Oscillometric blood pressure measurement using constant cuff pressure intervals

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***Abstract*—Oscillometric blood pressure (BP) measurement is a widely used method to assess the state of the cardiovascular system. Fast inflation and slow deflation of the cuff causes a constantly changing excitation for the cardiovascular system. This paper describes an electronic device and a measurement method using a special cuff pressure profile containing constant pressure intervals. Keeping cuff pressure (CP) at constant value can help measure and compensate the reaction of the cardiovascular system to the occlusion. Pulse wave transit time (PWTT), heart rate variability (HRV) as well as the amplitude of the photoplethysmographic (PPG) signal at the fingertip were examined. The device aids home health monitoring, it does not require trained operator.**

Keywords—oscillometry, blood pressure measurement; pulse wave transit time; heart rate variability

I. Introduction

High BP is an important cardiovascular risk factor, if it is left undetected and uncontrolled, it can lead to vascular and cerebrovascular diseases. Elevated BP is also linked causally to kidney failure and dementia. Accurate BP measurement is the basis of optimal diagnosis and treatment of hypertension [1]. Most indirect BP measurement techniques are based on fast inflation and slow deflation of the cuff, typically placed on the left upper arm [2]. The occlusion of the brachial artery caused by the cuff changes the diameter of the artery as well as the strain in the arterial wall. These effects can be considered an excitation, to which the cardiovascular system reacts [3]. This means that the measurement method itself influences the measured quantity. Keeping CP at constant value can help observe the reaction of the cardiovascular system to a constant excitation. Breathing also influences BP [4]. This influence is superimposed on the changes caused by cuff occlusion and if CP is changing constantly, the effect of breathing is difficult to analyze separately. Applying constant CP can also help overcome this problem. Oscillometric BP measurement is a commonly used method to determine systolic and diastolic BP. The method basically estimates the mean arterial pressure, systolic and diastolic pressure are calculated. Arterial stiffness can have great impact on accuracy of the calculated values, thus reliability of the method is questionable for those with cardiovascular diseases [5].

II. Materials and Methods

A. The measurement device

A home health monitoring device (HHMD) was developed at our laboratory more than a decade ago. A novel method for the examination of the state of the cardiovascular system is PWTT, which is the time while the pressure wave generated by the heart propagates from the aortic valve to a peripheral part of the body (typically the fingertip). PWTT can also be used to determine the frequency and the phase of breathing [6]. In order to calculate PWTT, the developed device measures not only CP, but also ECG and PPG signal. In the past 15 years, more than 2000 measurements have been recorded by the device including measurement of patients with cardiovascular disease. Analysis of the measurements has pointed out some weak points of the device and raised the need for the development of a new device. The HHMD used reflection type PPG sensors without fixation of the sensor to the measured finger. As a result of motion artifacts, signal-to-noise ratio of the PPG signal was not sufficient in several measurements, making the calculation of PWTT inaccurate. The new device contains a transmission type PPG sensor that is fixed to the measured finger. The HHMD used ECG electrodes integrated into the housing of the device, the tested person had to place their palms onto the housing. As a result, size of the housing in the longest dimension exceeded 45 cm, making the device hardly portable. The new device uses conventional limb electrodes connected to the device by wires, enabling a housing with portable size (26 cm in the longest dimension). Both HHMD and the new device measure ECG in Einthoven I lead. The sampling frequency is 1 ksample/s for both devices. The HHMD used a single controllable one-way valve for fast deflation of the cuff and a constriction element for slow deflation. The device was not able to keep CP at constant value. In addition to the one-way valve and the constriction element, the new device also contains a two-way valve. The one-way valve and the constriction element are connected in parallel and to them, the two-way valve is serially connected. Thus, when the two-way valve is closed, CP can be kept at constant value. The new device with transmission type PPG sensor, limb electrodes connected by wire, two valves and reduced size is more appropriate for the planned measurements than the original device; it is portable and can be used without special training. Figure 1 shows a picture of the developed device.

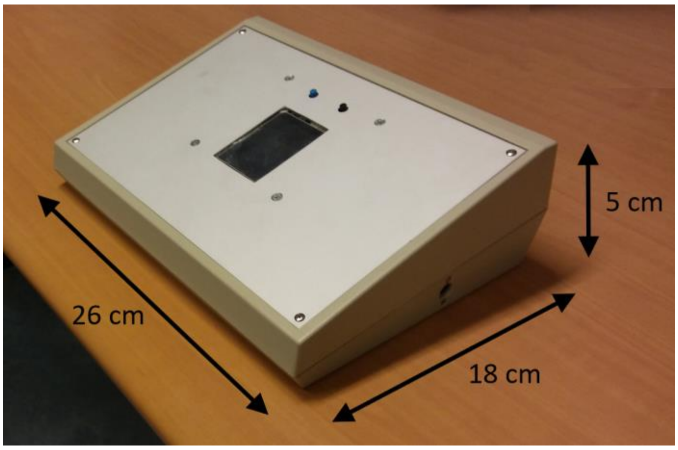

Fig. 1. The developed measurement device and its dimensions.

