Results of geometric ballistocardiography

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***Abstract*—**Results of application of differential geometry on ballistocardiographic signals is presented. Three measurements are discussed – blood pressure monitoring, pulse wave velocity monitoring and arrhythmias monitoring. Patients were measured using piezoelectric foil sensors placed under the mattress of clinical bed. Data from sensors was compared with the data from ECG and blood pressure monitor to determine the possibility of unobtrusive measurements. Few volunteers who suffer from atrial fibrillation were measured and the occurrence of arrhythmias was examined.

***Keywords*—**arrhythmia, ballistocardiography, blood pressure, pulse wave velocity, unobtrusive

I. Introduction

SEEKINGfor new unobtrusive methods of measurement of human biosignals has big importance in modern medicine [1]. The blood pressure is typically measured using the inflatable strap on the arm, which pushes on the arteries. Physician can hear the pulse wave in the artery using the stethoscope and then the systolic blood pressure is set equal to the pressure in the strap at which the pulse wave stops propagating through the veins. More precise measurement can be done by injecting the pressure sensor directly in the arteries (typically into the radial artery). This sensor can continuously monitor the blood pressure over time (i.e. blood pressure variability - BPV). The first method is obtrusive, since inflating strap on the arm can cause discomfort to the patient and affect the results. Second method is invasive and can cause various harm to the patient. It is needed to find other methods of blood pressure monitoring which are unobtrusive. For this purpose we used piezoelectric foil sensors which were put under the mattress so they are in no direct contact with the patient.

A signal measured by piezoelectric foil sensors is called the ballistocardiogram (BCG). The signal corresponds with small mass movements of the whole body, generated by the forces of heart contraction and by the blood evicted to large arteries (the principle of action and reaction) [2]. These movements are transferred through the mattress to the sensors. Since the blood pressure directly corresponds with the forces that are moving with the whole body [3], the amplitude of the signals must correspond with the amplitude of the blood pressure in the beat-to-beat precission. Difficulty with BCG signal is that it strongly depends on the position of the patient on the bed and it generates a lot of artifacts caused e. g. by patient's movement or when the hospital personnel is moving around the bed. For the precise BPV measurement it is needed that the patient does not change its position on the bed.

Human cardiovascular system is a branching graph consisting of aorta, aorta branching, arteries, etc., on which the pulse wave generated by the heart contraction is propagating. There is a strong correlation between the variability of the blood pressure and the pulse wave velocity [4], so time-based experiments were performed by [5]. According to the Moens-Korteweg [5] equation the pulse wave velocity (PWV) is determined by the arterial elasticity and its diameter. If we assume, that the elasticity does not change significantly during the experiment, the changes of PWV can be considered being caused by the changes of the aortal blood pressure.

Relation between the blood pressure and PWV (called the Moens-Korteweg equation) is presented in [1] and [5]:

$$BP = a \ln\left(\frac{b}{\left(\frac{d}{PWV} - c\right)^2 - 1}\right),$$

where BP represents the blood pressure, PWV is the pulse wave velocity and a, b, c and d are constants dependent on the human physiology. So the relation between the pulse wave velocity and the blood pressure is exponential.

Atrial fibrillation is a special type of arrhythmia. It is caused usually by problems with electrical conductivity on the heart muscle. It is very common among people over 60 years age. It is by itself dangerous only when untreated, the arrhythmia can generate precipitate which can harm the patient. Big problem with atrial fibrillation is that a lot of patients do not know that they suffer from it since it can be proven only using ECG. Unobtrusive continuous monitoring of patients in the hospital without ECG monitors can discover atrial fibrillation among patients and can save their lives.

II. Experimental setup, description of hardware

Patients were measured on clinical bed equipped with six piezoelectric foil sensorswhich were close connected to charge amplifier. Each sensor with amplifier was stuck on a plastic ledge with length about 60 cm. These ledges were located in parallel under the mattress equidistantly 30 cm (see Fig. 1 and Fig. 2).

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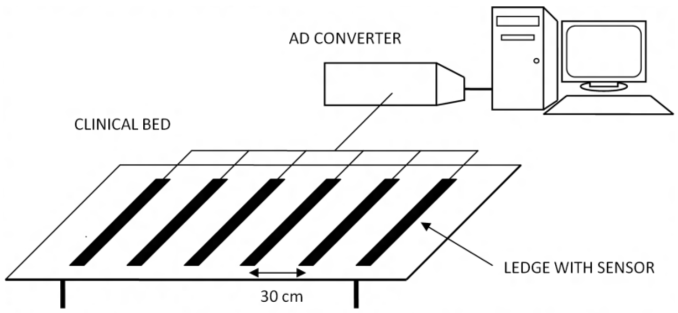

Fig. 1: Scheme of the measurement hardware.


