ACCURATE BLOOD PRESSURE MEASUREMENT AT HOME

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Abstract: Automatic and semi-automatic blood-pressure meters are simple-to-use thus widespread in home health monitoring. However, their results are not accurate and reproducible enough, the reliability of self-assessment is not satisfactory, medical doctors have reservations for the results. The occlusion by the cuff – applied in the majority of indirect blood-pressure meters - changes the biomechanical properties of the arteries resulting in a change in the systolic and diastolic values. Presently available devices neglect the variation caused by breathing. This can be as high as 10 Hgmm in the systolic pressure. The aim of the research work has been to increase the accuracy and reproducibility of the indirect, cuff-based blood pressure measurement with the help of the photoplethysmographic (PPG) signal. The PPG signal helps to measure the systolic pressure directly unlike the oscillometric method that measures the mean pressure and gives only an estimate for the systolic and diastolic pressures. The additional information gained by monitoring the PPG signal before and during slow inflation provides more accurate results than conventional indirect methods and assures that the cuff pressure only slightly (by less than 10 Hgmm) exceed the systolic pressure. The PPG signal also indicates if the cuff is placed or inflated improperly.

Introduction

A single measurement does not give enough information to qualify the blood pressure of a person as normal or pathologic. The blood pressure is varying during the day, 20...30 Hgmm differences are not uncommon even for healthy subjects. The white-coat effect is also well known. Many have increased blood-pressure values at the doctor's office. Self-measurement of blood pressure at home eliminates the white-coat effect, makes possible the measurement always at the same phase of the daily activity and promotes the devotion of a person to be involved in the health keeping process. Inaccurate or low reproducibility meters prevent subjects from being motivated. Neither help the inaccurate measurement results the medical treatment. It is important to provide accurate blood-pressure meters for self-monitoring.

The accuracy of commercially available blood-pressure meters has been investigated, good reviews are given in [3], [4]. Both the AAMI (American Association for the Advancement of Medical Instrumentation) and the BHS (British Hypertension Society) published standards for grading sphygmomanometers. Both standards define the mercury sphygmomanometer as the reference device and allow substantial deviation. The best grade (A) in the BHS standard allows 40 % of the results deviate from the reference by more than 5 Hgmm, 15 % of the results by more than 10 Hgmm and 5 % of the results by more than 15 Hgmm. A clinical review of a number of presently used blood-pressure meters revealed that the majority of devices could not meet the standards [5]. Guidelines are available for self-monitoring the blood pressure [6].

The oscillometric method is used in the majority of presently available devices applicable for home use. These devices are simple-to-use but not accurate enough. The PPG signal ([1], [2]) recorded at the fingertip during the measurement helps increase the accuracy by providing extra information about the blood-pressure. This additional information can also be used to detect if the cuff is wrapped up and inflated correctly.

During cuff-based blood-pressure measurement the occlusion with the cuff changes the biomechanical properties of the brachial artery. Its consequences have also been investigated.

Materials and Methods

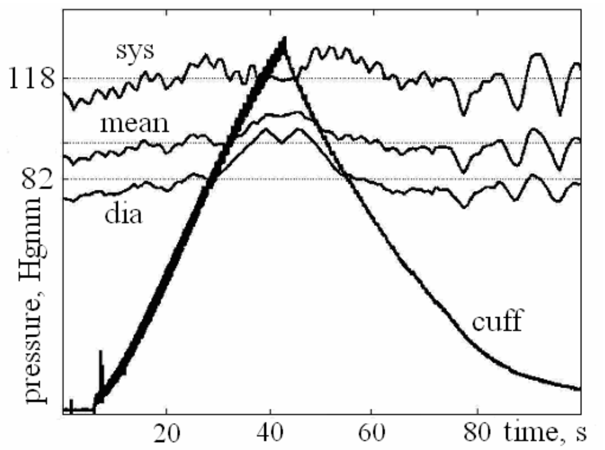

Figure 1: Pressure values (upper arm cuff, systolic, diastolic and mean values monitored at the wrist) during slow inflation and deflation.

Cuff-based indirect methods

Figure 1 shows the pressure of the upper-arm cuff during slow inflation and deflation together with the systolic, mean and diastolic pressures recorded simultaneously at the wrist of a person using a wrist tonometer. It can be seen that both the systolic and the diastolic pressure increase as the cuff pressure increases. This means the occlusion by the cuff may change the pressure values to be measured! Figure 1 shows also that breathing influences the systolic pressure.