B. Tested Persons

Ten healthy test subjects volunteered for the study, two seniors (age between 66 - 67 years), four middle aged persons (age between 39 - 57 years) and four young adults (age between 22 - 26 years), male:female ratio was 6:4.

C. Measurement protocol

During the measurement, tested persons were sitting at rest in a silent room with 25°C temperature. In the first 24 s of the measurement, only ECG and PPG signals were recorded, the cuff was not inflated. After 24 s, inflation started with approximately 6 mmHg/s speed, until 150 mmHg was reached. At 150 mmHg, inflation stopped and deflation started immediately, approximately with the same speed as inflation. Then, deflation stopped at CP = 90 mmHg for 1 minute and at 60 mmHg for 1 minute. When 40 mmHg was reached during deflation, CP changed abruptly to 0 mmHg. After complete deflation, only ECG and PPG signals were recorded for further 24 s, then the measurement ended. Cuff pressure as a function of time during the measurement is shown in Figure 2.

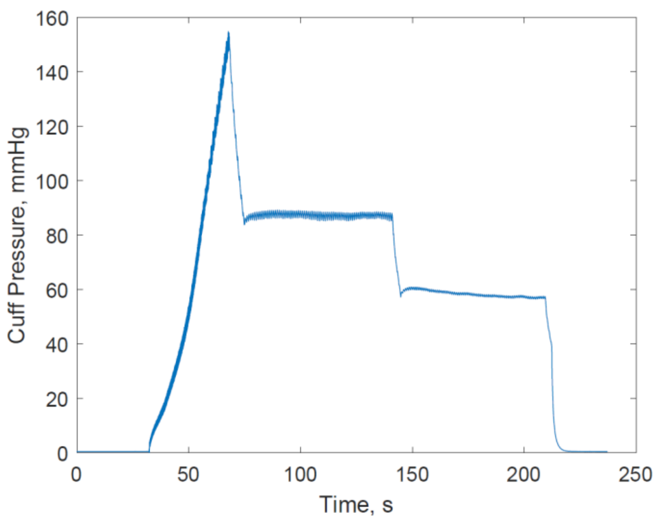

Fig. 2. Cuff pressure as a function of time during the measurement.

III. Data Analysis

A. Improving signal-to-noise ratio

ECG, and PPG signals are likely to be distorted by motion artifacts and electrical noise of the measurement device and the measurement environment. Therefore, the signals have to be filtered. However, distortion caused by filtering must be minimized in frequency ranges corresponding to physiological processes of interest. We filtered the ECG and PPG signals using band-pass filters with cutoff frequencies, conventionally used for ECG and PPG filtering. In case of the CP signal, recorded by our device, spectral energy is concentrated below 8 Hz. We used a low-pass filter with cutoff frequency at 8 Hz. Table I shows cutoff frequencies of the applied filters.

Using the CP signal, the time of the propagation of the pulse wave from the heart to the cuff can also be determined. A widely used method for the examination of oscillometric pulses is to use a high-pass filter [7]. For the detection of onset points of signals in general, zero crossing points of the first derivative are commonly used. High-pass filtering however, works as differentiation, therefore we recommend detrending of CP without high-pass filtering, before taking the first derivative. As inflation and deflation speed is not perfectly constant, the method we used performed detrending for each heart cycle separately based on local minima in CP.

TABLE I. Cutoff Frequencies of the Applied Filters

Signal	Lower cutoff frequency (Hz)	Upper cutoff frequency (Hz)
ECG	6	16
PPG	0.5	10
CP	-	8

B. PWTT calculation

PWTT was calculated using ECG and PPG signals from the heart to the fingertip, therefore we denote it by PWTTHF. We calculated PWTTHF as the time difference between the R-peak in ECG and the local minimum in the PPG signal, corresponding to the same heart cycle. PWTTHF defined this way is thus the sum of the cardiac pre-ejection period (PEP), that is the period of isovolumetric ventricular contraction, and the vessel transit time [8]. Ahlstrom et al. [8] and Wong et al. [9] pointed out that PEP is an important contributor to the correlation between PWTT and BP, and the inclusion of PEP in PWTT increases the accuracy of BP estimation and respiration monitoring. Detection of the arrival of the pulse wave to the cuff makes it possible to cut PWTTHF into two parts, the propagation time from the heart to the cuff (PWTTHC) and from the cuff to the fingertip (PWTTCF). Mean values of the PWTTHF, PWTTHC and PWTTCF parameters can be calculated for time intervals with constant CP. Denoting the mean PWTTHC value while CP equals 90 mmHg as PWTTHC_90 and the mean PWTTHC value while CP equals 60 mmHg as PWTTHC_60, ratio of these mean values can be defined. PWTTHC_90_60 is defined as in (1).

$$PWTTHC\_90\_60 = PWTTHC\_90 / PWTTHC\_60 \quad (1)$$

For PWTTHF and PWTTCF, similar ratios can be defined. These ratios can help quantify the change of PWTT as a result of the change in CP.