Fig. 2: Ledges with sensors.

Signal from sensors was led to 20 bit analog-to-digital converter and then via optical fibers to receiver, which was connected to personal computer by means of USB. The usage of optical fibers guarantees galvanic isolation from the computer. The sampling frequency used was 1 kHz.

The measurement was done in the Resuscitation Department of the IKEM Cardiology Centre in Prague. Two diseased patients were measured on clinical beds. Both patients had their blood pressure measured using the pressure sensor stuck into radial artery and were also measured using ECG monitor. The pressure sensor and the ECG were connected to the standard hospital monitor, from which the analog signal was led to AD converter (as well as piezoelectric foil sensors) to ensure time synchronization of the signals. Each measurement lasted for 15 minutes. The health condition of the patients made them unable to move, so the BCG signal was affected only by the hospital personnel moving around the bed and sometimes performing basic medical actions.

III. Theory of Measurement

A. *Blood pressure variablity*

From the BCG measurement, six signals were obtained. To achieve stronger correlation, so called euclidean monitoring function was calculated (see [6], [7] and [8]). Then typical peaks, corresponding with the cardiac cycle were found and their amplitude measured. The signal from the blood pressure sensor was analyzed and the peaks in the signal (see Fig. 3) were found. The amplitude of those peaks directly corresponds with the systolic blood pressure. Unfortunately, the autozero function of the AD converter resets the mean value of the signal to zero in random intervals. This phenomenon made us unable to derive direct equation to convert between the blood pressure (in Torr) and the amplitude of the signal (in mV). Thus auxiliary units were used in each next step of the signal processing. To ensure that the amplitude of the peaks is compared up to beat-to-beat precision, the threshold for the time diference between the peaks in pressure and monitoring function was set to 300\,ms. This time difference occurs due to unsharp edge of the peaks in monitoring function and also because of the variability in the mechanical response to the heartbeat. After calculation of the amplitudes, two time series were made. First time series was the series of amplitudes of the blood pressure (i.e. BPV) and second time series was the series of amplitudes of the monitoring function. %The derivatives of those two curves were calculated and then the sign of the derivative for each heart beat was derived. If the sign of the derivative is the same for both time series, it means, that the monitoring function can give us the information about the changes in the blood pressure.

B. *Pulse wave velocity*

Position of R-waves in ECG diagram were found and the time difference between corresponding (with beat-to-beat precision) peaks in blood pressure and monitoring function were compared with the amplitude of the corresponding peak of blood pressure. These times are often called pulse arrival times (PAT) [3] since it is the quantity which tells us how long does it take for the pulse to arrive to some specific point with the time of R-wave set to zero. From the Moens-Korteweg equation, the dependence of the quantity $\frac{1}{PAT} \approx PWV$ on the amplitude of blood pressure should belinear.

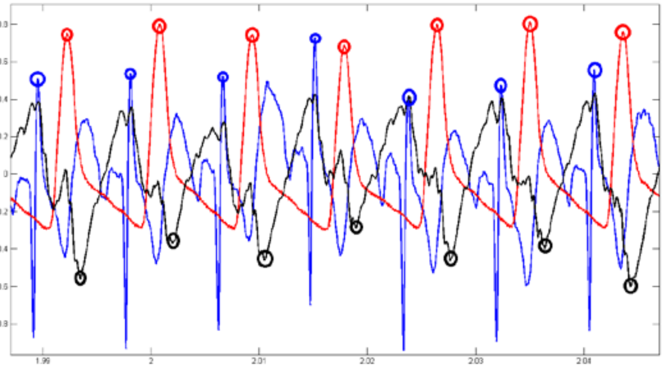

Fig. 3: Comparison between the raw signals of ECG, blood pressure and monitoring function. Blue circles denote the position of R-wave, red circles denotes position of blood pressure maxima, black circles denotes peaks in monitoring function.

C. *Arrhythmias monitoring*

Occurrence of atrial fibrillation is associated with the decrease of blood pressure. During the phenomena the atria do not contract properly so less blood is ejected into the chambers. Also the P-wave in ECG signal is not present. Analysing the data from ECG and blood pressure it is possible to find the occurrence of arrhythmia and to compare the signals with the monitoring function.