Pulse wave velocity

The PPG signal indicates volume changes in the blood vessels. The occlusion of the brachial artery influences the pulsation in the PPG signal measured distal from the cuff.

Pulse wave velocity in the brachial artery can be calculated by recording the ECG and the PPG signal. The velocity of the pulse wave, progressing through the arteries depends also on blood pressure. Many attempts have been made to make use of pulse wave velocity during blood pressure measurement. Based on the pulse wave velocity blood-pressure variation can be estimated even without using a cuff [7], [8], [9], [10], [11].

$$v = \frac{L}{\Delta T_{PT}} = \sqrt{\frac{Eh}{\rho d}} \qquad (1)$$

$$E = E_0 e^{aBP} \qquad (2)$$

$$BP = \frac{1}{a}\left[\ln\left(\frac{L^2 \rho d}{E_0 h}\right) - 2\ln(\Delta T_{PT})\right] \qquad (3)$$

where v is pulse wave velocity, E is the Young modulus of arterial wall (E_0 is its value at zero pressure), h is the thickness d is the inner radius of the artery, ρ is blood density, α is constant, L is the distance between the heart and the fingertip and ΔT_{PT} is the pulse transit time. ΔT_{EP}, the time delay between the ECG and the PPG signal, is the sum of the pre-ejection time, ΔT_{PE} and the pulse transit time, ΔT_{PT}.

$$\Delta T_{EP} = \Delta T_{PE} + \Delta T_{PT} \qquad (4)$$

Pulse wave velocity, as defined in (1) is an average over the distance from the heart to the fingertip. ΔT_{PT} cannot be measured easily, ΔT_{EP} is used instead.

ΔT_{EP} is influenced also by factors other than blood pressure. This would cause substantial error if blood pressure were estimated based ***only*** on ΔT_{EP}. [8] suggests intermittent calibration with a cuff-based meter in every 5 minute.

The pulse wave velocity can also be used to characterize the arterial distensibility [13], [14].

[15] proposes that the arterial system has natural frequencies and these are related to the heart rate. This involves a correlation between ΔT_{EP} and the heart rate.

The measurement set-up

The measurement set-up was built around a PIC16F877. Four channels (cuff pressure, Einthoven lead I ECG, 2 PPG signals) were sampled at 1 ksamples/s each and the sampled data were transferred to a PC via serial I/O. The resolution of measuring the ECG and the PPG signals was 9 effective bits ($\Delta U/U_{pp}$). The control circuitry of the motor inflating the cuff has been developed. This makes possible a slow inflation, an average slope of 3 Hgmm/s was used. The cuff pressure was measured with a resolution of 0.05 Hgmm.

A COLIN CBM 7000 blood pressure monitor was used to record the blood-pressure – time function of the tested person. This is a tonometric device; the sensor must be attached to the artery at the wrist. The blood-pressure was always monitored on the left wrist.

The cuff was wrapped around either the left or the right upper arm. This made possible to study the effect of the occlusion by the cuff.

Measurements were taken using a PISTON spirometer to study the effect of breathing on blood-pressure.

Results

The airflow and ΔT_{EP} were monitored simultaneously to determine the effect of breathing on blood-pressure. This test requires no occlusion by the cuff. A senior (52 years old male) and ten young (22…25 years old, 4 females and 6 males) healthy subjects participated in the study, altogether 90 recordings were made. The tested person was asked to perform different breathing patterns. The air flow was monitored with a spirometer, ΔT_{EP} and the heart rate were calculated from the Einthoven lead I. ECG and the PPG signal. Figure 2 shows a typical recording.