C. *Assessment of the change in the PPG signal amplitude*

Amplitude of the PPG signal also depends on the blood flow rate into the body part where the PPG sensor is placed. This rate is influenced by cuff occlusion, when the cuff CP exceeds diastolic BP, the artery is closed during a certain part of the cardiac cycle. When the occlusion is eliminated, the blood flow rate in body parts distal to the occluded region increases and exceeds the flow rate that was present before occlusion was applied. This phenomenon is called reactive hyperemia [3]. Increase of blood flow rate during reactive hyperemia is impaired in patients with cardiac risk factors [10]. Denoting the mean PPG amplitude while CP equals 90 mmHg as PPG_90, and mean PPG amplitude while CP equals 60 mmHg as PPG_60, ratio of these mean values can be defined. PPG_90_60 is defined as in (2).

$$PPG\_90\_60 = PPG\_90 / PPG\_60 \tag{2}$$

The defined ratio can help quantify the change in the blood flow rate arriving to the index finger as a result of the occlusion and elimination of the occlusion of the brachial artery.

D. *Effect of breathing*

Breathing influences BP and PWTT. Systolic pressure decreases during normal inspiration while PWTT increases. The effect of breathing makes the analysis of the dependence of PWTT on CP difficult. Burdened by this distortion, PWTT cannot be interpreted as patient specific diagnostic information, therefore, compensation of this effect is necessary. Respiratory oscillations are present in the ECG and the PPG as amplitude variations as well as frequency variations (Respiratory Sinus Arrhythmia) [6]. Breathing can be estimated based on ECG and PPG [6], [11].

E. *Stress level estimation*

Stress level of the tested person also influences BP. HRV is a recommended measure to determine momentary stress level. HRV characterizes the variation of the beat-to-beat time intervals [12]. In the frequency domain, dominant bands of HRV range from 3.3 mHz to 0.4 Hz. Some sources define a frequency band even below 3.3 mHz. Analysis of the lowest frequency band needs a resolution of at least 2 mHz, requiring a minimum 500-s long recording, during which HRV cannot be considered constant. For short time recordings, time domain analysis is required to characterize HRV. Here, usually the length of heart cycles (NN) is examined. pNN50 is a widely used parameter, it characterizes the differences in successive NN intervals. pNN50 is the ratio of differences exceeding 50 ms to the total number of differences [13]. We also calculated pNN0_20 and pNN20_50, which are the ratios of differences between 0 and 20 ms as well as 20 and 50 ms to the total number of differences, respectively [13]. The CP(t) protocol with 60-s constant pressure values makes a good estimation of the tested person's stress level possible. For the time interval where CP is equal to 90 mmHg the following notations are used: pNN0_20_90mmHg, pNN20_50_90mmHg, pNN50_90mmHg. For the time interval, where CP was equal to 60 mmHg the notation is similar.

IV. RESULTS

Changes of the PWTTHF, PWTTHC and PWTTCF values as a result of cuff occlusion are person specific, but not age-group specific. However, PPG amplitude exhibited a larger change as a result of changes in CP for healthy young persons than for healthy middle aged and senior individuals. Figure 3 shows the PPG signal as a function of time during the measurement for a healthy young adult (upper trace) and a healthy senior (lower trace). Figure 4 shows the values of the PWTTHC_90_60 and PPG_90_60 parameters for each tested person. It can be seen that healthy young adults can be separated from healthy middle aged and senior individuals based on PPG_90_60 values but not on PWTTHC_90_60 values.

For pNN parameters, neither mean values, nor ratio of mean values corresponding to intervals with constant CP are age-group specific. Figure 5 shows the values of the pNN50_60mmHg and pNN50_90mmHg parameters for each tested person. Separation of groups based on these parameters is not possible.

