# Blood Pressure Measurement: Assessment of a Variable Quantity

## Merjenje krvnega tlaka: določanje variabilne spremenljivke

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### Abstract
Blood pressure (BP) is used to assess the cardiovascular system of a person. Assessment is however not possible based on a single measurement even if it is accurate. BP varies along the circulatory system, and at a given point fluctuates in time. Many internal and external factors influence the actual value of BP. Nevertheless, it is a common practice to characterize the BP of a person simply with two numeric values, one standing for the systolic and the other one for the diastolic pressure. This is meaningful only if the tested person is at rest, both systolic and diastolic pressures are constant, and pressure in the upper arm artery is measured by placing the cuff properly at the level of the heart so that the measurement does not alter the pressure to be measured. There are both short-term (even beat-to-beat) and long-term variations in BP, and therefore diagnosis must not rely on a single measurement. The paper shortly reviews the history of BP measurement, analyzes the accuracy and limits of reproducibility of indirect assessment in general and of the oscillometric method in particular. Examples are given, demonstrating how the most common errors distort the result of a non-invasive BP measurement. It is also advised how the best result can be achieved using the available BP meters.

### Izvleček
Srčno-žilni sistem posameznika ocenjujemo z merjenjem krvnega tlaka. Krvnega tlaka pa ne moremo pravilno določiti le z enkratnim merjenjem, čeprav so meritve, ki smo jih dobili, točne. Krvni tlak namreč v obtočilnem sistemu dosega različne vrednosti in se spreminja tudi v času. Na dejansko vrednost krvnega tlaka vplivajo številni notranji in zunanji dejavniki. Ne glede na to pa v vsakdanji praksi opredeljujemo krvni tlak posameznika preprosto z dvema številčnima vrednostima, s sistolno in z diastolno vrednostjo krvnega tlaka. Ti vrednosti pa sta povedni samo v primeru, da sta izpolnjena dva pogoja: preiskovanec v trenutku merjenja počiva in sta tako sistolna kot diastolna vrednost krvnega tlaka konstantni; krvni tlak pa merimo tako, da je manšeta merilca ustrezno nameščena v višini srca in tako s samim merjenjem ne spreminjamo vrednosti krvnega tlaka. Spremembe v krvnem tlaku so lahko kratkoročne in dolgoročne, zato diagnoze ne moremo postaviti le na osnovi enkratnega merjenja. V prispevku podajamo kratek pregled zgodovine merjenja krvnega tlaka, analiziramo točnost meritev in omejitve glede reproducibilnosti meritev tako pri posrednem načinu določanja krvnega tlaka nasploh kot tudi pri uporabi oscilometrične metode. S primeri osvetljujemo najpogostejše napake, ki lahko vplivajo na rezultate neinvazivnega merjenja krvnega tlaka in jih popačijo. Svetujemo tudi, kako z uporabo obstoječih merilcev krvnega tlaka meritve opravimo kar najbolj pravilno.

## Introduction

Blood pressure (BP) is one of the most important vital signs. Though, at first sight the measurement of BP seems simple, in fact, it is not. Blood pressure is the pressure exerted by circulating blood on the walls of blood vessels.[1] There are three components of BP: the hemodynamic (static) pressure, the hydrostatic pressure and the kinetic pressure (resulting from the blood flow). Medical doctors are interested in the hemodynamic pressure, which is determined basically by the heart (the stroke volume), the rigidity of the arteries and the impedance of organs. Unless otherwise specified, BP should be measured at the level of the heart. The hydrostatic pressure results from the vertical distance between the heart and the point of the brachial artery where BP is measured. Due to the difference in density, 13 cm vertical distance results in 10 mmHg difference in BP. The BP in the upper arm held horizontally may easily be 15 mmHg lower than at heart level. The pressure caused by the blood flow at normal speed (0.3 … 0.6 m/s) is less than 1 mmHg, i.e. negligible.