IV. Results

The comparison between the amplitudes of blood pressure and monitoring function are on Fig. 4 and Fig. 5. It was not possible to use all the heart beats because the hospital personnel often performed some basic medical actions, which affects the amplitude of the monitoring function. Only heartbeats with patient lying still and no other disturbance were used. Similar patterns can be observed at various times. The correlation coefficients between the time series are 82% for the first patient and 70% for the second patient.

The dependence of blood pressure on PWV for patient 1 is on Fig. 6. On the x-axis is the quantity $\frac{1}{p_x-m_x}$, where p_x is the time difference between the peak in blood pressure and R-wave in ECG and m_x is the time difference between the peak in monitoring function and R-wave in ECG (see Fig. 3). The peak in monitoring function occurs later than the peak in blood pressure as it is shown on Fig. 3. This peak in monitoring function can be assigned to the movement of the whole body due to pulse absorption in the cardiovascular system. It can be seen that the autozero function reset the data three times thus making three different linear dependencies, which can be clearly distinguished. Because of this autozero function, only qualitative conclusions can be made. The dependence of blood pressure on PWV for patient 2 is on Fig. 7. On the x-axis is for comparison only the quantity $\frac{1}{p_x}$. Again, two autozero resets occured and two linear dependencies can be distinguished.

Examples of arrhythmia occurrences are on Fig. 8and Fig. 9. It is clearly possible to determine the occurrence of atrial fibrillation. Corresponding reaction such as pause in the heart cycle and increase or decrease of blood pressure can be also determined from the monitoring function. Using piezoelectric sensors it is thus possible to easily detect atrial fibrillation which is very important for the patients who do not know about their arrhythmias.

Sex	Male
Age	82 years
Weight	65 kg
Height	170 cm
Surgery	aortic valve replacement for pig's valve
Time after surgery	3 days
Health condition	irregular heart action, atrial fibrillation, double aortocoronary bypass, ischemic heart disease
Total no. of heartbeats	1114
No. of heartbeats analysed	302

Table 1: Patient 1.

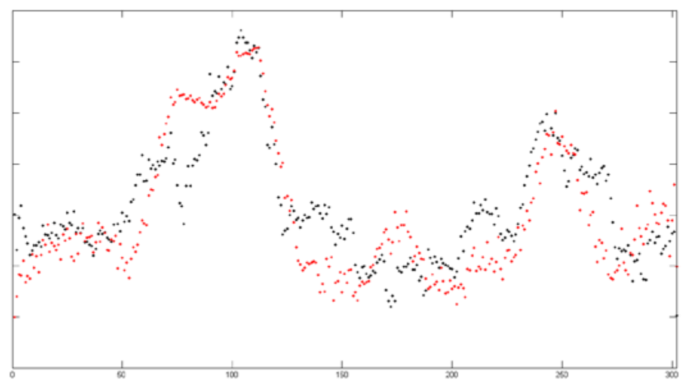

Fig.4: Comparison between the maxima of monitoring function (black) and blood pressure (red) - Patient 1, on the x-axis is the number of heartbeats.

Sex	Male
Age	88 years
Weight	82 kg
Height	168 cm
Surgery	aortic valve replacement for pig's valve
Time after surgery	90 minutes
Health condition	hypertension, chronical obstruction of lungs
Total no. of heartbeats	970
No. of heartbeats analysed	659

Table 2: Patient 2.

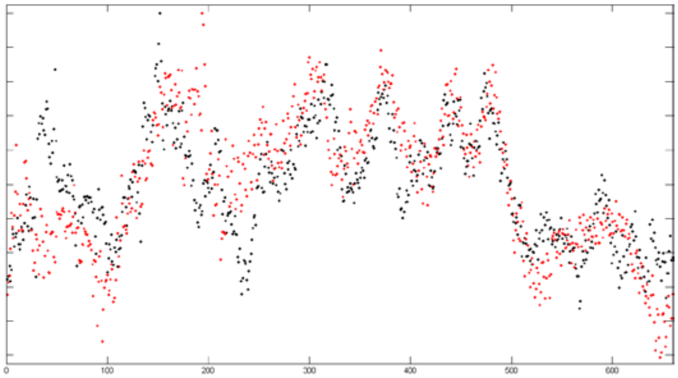

Fig.5: Comparison between the maxima of monitoring function (black) and blood pressure (red) - Patient 2, on the x-axis is the number of heartbeats.