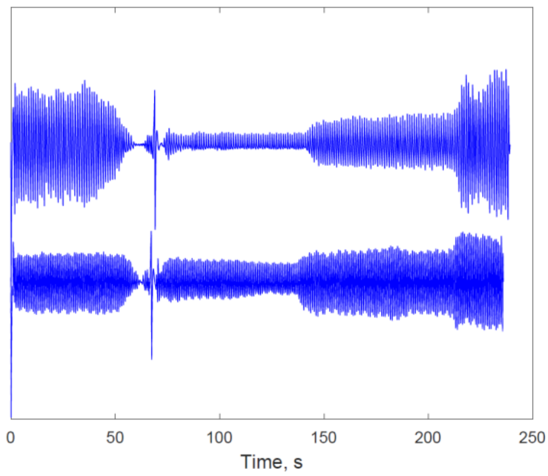

Fig. 3. PPG signal as a function of time during the measurement for a healthy young adult (upper signal) and for a healthy senior (lower signal).

V. DISCUSSION

The extent of the change in PPG amplitudes as a result of decreased CP from 90 mmHg to 60 mmHg was found to be larger for young adults than for middle aged and senior individuals. It can be supposed that this result indicates age related increase in the rigidity of arteries. However, it is difficult to determine whether the used PPG_90_60 parameter characterizes mainly the state of the brachial artery, or the microvascular system in the fingertip. The fact that the change in PWTTHF, PWTTHC and PWTTCF as a result of decreased CP from 90 mmHg to 60 mmHg do not correlate well with the PPG_90_60 parameter suggests that impaired vascular function during reactive hyperemia does not necessarily imply increased PWTT from the heart to the cuff or from the cuff to the fingertip.

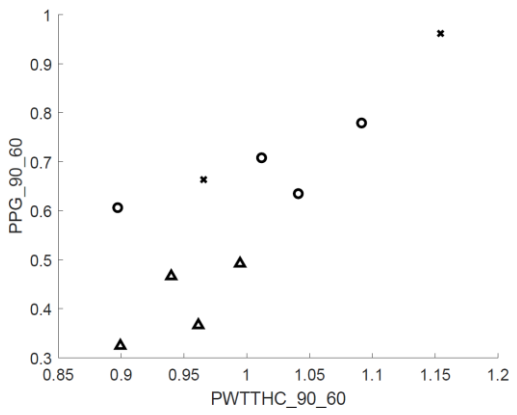

Fig. 4. PWTTHC_90_60 and PPG_90_60 parameters for each tested person. x: healthy seniors, o: healthy middle aged persons, Δ: healthy young adults.

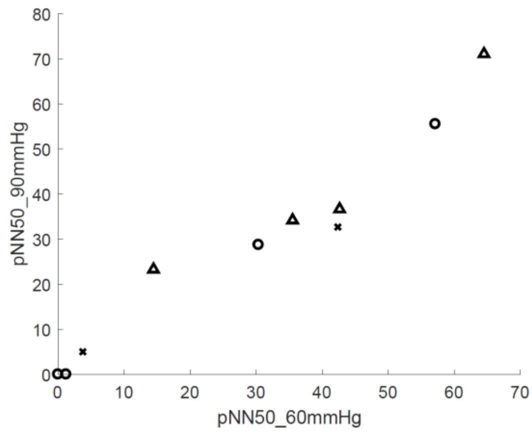

Fig. 5. pNN50_60mmHg and pNN50_90mmHg parameters for each tested person. x: healthy seniors, o: healthy middle aged persons, Δ: healthy young adults.

For the pNN50 parameter, decreased CP from 90 mmHg to 60 mmHg resulted in increased value of the parameter in case of 3 persons, decreased value in case of 6 persons and no change for 1 person. For pNN0_20 and pNN20_50 the direction of change as a result of decreased CP from 90 mmHg to 60 mmHg was also not the same for all persons. This result suggests, that the measured stress level of tested persons changed differently. This is in accordance with our previous experiences: a given stimulus can increase stress level of one individual while the same stimulus decreases stress level of another individual in the same experiment.

VI. Conclusion

Continuous change of CP during oscillometric BP measurement affects accuracy of the assessment of the state of the cardiovascular system in several ways. In this paper we described a BP measurement device that stops cuff deflation at 90 mmHg and 60 mmHg CP and records ECG, PPG and CP signals. We introduced parameters that characterize changes in PWTT, HRV and PPG amplitude values as a result of change in CP. Age-group specific differences were found only for the change in the PPG amplitude. This article presents that using ECG, PPG and CP, doctors can be provided with more information about the patient, than using conventional BP measurement. However, the measurement series, needed to evaluate this extra information has not been carried out yet. For the explanation of the observed phenomena and validation of preliminary results, we aim to organize a new measurement series with more participants in hospitals. BP measurement using the suggested CP(t) protocol not only gives a good estimate of systolic and diastolic pressures but also provides information on the rigidity of arteries. The device we have developed is meant for home health monitoring helping personalized health care.

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