As early as 1837, Stephen Hales published his experiments in his essay *Haemastaticks* measuring the value and demonstrating the fluctuation of BP. In the 19$^{th}$ century, Etienne-Jules Marey constructed the sphygmograph . This device – a tonometer – was able to record the time function of BP non-invasively. In 1896, Scipione Riva-Rocci published the description of the cuff-based mercury sphygmomanometer considered as the precursor of the current non-invasive BP measurement. Further details on the history of BP measurement can be found in.[1-6]

Cuffless indirect BP measurement would be advantageous, but it is not widely used. Pulse wave velocity (PWV) and pulse transit time (PTT) also depend on BP.[7-16] As other parameters (especially vessel wall elasticity) also have an influence on PWV and PTT, this method is inaccurate without frequent (at intervals of a few minutes) cuff-based calibration.

Hypertension – elevated BP – is called the silent killer. It is a risk factor for stroke but can also cause heart attack, chronic renal failure and retinopathy. Hypertension leads to shortened life expectancy. Early detection of elevated BP values requires accurate and reproducible measurement. This is not easy as BP varies along the cardiovascular system and also varies in time at a given site. Both short-term and long-term variations – fluctuations – exist. *A single measurement of a momentary value is not sufficient for characterizing the BP of a person.*

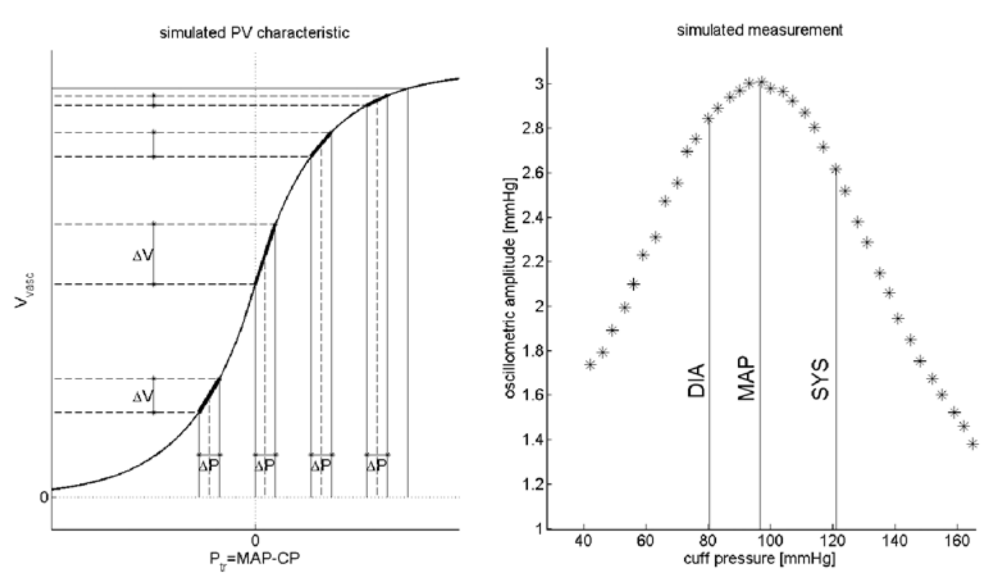



**Figure 1:** Vessel segment (under the cuff) volume as a function of transmural pressure (left). Resulting from the same pulse pressure (ΔP), the change in the volume of the vessel segment (ΔV) is maximal when the cuff pressure equals the mean pressure. Oscillation amplitude vs. cuff pressure is also given (right).

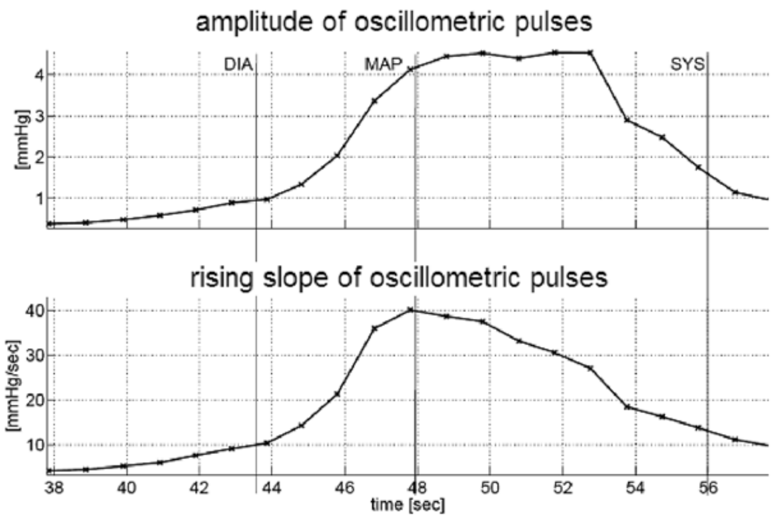



**Figure 2:** Maximum rising slope of oscillometric pulse can indicate mean pressure more accurately than maximum amplitude. Pressure values DIA, MAP and SYS were measured simultaneously invasively.

## Methods

### Basic idea of non-invasive BP measurement

A cuff is applied that is able to completely occlude the artery at a given point (most often the brachial artery in the upper arm).[17] Cuff pressure is measured and the equivalence of cuff pressure with systolic and diastolic pressure is determined by observing indicators, i.e. changes in physiological signals. There are different procedures to establish the equivalence. The blood flow in a partly occluded artery generates sounds (Korotkoff sounds).[18] As the cuff pressure is reduced from systolic to diastolic pressure, the spectrum of Korotkoff sounds changes. An experienced person is able to recognize these sounds: tapping, soft swishing, crisp and blowing sound. The automatic detection and evaluation of Korotkoff sounds has not reached the effectiveness of human operators. Different evaluations of such BP meters are available. Medical experts often use palpation: pulsation in artery starts when the pressure of the inflated cuff during deflation drops below systolic pressure. Blood flow and movement of artery wall can be detected using different methods.[20,21] For example, ultrasound based equipment is able to sense both arterial flow and vessel wall displacement. These devices are sensitive to positioning; integration of ultrasound sensors into blood pressure meters for home use has not been solved adequately.

An indirect method for continuously measuring the arterial pressure is described in references 22 and 23. The basic idea is to assure zero transmural pressure by regulating the pressure of a cuff wrapped around a finger.

### The oscillometric method

The oscillometric method[24-27] calculates BP based only on measuring the cuff pressure, no additional sensors are needed. The method makes use of the fact that the elasticity of the artery is a function of the transmural pressure, which is equal to the BP minus base cuff pressure. (Base cuff pressure means that the oscillometric changes are filtered out.) Constant pulse pressure results in maximum change in vessel segment volume when base cuff pressure is equal to mean arterial pressure, $p_{cuff} = p_{mean}$. Change in vessel segment volume results in cuff pressure change, called oscillometric pulse. Figure 1 shows the volume of a blood vessel segment (under the cuff) as a function of transmural pressure (left). Oscillometric pulse amplitudes vs. cuff pressure are also shown (right).

**Table 1:** Cuff sizes should be selected according to the upper arm circumference.[52]

| British Hypertension Society | | American Heart Association | |
|---|---|---|---|
| Small | 12x18 cm<br>for lean adult arm and children | Small adult | 10x24 cm cuff<br>arm circumference 22–26 cm |
| Standard | 12x26 cm<br>for the majority of adult arms | Adult | 13x30 cm cuff<br>arm circumference 27–34 cm |
| Large | 12x40 cm<br>for obese arm | Large adult | 16x38 cm cuff<br>arm circumference 35–44 cm |
| | | Adult thigh | 20x42 cm cuff<br>arm circumference 45–52 cm |

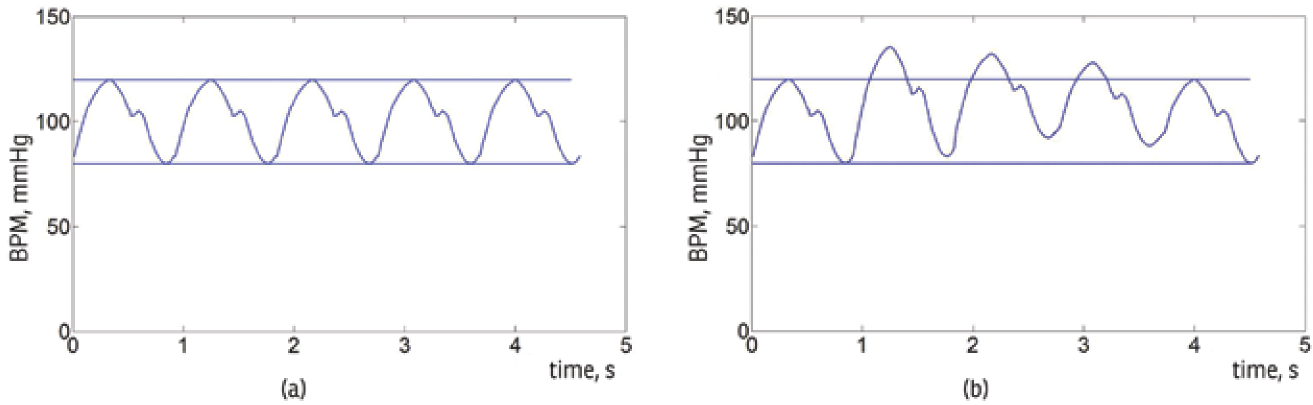



**Figure 3:** A single value (systolic/diastolic) is enough to characterize BP (a) but it can also be misleading (b).

The classic oscillometric method finds the oscillometric maximum pressure amplitude ($pa_{max}$) and calculates the systolic and diastolic pressure by using constants for the ratios $pa_{sys}/pa_{max}$ and $pa_{dia}/pa_{max}$. $pa_{sys}$ ($pa_{dia}$) is the oscillometric pressure amplitude when $p_{cuff}$ equals the systolic (diastolic) pressure. The oscillometric pulse amplitudes are also affected by the RR interval preceding the ventricular contraction. Breathing also influences oscillometric pulse amplitudes. Conventional oscillometric algorithms are unable to handle PVB (premature ventricular beat) and ES (extrasystole). As a result, in case of arrhythmia the standard oscillometric method can hardly be applied.

Also, increased arterial stiffness can be the reason for disagreement between an oscillometric BP monitor and a sphygmomanometer.[28] In summary, we can conclude that devices based on the oscillation method can show results that deviate from the reference value by 10 to 15 %. Quite often they also fail to complete the measurement.

## A new oscillometric method

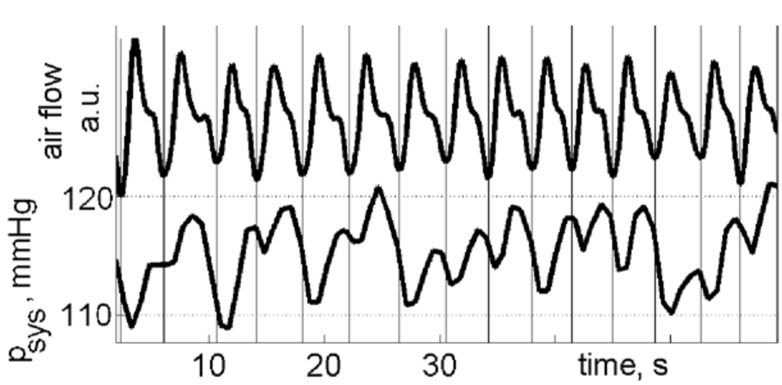
Estimation of arterial mean pressure based on the slope instead of the amplitude of the oscillometric pulses can give more reliable result.[29] In the Zala County Hospital, Zalaegerszeg, blood pressure of a postoperative patient was measured invasively in the femoral artery and also non-invasively by placing a cuff on the right upper arm. In Figure 2, the time instants are marked SYS, MAP, DIA, when the cuff pressure equals to the systolic, mean and diastolic pressure measured invasively in the femoral artery. The maximum rising slope of the oscillometric pulse is at t=48 s (bottom). At this moment $p_{cuff}$ is equal to the arterial mean pressure. There is no sharp maximum of the oscillometric amplitudes (top). There are five pulses with greater amplitude than the one when $p_{cuff}$ is equal to the arterial mean pressure.

## Difficulties of non-invasive BP measurement

The present definition of blood pressure implies that a momentary value is measured. Even if the measured value is accurate, there is no possibility to express its fluctuation. Figure 3 shows two BP–time functions where the measured systolic/diastolic value is 120/80 mmHg. In Figure 3a this is a correct characterization of BP while in Figure 3b – depending on the measurement method – 135/92 or 135/80 mmHg could also be measured.

Figure 4 shows the relation between breathing (measured with a PISTON spirometer)[30] and BP (measured with a COLIN

**Figure 4:** There is strong correlation between breathing (air flow, above) and systolic blood pressure (below) of a young healthy person at rest.



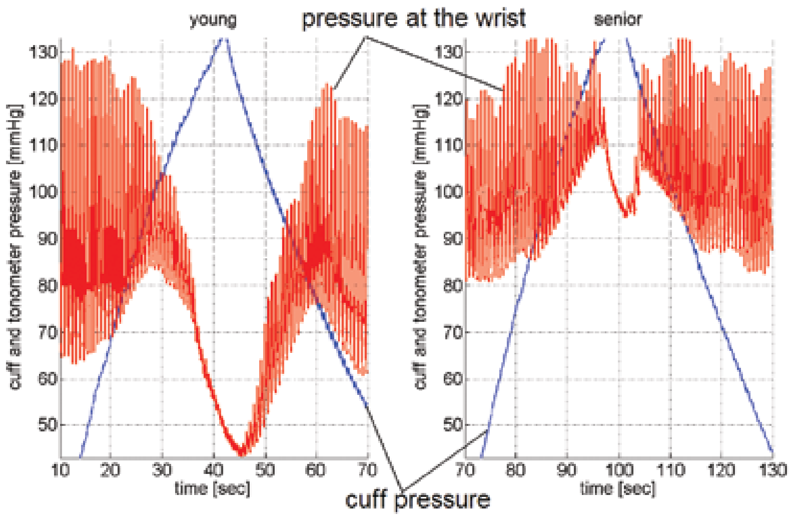



**Figure 5:** Effect of occlusion by the cuff. Pressure change at the wrist. Senior healthy person reacts differently from young healthy person.

CBM 7000 wrist tonometer)[31] in a healthy young person. Breathing influences systolic pressure with a short lag. The relation between breathing and BP is person-specific and also depends on the frequency of breathing.[32]

The circadian rhythm as well as different activities, stress, environmental temperature, caffeine, alcohol, even full bladder can substantially modify systolic/diastolic pressure resulting in fluctuations in BP.[33,34] Depending on the difference between BP during daytime and at night there are two groups of persons. Non-dippers who maintain the same BP during 24 hours and dippers who have significantly lower BP at night than during daytime.

The occluding cuff also changes BP. Vessel rigidity affects the physiological signals used to determine when systolic or diastolic BP is equal to cuff pressure and also affects oscillometric pulses. Ursino et al.[35] presents a mathematical lumped parameter model of the oscillometric technique for indirect blood pressure measurement. Their simulations indicate that the critical parameters are vessel wall viscoelastic properties and pressure pulse amplitude. Changes in these parameters can result in 15 – 20 % error during calculation of the systolic and diastolic value using the oscillometric method.

Jones et al.[36] gives three sources of error: the inherent biological variability, the white coat effect and the inaccuracies related to suboptimal technique. Apart from the invasive monitors and a few expensive and bulky devices (e.g. tonometers) blood pressure meters give a momentary value.

In present-day non-invasive devices the cuff is inflated above systolic value in a few seconds and then deflated relatively slowly. The usual deflation rate is 3–4 mmHg/s. For manual devices 2–3 mmHg/heart beat is recommended. Automated devices either use faster (even 10 mmHg/s) or step-wise deflation. Complete occlusion of the artery influences blood pressure; the influence differs from person to person. Figure 5 shows the blood pressure change in a young and in a senior healthy male person during slow inflation and deflation. A tonometer (COLIN CBM 7000) was applied to the radial artery at the wrist, distal to the inflating cuff. The change in blood pressure at the wrist resulting from occlusion of the brachial artery is significant in both subjects while the type of change is different.

**Table 2:** Recommendations and compliance with them during 114 BP measurements.[52]

| Recommendation | Respected by medical staff in percentage of measurements |
|---|---|
| cuff at heart level | 90 % |
| palpation of SBP | 38 % |
| both arms | 23 % |
| deflation speed | 18 % |
| ideal position | 10 % |
| 30-minute rest | 4 % |
| adequate cuff size | 3 % |
| Wrong results: 30 % ≥ 10 mmHg, as a consequence of ignoring the recommendations. | |

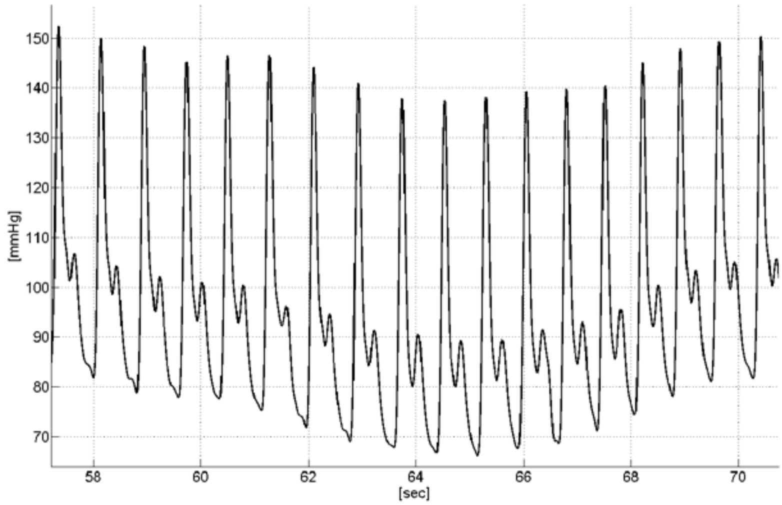



**Figure 6:** Beat-to-beat variation in BP, young healthy person, measured with a wrist tonometer. In 7 seconds BP drops from 152/83 to 137/68 mmHg.

## Testing non-invasive BP meters

Accurate BP measurement is essential for diagnosis as well as for medication. The British Hypertension Society (BHS)[37,38] protocol renders best grade to a BP meter if the difference between the actual and the measured value is greater than 5 mmHg in less than 40 %, greater than 10 mmHg in less than 15 % and greater than 15 mmHg in less than 5 % of measurements. According to the BHS protocol, both healthy subjects and patients with different cardiovascular diseases should be tested to classify a device. It must be taken into account that BP meters usually give more accurate results for healthy subjects than for patients.

Various authors[39,40,41] analyzed the accuracy of indirect BP measurement. Their results clearly show the limits of accuracy. Gersak et al.[42] concluded that automatic blood pressure measurement devices for home use cannot be fully tested because their measuring accuracy is not assessed. Jazbinek et al.[43] analyzed the influence of different presentations of oscillometric data on automatic determination of systolic and diastolic pressures. Proper handling of BP monitors is detailed in 44. According to Jones et al.[36] only 5 mmHg systematic error can prevent 21 million American people from a beneficial antihypertensive medication (underestimation) or force 27 million American people to get antihypertensive medication needlessly (overestimation). There are international standards on test procedures to determine the overall accuracy of sphygmomanometers.[45-47] The American protocol for validating sphygmomanometers was defined by the Association for the Advancement of Medical Instrumentation, AAMI.[48-50]

The clinical evaluations of automatic BP meters should be done in harmony with the standards. The specification of accuracy is not simple for two reasons. Firstly, there is no gold standard to compare measurements to. Secondly, the accuracy of the measurement can vary from person to person and also in the same person under different psychophysiological conditions.

Standards issued by the British Hypertension Society (BHS) and the Association for the Advancement of Medical Instrumentation (AAMI) are slightly different. For both standards the reference value is taken as the one obtained by an invasive BP meter or by trained medical personnel using a conventional sphygmomanometer. As a result the objective evaluation of the accuracy of a given device would require a number of persons, each with constant blood pressure.

Calibration of a BP meter means the calibration of its pressure sensor not the complete device. It does not guarantee accurate measurement of a person's BP. There are blood pressure simulators with pneumatic output.[51] These simulators allow for testing BP meters by simulating different cuff pressure profiles. They greatly help algorithm development but are not used for calibration of individual BP meters mainly because of their price. Resulting from these difficulties and also from device errors, the indirect BP measurement data are often not accurate enough.

## Sources of error

a. During a heartbeat, at a given point of the cardiovascular system, BP changes from the minimum (diastolic) to the maximum (systolic) value. Minimum and maximum values are not necessarily constant during the measurement. There are both short-term and long-term variations caused by the human physiological control system. Figure 6 shows the BP of a young healthy subject during 18

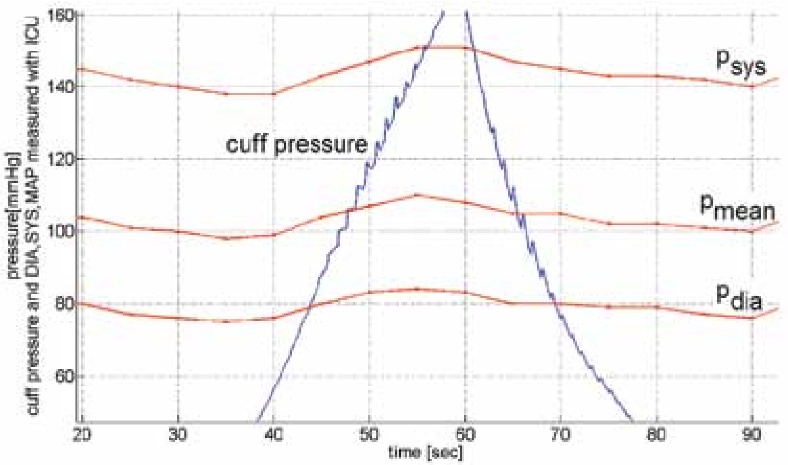



**Figure 7:** BP in the femoral artery may change while the cuff occludes the brachial artery.

heartbeats measured noninvasively with a wrist tonometer (COLIN CBM 7000). The beat-to-beat change can be as high as 5 mmHg, in 7 seconds BP drops from 152/85 to 138/67.

b. Inflation of the cuff can change BP. Figure 7 shows the change of BP in a postoperative patient. BP was continuously monitored invasively when a non-invasive measurement was completed using a cuff on the upper arm. The BP measured in the femoral artery changes as the cuff pressure occludes the brachial artery.
c. Most methods are quite fit for healthy persons but are not so good when testing patients with cardiovascular diseases. Arrhythmia, for example, prevents oscillometric devices from accurate readings. Also, rigidity of arteries can distort the result of any non-invasive BP meter.
d. Cuff size and placement also have an effect on the measurement. The size of the cuff must be selected according to the circumference of the upper arm (see Table 1).[52] Very often the BP meter is equipped with a single cuff. Thus, cuff size cannot be appropriate for all persons tested. Loose or above sleeve placement may result in 5–10 mmHg overestimation of the systolic pressure. Appropriate size cuff and its proper placement are essential for accurate BP measurement.[53] *Cuff should not be placed loosely or above sleeve.* Figure 8 shows the pressure of the cuff placed above sleeve on the left upper arm and the first derivative of the photoplethysmographic (PPG) signal taken from the left index fingertip. The pulsation of the PPG signal indicates that even though the cuff pressure was raised above $p_{sys}$ (130 mmHg) it did not occlude the brachial artery. The oscillometric method overestimated $p_{sys}$ by 6 mmHg.
e. There is no 'gold-standard' which could be the basis for verification of devices and algorithms.
f. McKay et al.[54] report that recommendations for the proper indirect BP measurement are generally neglected (human error). Table 2 gives the recommendations and also shows how seriously they were respected by medical personnel based on 114 cases. Even the measurement (cuff placement) at heart level is not followed consistently in 10 % of cases, and adequate cuff size is not considered in 97 % of measurements. It is clear that neither diagnosis nor treatment can be based on such readings.

## Results

More than 1500 BP measurements were taken with a device developed for home health monitoring.[55] Patients with cardiovascular diseases as well as healthy control subjects measured their own BP at home or in the university laboratory. The cuff pressure protocol was the following: 24 s completely deflated, slow inflation (5–6 mmHg/s) until maximum 150 mmHg (inflation was stopped at lower cuff pressure if systolic pressure could have been determined) slow deflation (5–6 mmHg/s) until 40 mmHg, fast deflation to 0 mmHg, further 24 s with completely deflated cuff. Resulting from the anti-hypertensive medication, no patient at rest had systolic pressure above 150 mmHg. The following parameters were sampled with 12 bit resolution and 1000 samples/s frequency: cuff pressure, Einthoven I. lead ECG, photoplethysmographic (PPG) signal at the right and left index finger tip. The recordings are available at www.mit.bme.hu/~csordas/

## Conclusion

The result of one BP measurement is not necessarily typical for a person. Measurement of BP at home eliminates the

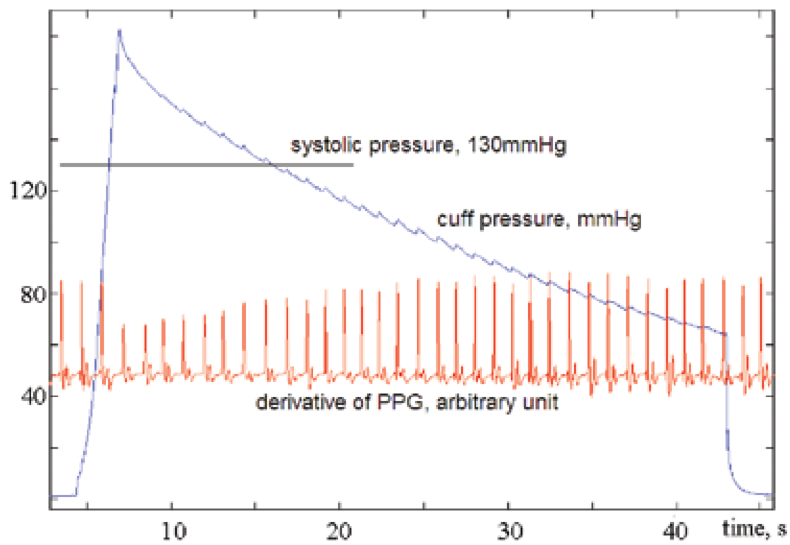



**Figure 8:** Cuff placed above sleeve. Photoplethysmographic signal (PPG) taken from the fingertip shows that brachial artery is not occluded even with above-systolic cuff pressure.

white-coat effect. However, subjects must be well trained for self BP measurement. A consensus report was published[56] in which guidelines are given for self-blood pressure monitoring. By evaluating more than 1500 BP measurements taken from patients with cardiovascular disease and from healthy persons we concluded that personalizing the parameters of the oscillometric algorithm could increase its accuracy and repeatability.

Using the presently available devices, the following should be taken into account for diagnostically relevant characterization of BP:

### Important for accurate BP measurement

a. selection and application of correct size cuff,
b. proper placement of the cuff,
c. holding upper arm so that the cuff is at heart level,
d. tested person must not be under physical or mental stress,
e. repetition of measurement after 10 minutes,
f. measurement on both upper arms,
g. if frequent BP check is needed, measure always at the same phase of daily activity, (e.g. right after waking up).

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