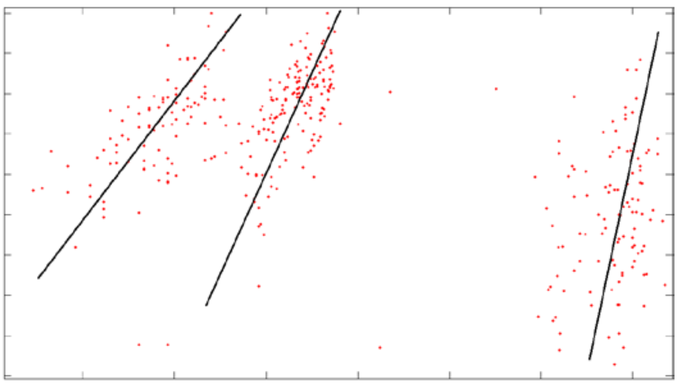

Fig. 6: The dependence of blood pressure on PWV – Patient 1.

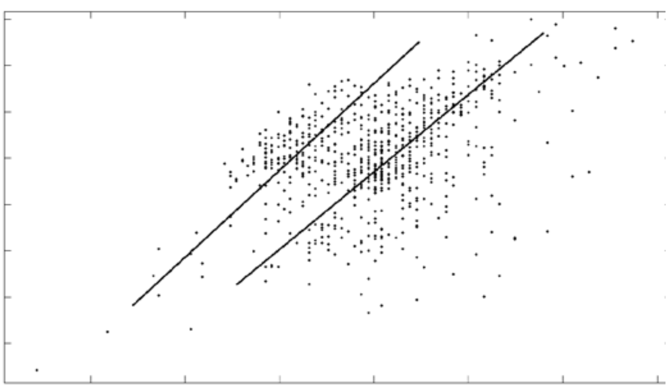

Fig. 7: The dependence of blood pressure on PWV – Patient 2.

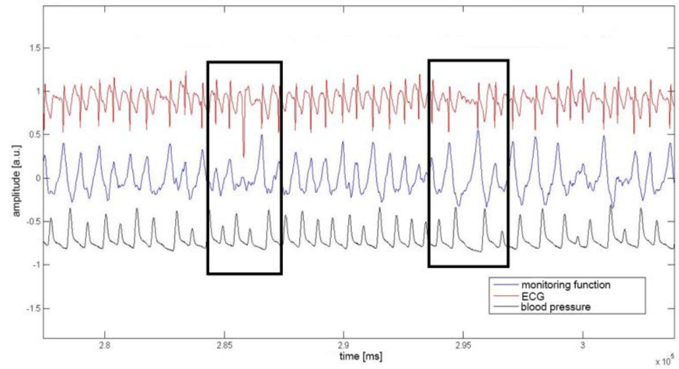

Fig. 8: Detection of atrial fibrillation – Patient 1.

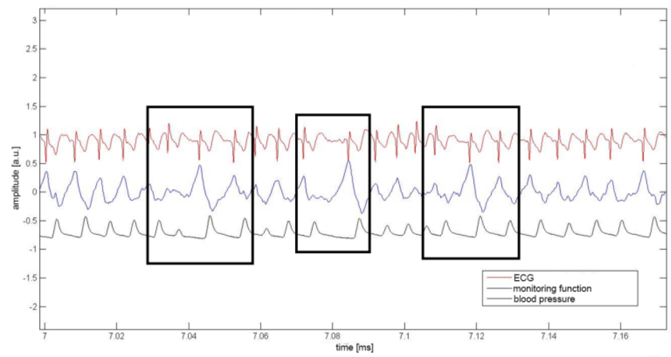

Fig. 9: Detection of atrial fibrillation – Patient 1.

V. Conclusion

Two patients were measured using piezoelectric foil sensors placed under the mattress of the clinical bed. Data from the sensors were processed and compared with data from blood pressure sensor stucked in the radial artery of the patients. It is shown, that blood pressure variability can be measured unobtrusively using piezoelectric foil sensors with sufficient precision to monitor e.g. the immediate effect of medicine on blood pressure, but only with patient lying still on the bed. The analysis of pulse wave velocity was made using the comparison between the signals from blood pressure sensor and piezoelectric foil sensors. It is shown, that both types of signals satisfy Moens-Korteweg equation. Because these sensors can also record the position similar to R-wave, it is possible, to use piezoelectric foil sensors to monitor the changes of pulse wave velocity.Finally the occurrence of atrial fibrillation was found and compared with the monitoring function. It is shown that atrial fibrillation can be also detected using piezoelectric sensors.

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