 [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 delay in a given position. One from two possibilities is to compare the ECG signal and the signal of photoplethysmograph [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]. 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.

2 Data Acquisition

Recorded biological signals has some special characteristics. ECG signal is signal associated with electrical activity of heart. It is measured by electrodes placed on skin. Amplitude of ECG signal is approximately from 50 µV to 5 mV and bandwidth is 0.01 - 150 Hz. PPG signal is obtained by optical measurement of light absorption which is associated with blood flow. Experimental data acquisition device was designed for these measurements. First condition is absolute safety for patient; therefore the device is powered by low voltage battery [4] and in special cases can be powered from USB port. Data to be used for subsequent analysis of the signal received in rela-
tion to blood pressure will be obtained on experimental persons. Since this is an experimental device, it should allow for easy replacement from the viewpoint of signal sensing and our intentions to find a relation between changes in signal parameters and blood pressure. In this experiment, it is possible to use two combinations of sensors with or without using of input for a calibration signal (e.g. Finapres):

- ECG + PPG sensors.
- Two PPG sensors.

As shown in Fig. 1, the device is divided into three subunits. The first of them is the analog part, which task is to gain obtained signals and prepare these for AD conversion. The second one is the digital part which is controlling gain in analog part, providing sampling and storing data. The third part is power supply.

Given that every channel has independent to adjust their levels prior to digitization, it is clear that variability will affect only the analog part, while the digital part will be the same for all inputs. Estimated maximum period for scanning is 48 hours. The frequency of measurement in this interval is at least 12 measurements during one hour. The time for one measurement capture is at least 90 pulses.

During the time when the device is in a state of waiting for the moment of measurement, power consumption of all parts of the device is low, because all integrated circuits are in the power save mode. Increased power consumption occurs at the time of measurement. This is due to two factors. The first factor is the high power consumption of IR LED, which is used in the photoplethysmograph sensor. The second factor affecting the power consumption is the SD card write operation, which is used to save the data acquired. The capacity of the SD Card is 2 gigabytes. Subsequent analysis of the signal measured will be carried out in a workstation using a specially created application.

2.1 Analog part
The analog part consists of four programmable gain amplifiers controlled by digital part and three pre-amplifiers, one for ECG and two for PPG.

Given that for each new turn on the ECG in the pre-event temporary plot this takes a relatively long time with regard to the lower marginal rate, which the amplifier transmits, the amplifier also contains the quick-start circuit whose task is to shorten the period of transition to a minimum. The quick-start circuit is commonly used in all electrocardiographs.

This process makes the analog part ready to capture the signal. When the time set for detection expires, the SD card write operation is blocked, and the system goes back to the standby mode. The proposed operating mode leads to significant savings in energy drawn from the device power supply and thus extends the period for which it can operate.

2.2 Digital Part
The basic part of the digital part is the ATxMEGA192 microcontroller in combination with precision AD converter. The microcontroller was chosen because of its good features and integrated peripherals and computing power. The microcontroller performs all calculations associated with the scanning of signal values, monitoring moments for measurement, SD card read/write operation, power management and pre-processing.

The signals measured are sampled by a 12-bit analog-to-digital converter, which resolution is sufi-
cient for this activity and with sleep mode support. The amplified ECG signal at the output of ECG amplifier, as well as the signal from the photoplethysmographic sensor is separately connected to one input of the AD converter, where they are sampled with a frequency up to 680 kHz using all of inputs. The sampling frequency is large enough to capture even relatively small temporal changes in the waveforms detected.

The device is equipped with a removable memory card, which is used for data storage. Saving the acquired data by this type of storage media is appropriate not only because of its large capacity, but also because of the subsequent processing of stored data, which is performed in the service application on a PC. To make working with the data easier, the FAT32 file system support was implemented in the microcontroller. For each patient their own file can be created, in which their measured ECG signal and PPG signal or two PPG signals are written with or without a signal for calibration obtained for example by Finapres.

The last element of the digital part is the acoustic crystal transducer. It is activated sufficiently long before the beginning of measurement. A sound signal informs the patient of the coming beginning of measurement, which should make the patient behave in accordance with the instructions received, to ensure a successful measurement.

2.3 Power Supply
The device is designed with symmetrical power supply, which is used by amplifiers. This solution has been chosen for overall simplicity of circuit. With non-symmetrical supply a positive voltage shift of PPD and ECG signals is necessary because their voltage range is from -0.1 V to +0.1 V. Symmetrical power supply is built up on low-noise CMOS switched-capacitor voltage converter. A battery or USB port is used as a source of power depending on the mode of measurement.

