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RESEARCH ARTICLE

Advanced indirect method for measuring blood pressure

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Abstract

Presently existing blood pressure meters require trained operator otherwise do not assure accurate measurement. An easy-to-use and accurate device would help the early detection of hypertonia as well as self-monitoring at home. This latter would mean an effective aid for the general practitioner to monitor the patient; providing a feedback for treatment and medication. The paper presents the results of the research work having been carried out for an indirect blood pressure measurement procedure in the Biomedical Engineering Laboratory of the Department of Measurement and Information Systems, Budapest University of Technology and Economics. The procedure improves the classical oscillometric algorithm and identifies improperly placed cuff. It was incorporated into eight home health monitoring devices that were used for three months by patients with cardiovascular diseases. More than 1000 recordings of patients and more than 500 of healthy control subjects have been analyzed. The presented algorithm has been validated by means of a non-invasive blood pressure meter tester. The bulk of the 100 tester records we have made simulates some kind of artifact or cardiovascular disease.

Keywords

blood pressure measurement · home health monitoring

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1 Introduction

Many cardiovascular diseases remain undetected until the symptoms are stressed. In Hungary hypertonia and arteriosclerosis affect a high percentage of the population. It is estimated that 30% of the Hungarian population has hypertonia, over age 65 this ratio increases to approximately 65%.

Blood pressure is an important physiological parameter [6],[11]. A single measurement does not give enough information to qualify the blood pressure of a person, usually not even to determine whether or not it is in the normal range. Blood pressure is varying during the day, 20...30 mmHg differences are not uncommon even for healthy subjects. The white-coat effect is also well known. Many people have increased blood pressure 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 increases the willingness of a person to be involved in the health keeping process. Inaccurate or low reproducibility meters prevent subjects from being motivated and the measurement results do not help the medical treatment. Consequently, ***it is essential to provide accurate blood pressure meters for self-monitoring***.

Numerous non-invasive blood pressure measurement methods are known. A good summary is given for example in [14]. However, in most cases these methods either require an expensive hardware or they are not robust enough. From this point of view, the oscillometric method has excellent performance. Thus, it is widespread and most of the innovations are connected to it (e.g. [7]).

Though systolic and diastolic values may vary as high as 5 mmHg between two consecutive heartbeats, the present definition of blood pressure implies that momentary value is measured. Even if the measured momentary value is accurate, there is no possibility to express the short-term variability. Should there be any physical or psychological impact influencing blood pressure (most frequently the tested person is not at rest); present day devices are unable to detect it. We analyzed more than 1500 recordings (cuff pressure, ECG and photoplethysmographic signal at the fingertip) taken from patients and healthy subjects.

2 The oscillometric method

2.1 The classical oscillometric algorithm

The oscillometric method is based on the observation first published by E-J. Marey in 1860. He observed that the amplitude of oscillation in cuff pressure (CP) increases up to a maximum and then decreases at a slower rate when the cuff pressure is decreased from above systolic to below diastolic pressure. The majority of present-day cuff-based (semi-)automatic blood pressure meters utilize this observation. The oscillometric method requires neither extra sensor nor operator expertise to detect the equality of the cuff pressure to different levels of arterial pressure (systolic, diastolic, and mean). ***The primary measured parameter is the arterial mean pressure*** (MAP) indicated by the maximal oscillometric amplitude [5]. Fig. 1 shows oscillometric changes in upper arm cuff pressure during slow inflation and deflation. The intra arterial pressure has been measured simultaneously by means of an invasive catheter. This has been placed in the arteria femoralis of the lying patient. The diastolic, mean and systolic pressure is depicted together with the cuff signal (upper subfigure). The cuff pressure trend has been filtered out by moving window averaging (lower subfigure, dashed line). After beat detection, the remaining baseline shift can be compensated (lower subfigure, solid line).

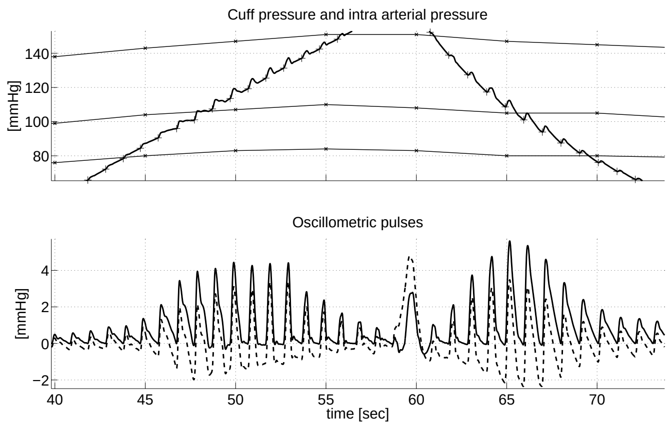

Fig. 1. Cuff pressure, SYS, MAP and DIA measured invasively (top) and oscillometric pulses (bottom) during slow inflation and deflation.

Systolic (SYS) and diastolic (DIA) pressure values are calculated based mainly on the amplitudes of pressure oscillations. The ratio of amplitudes (SM = systolic/mean, DM = diastolic/mean) were first determined by supposing average values for physiological parameters. When the cuff is on the upper arm, SM = 0.4 ... 0.6 and DM = 0.70 ... 0.85 are reported. [4] gives a theoretical analysis and suggests a model for arterial mechanics. The model yields the following values: SM = 0.593, DM = 0.717, so that SM and DM show little variation over the normal range of blood pressure. However, at high values of systolic pressure SM should be lowered and at low values of diastolic pressure DM should be lowered. [15] analyzes different physiological parameters that affect SM and DM.

Our detailed analysis of cuff pressure-time functions revealed that ***the value of SM and DM may vary from measurement to measurement even for the same person tested at rest!*** The actual values of these parameters are unknown during an oscillometric blood pressure measurement. Consequently, the oscillometric blood pressure meters give only an estimate for the arterial systolic and diastolic pressures. The difference in two adjacent oscillation amplitudes in cuff pressure during deflation can also be used to determine systolic and diastolic pressure. The method is called derivative oscillometry [5]; its accuracy is about the same as that of conventional oscillometry.

New oscillometric blood pressure meters take into account not only the amplitude but also the shape of oscillometric pulses. Shape evaluation substantially decreases the ratio of results with unacceptable (> 15%) error.

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.

2.2 Improving the oscillometric algorithm

There are basically two reasons why the oscillometric algorithm can result in a wrong estimate for the tested person. (1) The maximal oscillometric amplitude does not occur at the arterial mean pressure. (2) The rate of change in oscillometric amplitudes deviates from usual. Furthermore, artifacts can cause significant changes in the oscillometric amplitude values. The compensation or the elimination of them is one of the most complex problems to solve. We have developed, implemented and tested a new oscillometric algorithm. Our most important suggestions are presented below.

We have found that ***determining the maximal slope instead of the maximal amplitude of the oscillometric pulses gives better estimate for SYS and DIA.*** The main reason is the more accurate detection of the MAP. The idea is to determine the cuff pressure value, at which the tension on the vessel wall (transmural pressure) under the cuff is minimal, thus its compliance (C) is maximal. The realization of this principle is based on the following approximation.

$$C_i \approx \frac{\Delta V}{\Delta P} \approx \max \frac{\delta V}{\delta P} \tag{1}$$

C_i is the estimated compliance for the i-th beat. In every beat the pulse volume (ΔV) and its first derivative (δV) are determined by measuring cuff pressure, while the changes in pressure pulse (and thus ΔP and δP) are considered to be constant. The dilation of the artery under the cuff ΔV causes the oscillometric pulses. Thus, it will be registered as a pressure change. At first, we can assume that C_{cuff} is constant in the relevant cuff-pressure interval. For detailed discussion, see section 3).

Fig. 2 illustrates that determining max. δV instead of maximal amplitude can give a better estimate for the MAP. Fig. 2 belongs to the inflation-part of the record shown in Fig. 1. The moments, when CP=MAP, DIA, SYS are determined and marked.

Another important idea is that ***the measurement can be done during the inflation of the cuff***. The only drawback is that the

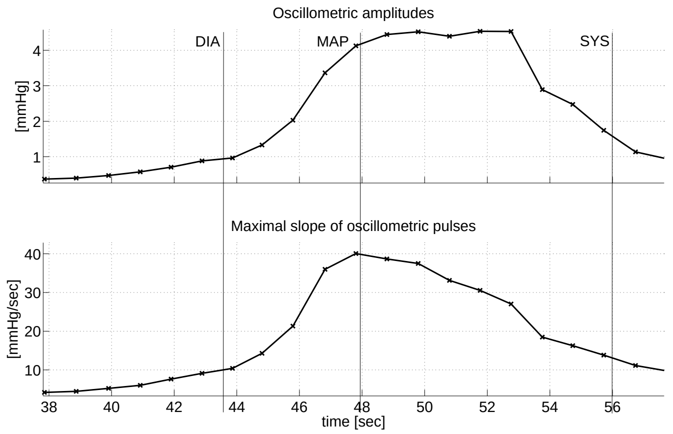

Fig. 2. The maximal oscillometric amplitude is not necessarily at arterial mean pressure

pump causes noise in the cuff signal. However, it can be easily eliminated, because the frequency components of the noise and the signal are not overlapping. Measuring during inflation instead of deflation has numerous benefits.

- The cuff-based measurement itself means an intervention to the patient's circulation and it may increase the stress level. Thus, the process should be as short as possible. This way, the blood pressure to measure is less influenced and the patient feels more comfortable. If measurement is completed during inflation then the maximum cuff pressure can be as low as possible.
- A further advantage is that applying a real-time algorithm, the inflation speed can be set adaptively. For example, if the heart rate is extremely low, or arrhythmias are detected, the inflation should be slowed down, in order to record sufficient number of normal beats. In case of artefacts of external origin, the inflation can be terminated. Thus, the number or at least the duration of unsuccessful measurements can be decreased.
- Measuring the pulse rate, and computing the heart rate variability (HRV) or tracking the oscillometric amplitudes at a given cuff pressure level gives the possibility of characterizing, whether the patient is at rest. If the answer is no, an automatic blood pressure meter should indicate, that the measured value is not representative for the patient.

When applying classical (non-derivative) oscillometry for the estimation of SYS and DIA, the appropriate choice of SM and DM is crucial. We have validated our new algorithm by means of a Biotek BP-PUMP NIBP tester [2]. SM and DM – applied for the maximal slope of oscillometric pulses – could be determined. Based on that, the mean error (considering all records generated by the tester) was 0.02 mmHg for DIA and 0.9 mmHg for SYS. Examining the maximal errors, we have found that according to the British Hypertension Society (BHS) classification standard [13], our algorithm satisfies classification Grade A. Nevertheless, we have found some records (taken from real patients), where our algorithm had pour performance. The solution of this problem is ***the personalization of SM and DM***.

Fig. 3 shows oscillometric and photoplethysmographic (PPG) pulses vs. time, and the maximal slope for every beat (as a function of cuff pressure during inflation) of a senior male subject. The PPG was recorded from the left index finger, while the arm was occluded by the cuff. As the pressure increases over DIA, the PPG slope decreases. Measuring the maximal slope of oscillometric pulses simultaneously, DM can be determined.

Using our presently available devices, recording suitable PPG signal needs extra effort [1]. If the sensor is applied over an artery (e.g. over the a. radialis) instead of the fingertip, the macro-circulation can be examined. In this case, the signal is more stable: we have found that it can even be scaled, and considered as a continuous blood pressure signal. However, the registration is even more complicated and it needs an expert. Finally, we have concluded that at the present technical stage, PPG can be used for every-day measurements with reservations, but it is highly applicable for calibration of other (robust) methods, like oscillometry.

This calibration or personalization is extremely useful. The record depicted in Fig. 4 was taken from the same person, as the one in Fig. 3, but three years earlier. (It can be seen, that in this case the blood pressure was strongly modulated by breathing.) We have found that calculating with the same DM for both records gives an acceptable result, while using the general DM optimized for NIBP tester records would mean approx. 10 mmHg underestimation of DIA. This is remarkable, considering that nowadays NIBP testers are spreading as acknowledged devices for oscillometric blood pressure meter validation. We can conclude that a "general" DM can be used for many patients, but not for all.

Personalization takes into account not only the individuality of the patient, but also the actual parameters of the measuring system, above all the characteristics of the cuff used.

3 The effect of the cuff

In indirect BP measurement it is important to use an appropriate cuff (the size should correspond with the arm circumference of the individual patient) affixed tightly [12]. These requirements would be easy to fulfill when the measurement is done by trained medical personnel although even they can forget about it [9]. Automatic blood pressure monitors are mostly used by the patients themselves. This brings on problems usually overlooked.

3.1 Types and placement of cuffs

A cuff is applied properly when wrapped around the arm tightly. However, in home health monitoring users often improperly place the cuff (miscuffing) [3]. Diverse modes of affixation are possible from a loosely wrapped cuff to putting on the bladder up-side down or over a shirtsleeve.

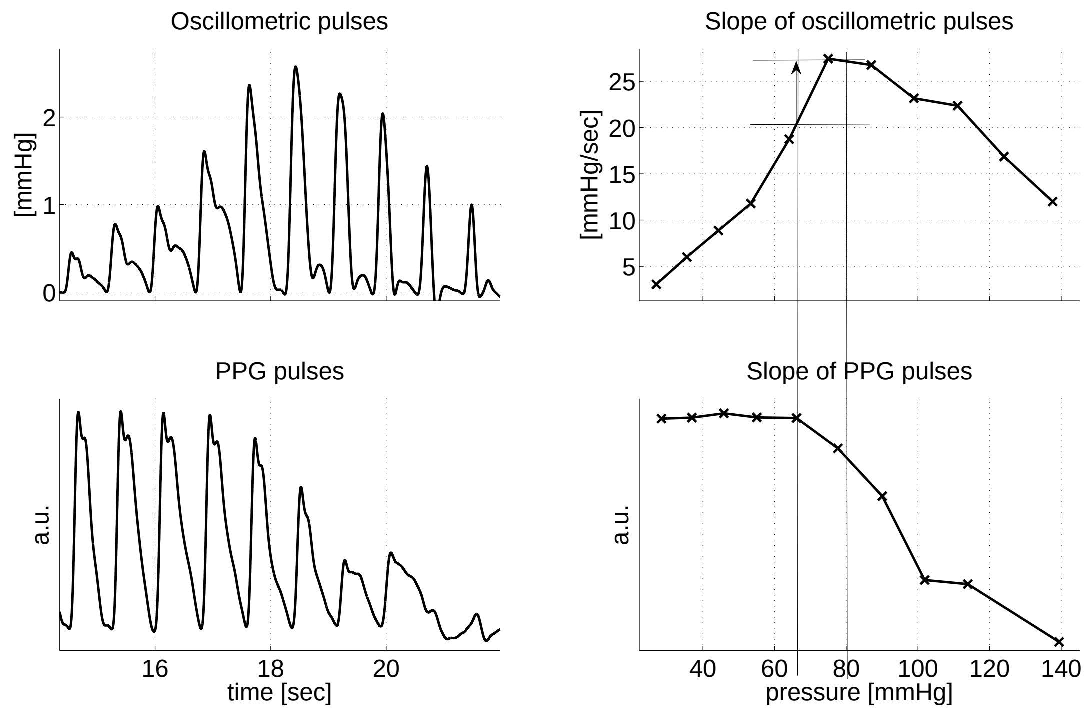

Fig. 3. Slope of oscillometric and PPG pulses during slow inflation recorded from S1 subject in 2008.

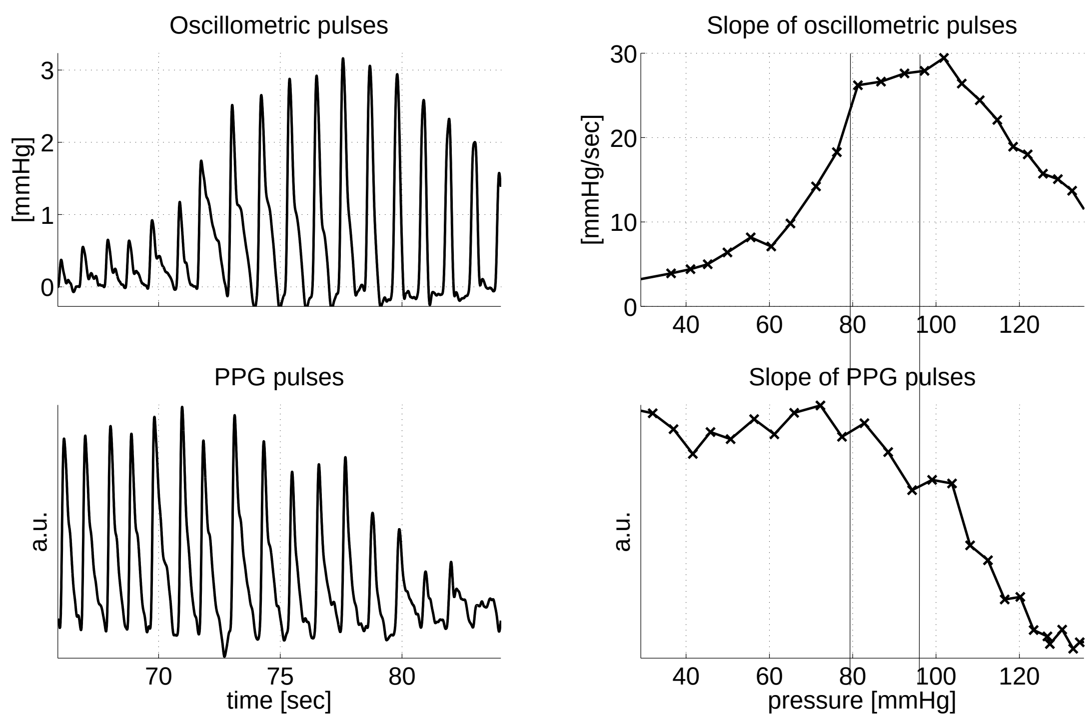

Fig. 4. Slope of oscillometric and PPG pulses during slow inflation recorded from S1 subject in 2005.

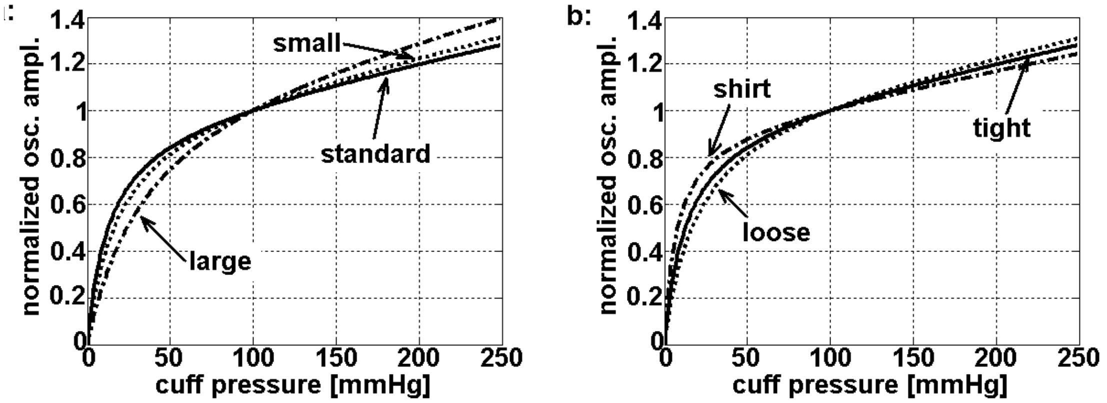

Fig. 5. Normalized measurement results for standard, small and large sized cuffs in case of tight, loose and over a shirtsleeve mode of affixation.

The (BHS) recommends cuffs of three different sizes for different upper arm circumferences, see Table 1. Even in clinical practice cuffs are not always selected and applied according to the recommendation [9]. Self measurement at home is made with automatic blood pressure meters that come with a single cuff. This is the standard size that fits for the majority of subjects but can cause substantial error when applied instead of the small or large size cuff.

Tab. 1. Cuff sizes recommended for different upper arm circumference.

British Hypertension Society recommendation	
Small	12x18 cm for lean adult arm an children
Standard	12x26 cm for the majority of adult arms
Large	12x40 cm for obese arm

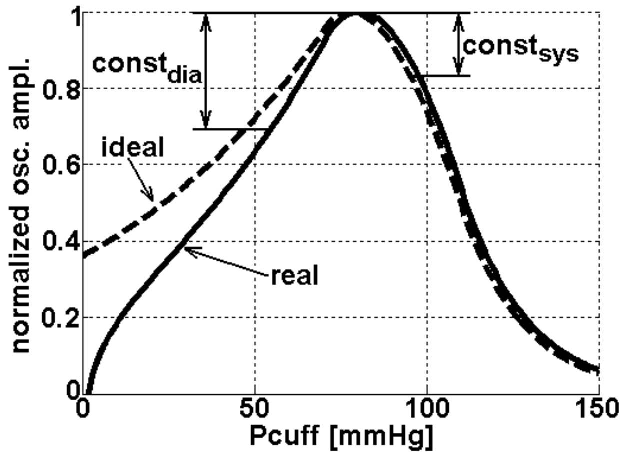

Fig. 6. Simulated oscillometric amplitudes as a function of cuff pressure for a patient with BP 120/80 assuming ideal and real (standard size tightly wrapped) cuff.

3.2 Determining the transfer function of the cuff

A measurement set-up was developed to measure the transfer function of the cuff. This comprises a PVC tube with an outer diameter of 63 mm and a small DC motor installed inside. The motor drives a cross shaped rotor that can swell about 2 mm out of the surface of the tube through a slit. Though a rigid cylinder with a slit in it is quite different from the human upper arm, the changes in cuff pressure caused by the rotor are similar to that caused by the pulsation of the brachial artery. The cuff was inflated fast then deflated in discrete steps of about 10 mmHg. At each step the cuff was hit approx. 24 times by the rotor. The resulting oscillometric amplitudes were then averaged and assigned to the corresponding DC value of the step. The discrete point function comprising the pairs of oscillometric amplitude - cuff pressure values has concave characteristics. A polynomial fraction in the form of Eq. (4) was then fitted to these measurement points [10]. The resulting continuous functions of average amplitude vs. cuff pressure are shown in Fig. 5.

3.3 Distortion caused by the improper cuff

Fig. 16 illustrates – based on simulation – the operational principle of classical oscillometry as described in section 2. The dashed curve depicts the oscillometric amplitude - cuff pressure function $P_{osc\_ideal}(P_{cuff})$ of an average patient should an ideal cuff be used. While an ideal cuff has a linear transfer function a real one has a hyperbolic H_{cuff} as depicted in Fig. 5.

This cuff transfer function is characteristic of bladder size as well as mode of placement. The solid curve of Fig. 6 represents the real oscillometric amplitude characteristics derived from $P_{osc\_ideal}(P_{cuff})$ via H_{cuff}:

$$P_{osc\_real} = H_{cuff}\,(\text{cuff properties}, P_{cuff}) \cdot P_{osc\_ideal} \qquad (2)$$

Through the modulating effect of H_{cuff} the patient dependent oscillometric curve is slightly shifted to the right and significantly depressed at low P_{cuff} values. This means that applying the classical oscillometric algorithm P_{sys} and P_{dia} will be overestimated.

This overestimation would not be a problem in itself if the shift would be a constant offset. However various cuffs – different either in size or mode of placement – have diverse H_{cuff} characteristics. To quantify what measurement errors are caused

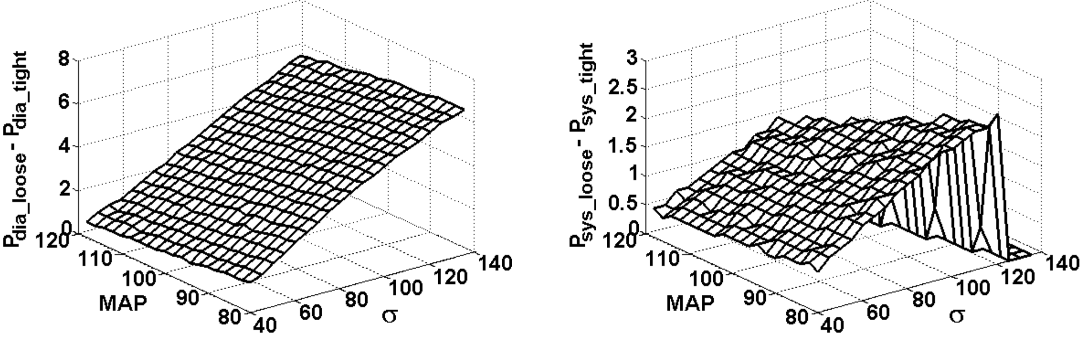

Fig. 7. Permanent error of the oscillometric algorithm when instead of a tight cuff a loose one is used. Parameters MAP and σ characterize patients with different BP and arterial elasticity.

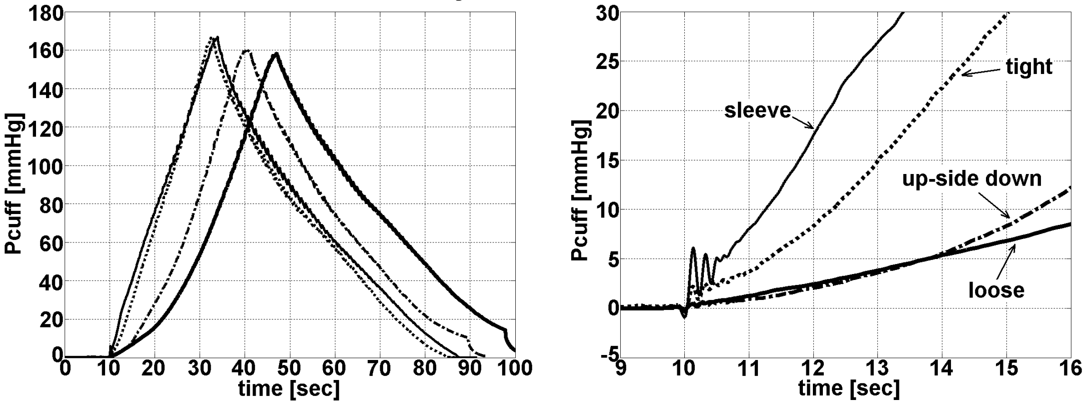

Fig. 8. A method to identify mode of affixation from the ramp up section of inflation.

if instead of a properly placed, tight cuff a loose one is used let us assume that P_{osc_ideal} is described by the following simple Gaussian function:

$$P_{\text{osc\_ideal}} = \exp\left[-\frac{(P_{\text{cuff}} - \text{MAP})^2}{2\sigma^2}\right] \tag{3}$$

where MAP is the cuff pressure related to the maximal oscillometric amplitude, σ characterizes the width of the curve and is related to arterial compliance. While an elastic arterial wall is represented by a small σ a stiff brachial artery produces significantly higher σ values [8].

To simulate the static measurement error caused by miscuffing two different oscillometric amplitude curves were calculated according to eq. 2. Each for the same cuff, but one tightly wrapped (P_{osc_tight}) while the other loosely (P_{osc_loose}). The corresponding H_{cuff} functions were determined in the measurement process described in section 3.2.

$$\begin{aligned} H_{\text{cuff\_tight}} &= \frac{P_{\text{cuff}} + 684.8}{P_{\text{cuff}} + 16.3} \cdot P_{\text{cuff}} \\ H_{\text{cuff\_loose}} &= \frac{P_{\text{cuff}} + 711.7}{P_{\text{cuff}} + 24.9} \cdot P_{\text{cuff}} \end{aligned} \tag{4}$$

The oscillometric algorithm was then performed on each P_{osc} function resulting in P_{dia_tight}, P_{sys_tight} and P_{dia_loose}, P_{sys_loose} respectively. Difference between the corresponding values can be seen in Fig. 7. During the simulation P_{osc_ideal} curves of various σ and MAP parameters were tested to represent patients of diverse circulatory properties.

From the simulation results it is clear that by applying a loose cuff instead of a tight one the oscillometric algorithm will overestimate blood pressure. For P_{dia} an average error of 3.7 mmHg is present while for P_{sys} it is 1 mmHg. Errors are more significant in the lower arterial pressure range (small MAP) and in case of a less elastic blood vessel (high σ). Concerning P_{dia}, errors in the 4-6 mmHg range are possible. The actual distortion resulting from insufficient cuffing is patient dependent.

3.4 Compensating the miscuffing error

Fig. 8 presents the pressure curves of a standard size cuff by different modes of affixation: tight, loose, up-side down and over a shirtsleeve. In each setup the cuff was inflated to 160 mmHg with the same compressor and deflated by the same passive valve. According to Fig. 8, even for automatic BP meters ***it is possible to identify the actual placement of the cuff*** by analyzing the ramp up section of pressure curves. Identification is best after personalization: making measurement on the subject with tight cuff.

4 Home health monitoring

The improved oscillometric algorithm was built into ten devices (called HHM) meant for home health monitoring, see Fig. 9. Patients have to put the cuff on their upper arm and then put their hands on the device so that ECG electrodes connect to their palms and photoplethysmographic sensors are touched by their index fingers. The device tests if the cuff is placed prop-

Fig. 9. Home health monitoring device

erly and if the ECG and the PPG signals have acceptable signal to noise ratio. Should it not be the case, the device can warn the patient tested. From autumn 2006 on, eight patients with cardiovascular disease used these devices for six months. Self-measurements were performed twice a day. The patients completed measurements at about the same time daily, synchronized to their usual activities. The results were stored on MMC cards. The HHM would help general practitioners get detailed information on the blood pressure of their patients between two visits. In addition, ECG record (Einthoven lead I or/and II) and oxygen saturation level can be stored in parallel with blood pressure measurement values. The eight patients made more than 1000 measurements. The recordings help validate the suggested blood pressure measurement method. Recordings are available on the web (`http://www.mit.bme.hu/projects/hhm02`).

HHM was validated also by making measurements in parallel with an intensive care unit monitor using invasive sensor. The upper diagram in Fig. 1 shows the result. Both the systolic and diastolic pressure of the tested patient was varying during slow deflation and inflation. The modified oscillometric algorithm proved to be excellent: it resulted in the average values of systolic and diastolic pressures during inflation and deflation. Based on the time delay between ECG and PPG at the fingertip (pulse transit time) it is possible to estimate the standard deviation of the systolic and diastolic value. This gives a better characterization of blood pressure than simple momentary values. However, medical doctors are not used to this parameter. Thus, it needs some time until it is transferred from research to widespread diagnostic application.

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