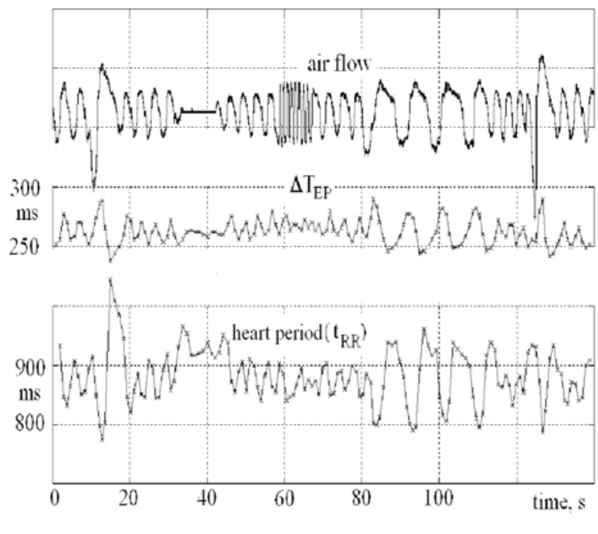

Figure 2: Breathing influences pulse wave velocity as well as heart rate.

Figure 3 shows the arterial pressure monitored with the COLIN tonometer on the left wrist of a young (23 years old) healthy male while a cuff-based measurement was made on the right arm. Ten minutes later this young man was tested again. The tonometer remained fixed to the left wrist but this time the cuff for the indirect measurement was wrapped around the left upper arm. The results are given in Figure 4.

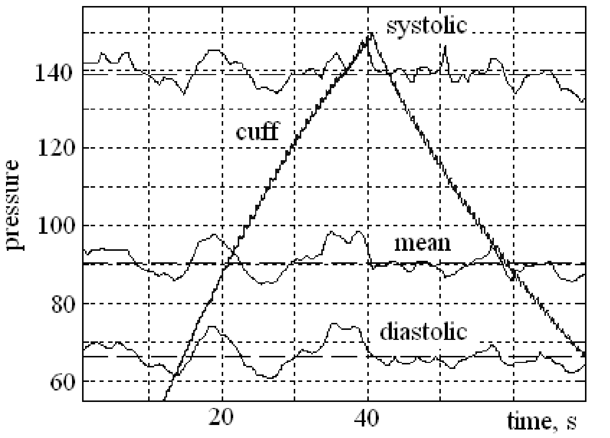

Figure 3: Variation in systolic, diastolic and mean pressures, monitored on the left wrist. The cuff is on the right upper arm of a young (23 years old) healthy male.

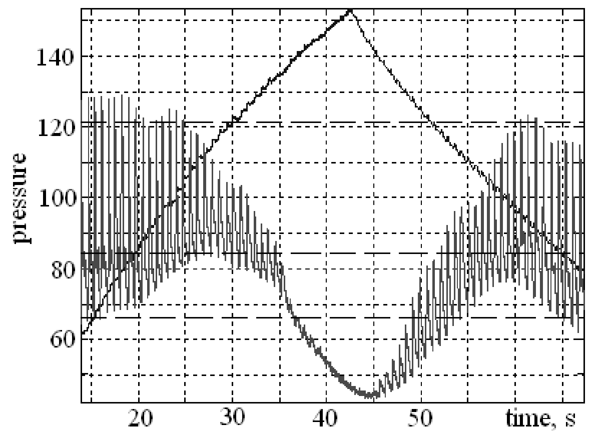

Figure 4: Variation in blood-pressure, monitored on the left wrist while the cuff is on the left upper arm of a young (23 years old) healthy male.

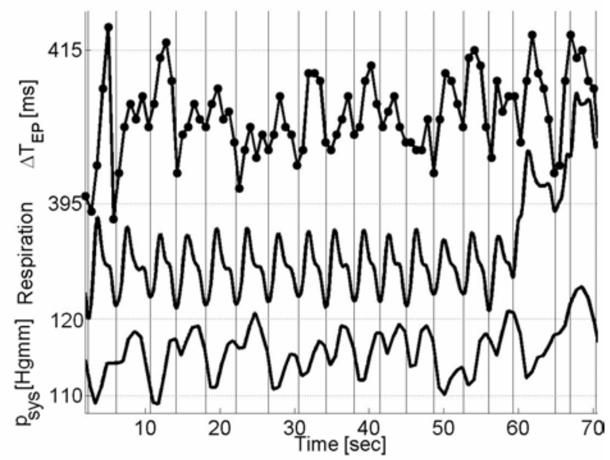

Figure 5: Respiration influences the systolic pressure.

Figure 5 shows the systolic pressure, ΔT_{EP} and the air flow of a senior healthy male during slow inflation. PPG was recorded from the left index finger; the cuff was wrapped around the left upper arm. The systolic pressure is given in Hgmm, ΔT_{EP} in ms and the air flow without scaling. Respiration was normal.