3 Methodology
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 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 signal from Finapres using data-acquisition device 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. Three male persons aged about 30, were the subject of measurement.

4 Experimental results
In the first phase of the experiment, the relation between the systolic blood pressure value, which was measured by Finapres, and the reciprocal value of the time delay $T$ 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 load a short section of 3 signals was recorded (see Fig. 5).

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

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. 2). For the other two persons the results are inconsistent (see Fig. 3 and Fig. 4).

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 $T$ delays, there are random time shifts between PPG and Finapres signal (see $\Delta T$ differences in Fig. 5). 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 time delay $T'$ between
the R-wave of ECG signal and the corresponding peak
of the Finapres signal. In this case the relation be-
tween \( T' \) delays and blood pressure values was al-
ways in agreement with the assumption that the delay
decreases with increasing blood pressure. The better
correlation between blue curve (systolic blood pres-
sure) and red curve \( (1/T') \) is clearly proved in Fig. 2
to 4.

<table>
<thead>
<tr>
<th>Person</th>
<th>( SBP ) [mmHg]</th>
<th>( DBP ) [mmHg]</th>
<th>( 1/T ) [s(^{-1})]</th>
<th>( 1/T' ) [s(^{-1})]</th>
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<td>2.902</td>
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<td>135.0</td>
<td>92.6</td>
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<tr>
<td></td>
<td>135.8</td>
<td>90.3</td>
<td>3.065</td>
<td>3.327</td>
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</table>

Table 1: Input data for correlation analysis

The problem originates from the location of the
photoplethysmographic sensor and the Finapres sen-
sor on the different branches of artery. It disap-
ppeared when the place for blood pressure measure-
ment and the place for detection of pulse wave delay
were the same. We suppose these random time shifts
between PPG and Finapres signal are caused by phe-
nomena 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 instabil-
ity 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 per-
son. This may cause significant deviations between
signals from Finapres and from the photoplethysmo-
graphic sensor. In some cases these difference may be
very small, as can be seen from our results for person
No.1.

5 Improvement

During a further period of our research we did a
multiple correlation analysis of the parameters ob-
tained from the signals measured. We were searching
for parameters with maximum correlation with blood
Subsequently obtained coefficients of approximating equation were used for the calculation of systolic and diastolic beat-to-beat blood pressure.

Finapres and photoplethymographic 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. One measurement lasted 1 minute. The calculated and real values of beat-to-beat blood pressure were averaged for each measurement. 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.

### Table 2: Results of improved method

<table>
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<tr>
<th>Person</th>
<th>Measured SBP/DBP [mmHg]</th>
<th>Calculated SBP/DBP [mmHg]</th>
<th>∆SBP/∆DBP [mmHg]</th>
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<td>97.1/50.5</td>
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<td>99.0/48.4</td>
<td>98.1/51.5</td>
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<td>107.9/54.3</td>
<td>109.1/54.4</td>
<td>-1.2/-0.1</td>
</tr>
<tr>
<td>No.5</td>
<td>153.6/84.7</td>
<td>153.6/84.8</td>
<td>0/-0.1*</td>
</tr>
<tr>
<td></td>
<td>139.6/77.6</td>
<td>136.4/74.3</td>
<td>3.2/3.3</td>
</tr>
<tr>
<td></td>
<td>152.9/85.8</td>
<td>155.9/85.4</td>
<td>-3.0/0.4</td>
</tr>
<tr>
<td>No.6</td>
<td>114.6/80.9</td>
<td>114.6/80.9</td>
<td>0/0*</td>
</tr>
<tr>
<td></td>
<td>112.5/76.1</td>
<td>111.9/79.1</td>
<td>0.6/-3.0</td>
</tr>
<tr>
<td></td>
<td>114.3/79.2</td>
<td>116.9/82.0</td>
<td>-2.6/-2.8</td>
</tr>
</tbody>
</table>

*calibration measurement

**6 Conclusion**

In this article, the biological data acquisition device and the method of measuring the pulse wave velocity and its correlation with blood pressure values have been introduced. Data acquisition device can operate in two different modes. The first one is continuous ECG and PPG signals recording directly to PC with possibility of calibrating signal recording. The second one is signal recording to SD memory card in specified intervals. Device is powered from battery and this mode is intended for long-term measuring on experimental person.
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 [6], 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.

Acknowledgements: This work was supported by the Ministry of Education, Youth, and Sports of Czech Republic under project No. 2B06111 and research programme MSM0021630513.

References:


