AN IMPROVED OSCILLOMETRIC METHOD

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I. Introduction

The home health monitoring device (HHMD) built at our department stores some physiological signals, like ECG and photoplethysmographic (PPG) signals of the patient. The records can be used for later medical analysis and research. The currently running research is focused on accurate non-invasive blood pressure measurement and on characterization of blood vessel properties. In this paper, the second area is outlined, while the first one is discussed in detail. After clarifying the main concept of the wide-spread oscillometric blood pressure measurement method (OBPM), the efficiency of the recently developed technique is demonstrated through the evaluation of a HHMD record.

II. Materials and Methods

To perform a standard measurement with the HHMD, the patient only has to fix a cuff on the left upper arm, press a button and put the hands on ergonomic designed platform. The Einthoven I. lead ECG signal is captured by means of the electrodes under the palms. (Optionally, the Einthoven II. lead ECG can be recorded using an extra electrode applied on the patients left leg). The index fingers rest upon PPG sensors. The pulsation in the PPG signal gives information about the volume changes of the vessels. For the left hand (which is occluded by the cuff during the measurement), two PPG signals are recorded, where the wavelength of the excitation light is different. Since the two signals are calibrated, the measurement of blood oxygen saturation is possible. The DC components of the left PPGs are also recorded. These deliver information about the changes of the *total* blood volume in the capillary vessels (arterioles and venules) of the fingertip. Naturally, the cuff pressure (CP) is also recorded. All these signals are sampled with 1 kHz.

The measurement process is fully automated. In the first 25 seconds, the ECG and PPG signals are recorded with deflated cuff. This makes the investigation of the physiological signals possible, while the patient is in rest. Optionally, it can be checked, whether the cardiovascular system is in steady-state, or some transient (caused e.g. by physical stress) is decaying [1].

After the rest phase, begins the inflation of the cuff. In case of the OBPM, the better accuracy can be achieved, the slower is the CP change. The applied approximately 6 mmHg/sec. is a compromise, which can be accepted by the users. The maximal CP depends on the patient's blood pressure, which is measured on-line. A maximal upper limit can be configured. Although the slow deflation phase is not strictly required by our algorithms, it is kept as a source of redundancy. After deflation, another 20 seconds of rest-state is recorded.

Currently, only a basic oscillometric algorithm is implemented. The results (calculated systolic and diastolic blood pressure) are indicated (spoken and displayed) at the end of measurement. Regarding the research, it is more important, that all of the recorded signals are stored on an MMC card for post-processing.

By means of a PC application, the records can be 'replayed'. This serves for testing and improving the algorithms, implemented in the HHMD. The thorough analysis of the signals and the development of further algorithms are aided by a user-friendly, easily extendable framework, written in MATLAB.

For the validation of the implemented oscillometric method, we have made measurements with a commercial oscillometric blood pressure meter (OMRON MX3) subsequent to the application of the HHMD. In a few cases, parallel measurements with a tonometer (COLIN CBM 7000) have been taken.

III. The Oscillometric Blood Pressure Measurement

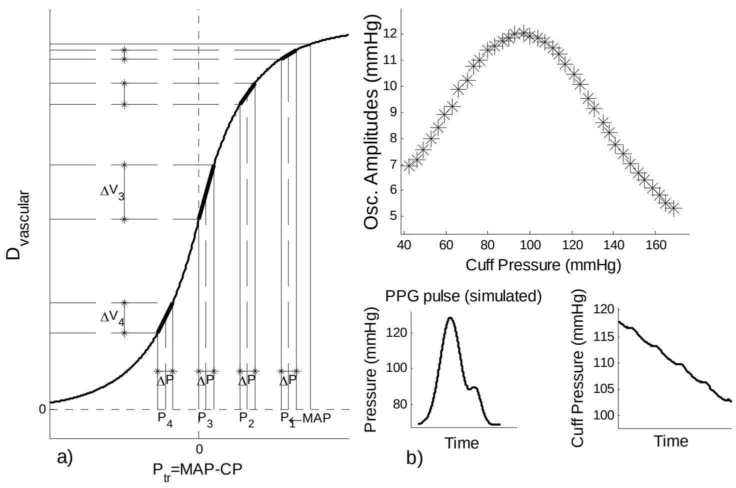

Figure 1: The principle of the OBPM

The principle of the OBPM is illustrated in Figure 1. The model of the vascular wall is simplified to the highest degree. Fig. 1/a shows the diameter changes of the brachial artery as a function of transmural pressure. It can be seen, that the volume pulsation caused by pressure waves ($C=\Delta V/\Delta P$ - Compliance) is maximal, if the external pressure, i.e. CP equals to mean arterial pressure (MAP). Thus, the pressure oscillation in the cuff (oscillometric amplitude - OA) is also maximal, if the volume-pressure characteristic of the cuff is assumed to be linear. This implies that the MAP can be detected as the maximum of OA values (Fig. 1/b.). However, systolic and diastolic (SYS, DIA) pressure can only be calculated. In most cases, they are assigned to CP values, where OA reaches $k_{sys} \cdot OA(MAP)$ and $k_{dia} \cdot OA(MAP)$, respectively. The parameters are determined with statistical methods. They are not well defined: most of the device manufacturers are using different values [3]. Some special properties of the vessel walls (e.g. collapse tendency) can cause slight changes in OA, when CP is near to SYS or DIA. The so called derivative OBPM is based on this phenomenon [5].

The algorithm implemented in the HHMD is presented in Figure 2. The detection of the oscillometric pulses is demonstrated in the right upper corner of Fig. 2. Since the ECG signal is recorded, the QRS detection is a great help for the segmentation of the CP signal (dotted line). After the subtraction of the pressure trend (dashed line) for each heart cycle, the OAs are easy to calculate. After the MAP is detected, two straight lines are fitted (with LS fit) on the OA points to estimate SYS and DIA. These are assigned to the CP values, where the fitted lines pass the SYS and DIA threshold levels. The parameters, used for the threshold calculation: k_{sys}=0.7, k_{dia}=0.6. The measured and estimated pressure values for the presented record:
DIA / MAP / SYS: 86/118/133 (mmHg).

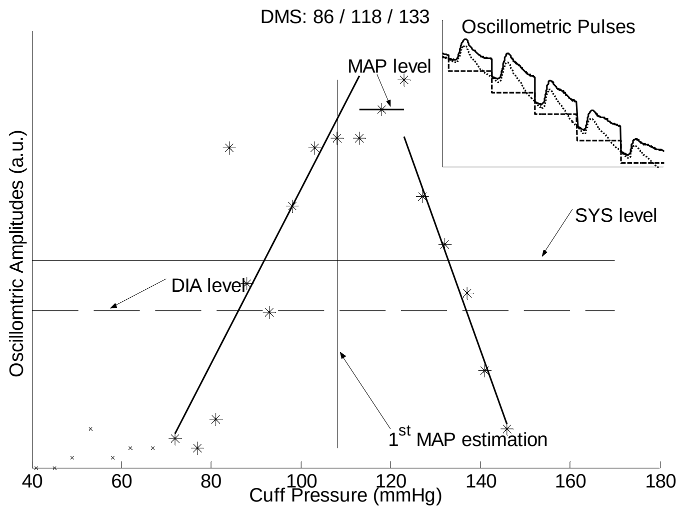

Figure 2: The implemented OBPM, running on a HHMD record.

IV. Improvement of the Method

The difference between the ideal (Fig. 1/b) and the real (Fig 2) CP-OA characteristics is conspicuous. This is only partly caused by measurement noise. The ‘physiological noise’ has an important role: the blood pressure is changing beat to beat (e.g. because of the respiration).

The techniques, presented below, have the following objectives:

- Eliminating the effect of respiration, getting coherent DIA, MAP and SYS values.
- Estimating the continuous blood pressure signal, calculating the blood pressure variance
- Validating and customizing the parameters k_{sys} and k_{dia} for the OBPM.

A. Examining the correlation of the PPG and CP signals

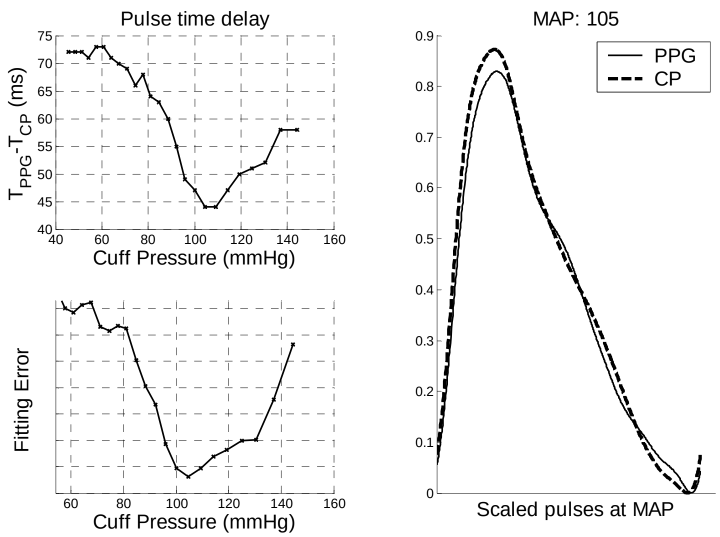

Figure 3: Correlation of CP and PPG signals

We assume, that the D-P (Fig. 1/a) function of the capillary vessels between systolic and diastolic pressure is nearly linear. If the pressure transfer between macro- and microcirculation is also considered to be linear, the PPG signal can be regarded as a rescaled pressure signal. Thus the effects, modulating blood pressure, are modulating the PPG as well. Besides, based on Fig 1/a, it is assumed, that regarding to linearity and augmentation, the blood pressure - cuff oscillation transfer is the better, the smaller is the transmural pressure. This means, that if CP=MAP, the D-P characteristic of the brachial artery is linear with maximal slope. Therefore, the pressure pulses are transferred to the cuff with maximal amplitude and with minimal shape distortion. The measured oscillation pulses and the PPG pulses, recorded from the fingertip of the free (not occluded) arm, are nearly identical, apart from a scaling factor. Practically, after an appropriate rescaling, the distance of the two signals can be calculated for each beat. The algorithm has the following steps:

- Detection of pulse upstrokes, beat to beat segmentation
- Getting the pulsatile components of the signals: $PPG^{\sim}$,$CP^{\sim}$
- Calculation of pulse amplitudes for each beat. ($PPG^{\wedge}(k)$, and $CP^{\wedge}(k)$ for beat k)
- Calculation of fitting error. N(k) stands for the length of beat k (in samples), $PPG^{\sim}(k,p)$ and $CP^{\sim}$ (k,p) for point p in the beat k, on the $PPG^{\sim}$ and $CP^{\sim}$ signals, respectively.

$$FE(k) = \sqrt{\frac{1}{N(k)} \cdot \sum_{p=1}^{N(k)} \left(\frac{CP^{\sim}(k,p)}{\max(CP^{\wedge})} - \frac{PPG^{\sim}(k,p)}{\max(PPG^{\wedge})} \right)^2}$$

The minimum of the error function indicates the MAP. Moreover, there are significant changes at DIA and SYS, coming up to our expectation. (If the CP is between SYS and DIA, complete pressure pulses are transferred to cuff pulses, therefore, FE is smaller than in other cases). The main advantage relative to standard oscillometric method is the compensation of the effects, modulating the blood pressure. The result of the described correlation check is illustrated in Figure 3. (DIA, MAP, SYS: 81,105,131 mmHg, respectively). The error function and the delay between the coherent

PPG and pressure pulses is plotted on the left side. The right side shows the normalized pulses at CP=MAP.

B. Continuous Blood Pressure Measurement

As described in section IV.A, the PPG signal can be considered as an uncalibrated pressure signal. Knowing at least two momentary pressure values (DIA, MAP or SYS), the PPG signal can be rescaled. For this, a reference PPG beat is needed, which is obtained as the average of a few subsequent beats, practically of those, which have been recorded, during the reference pressures have been measured. The averaging helps decreasing the effect of blood pressure modulation.

The result of a PPG rescaling is remarkable. While the calibration has been done by means of SYS and DIA values, the MAP calculated from the scaled PPG equals to the MAP obtained in IV.A. This means, that the assumption about linear pressure-PPG pulse transfer is admissible.

By means of the short term continuous blood pressure signal, the statistical parameters of the blood pressure can be investigated.

V. Results and Future Plans

Ten prototypes of HHMD have been assembled and they are ready for everyday application. Beyond the methods discussed above, there are several other techniques aiding accurate blood pressure measurement at home [1]. Using these together, the customization of the standard OBPM is possible. Moreover, extra information about the patient can be obtained. The statistical properties of the blood pressure, the validated parameters of the OBPM are not less important for the characterization of the vessels state. At this field, the investigation of the pulse wave shape can be a further step. Another aim is the non-invasive measurement of the compliance function for the brachial artery [5]. Since the HHMD is ready for use, measurements with participation of patients suffering from cardiovascular diseases can be done. Thanks to the cooperation with other researchers in the field, the new measurement techniques can be validated by means of a physical model of the human arterial system [2].

Acknowledgement

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