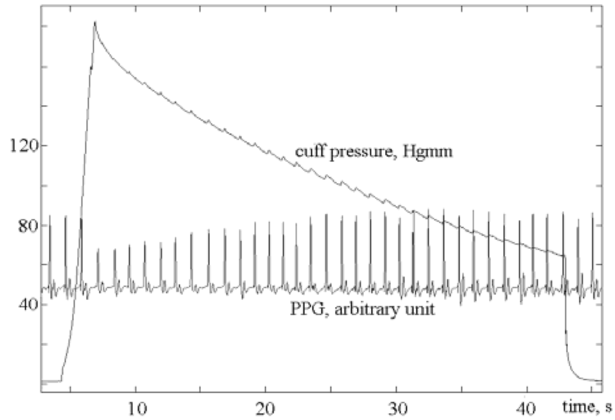

Figure 6: Improperly wrapped up cuff was unable to block pulsation in the arteries distal from the cuff.

Figure 6 was recorded when the cuff of a commercially available indirect blood-pressure meter (OMRON M4) was not properly wrapped around the upper arm. A ruler was placed between the upper arm and the cuff. The cuff was unable to occlude the brachial artery; pulses in the PPG signal are present during the whole measurement.

Discussion

The occlusion of the brachial artery influences the local value of blood-pressure. In other words, *the measurement changes the parameter to be measured.* The change in blood-pressure is different in different parts of the body. The change caused by the inflation of the cuff is different from person to person. Even the same person can react to the occlusion differently.

The widely used devices determine the momentarily value of blood-pressure. This results in an unpredictable error. According to BHS and AAMI the reference blood-pressure value is also determined by using a cuff. As a result of the occlusion the reference value can also be biased. Based on the PPG signal the average systolic and diastolic pressure can be calculated. This requires monitoring the PPG signal – and calculating ΔT_{EP} - before inflation and after deflation.

Breathing influences blood-pressure, especially the systolic value. Good correlation was found between ΔT_{EP} and the air flow. Although ΔT_{EP} is influenced by factors other than blood-pressure, when breathing was synchronised to a pacing signal the correlation was between 0.92 and 0.95. There is a time delay between the air flow – time function and the time function of the systolic pressure. Based on ΔT_{EP} the breathing phases can be estimated and their effect on the systolic pressure can be compensated for. Further details are given in [12].

Pulses in the PPG signal disappear during inflation when cuff pressure exceeds the systolic pressure. While pulsation of the blood-pressure is present ($p_{sys} > p_{cuff}$), it can be detected in the PPG signal. Monitoring the PPG signal helps determine the systolic pressure and makes possible to control the cuff pressure so that it should not exceed the systolic pressure by more than 10 Hgmm. Based on the PPG signal the *proper placement and inflation of the cuff can be checked.* When the cuff pressure is above the arterial pressure, pulsation in the PPG signal should cease. In Figure 6 pulses in the PPG signal are present during the whole measurement process. This indicates that the cuff was unable to occlude the brachial artery. However, based on the amplitudes of the oscillometric pulses the blood pressure meter (OMRON M4) was able to calculate the systolic blood pressure. Resulting from the improper occlusion, the meter displayed both the systolic and diastolic pressure by 15 Hgmm (12 %) above the real value.

Conclusions

Systolic and diastolic pressure values of a person are varying. There are variations of different origin. Presently applied measurement methods determine the momentarily value, this results in a low reproducibilty. It is recommended to calculate the systolic and diastolic blood-pressure values by averaging. The shape of the PPG signal depends also on the systolic and diastolic pressure. Monitoring the PPG signal gives the possibility to determine the average systolic and diastolic value over a time interval.

The effect of breathing can be compensated for by monitoring the PPG signal and calculating the delay between the ECG and PPG signals, ΔT_{EP}.

Occlusion changes the biomechanical properties of the brachial artery. Measurement during slow inflation instead of slow deflation gives more accurate results.

The improperly wrapped or inflated cuff may result in erroneous blood-pressure readings. Based on the analysis of the PPG signal the improper placement or inflation of the cuff can be detected.

Monitoring the PPG signal and calculating ΔT_{EP} during cuff based indirect measurement increases the accuracy without requiring the presence of trained personnel. The PPG and ECG sensors can easily be added to commercially available blood-pressure monitors.

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