# The effect of cuff occlusion on the pulse wave transit time from the heart to the cuff

## Vpliv zapore manšete na hitrost prenosa pulznega vala od srca do manšete

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## Abstract

**Background:** Pulse wave transit time (PWTT) is widely used to characterize the dynamic properties of the arteries. PWTT is most often calculated as the time interval from the R peak in the electrocardiogram (start of the pulse wave) to the rise in the finger photoplethysmogram (arrival of the pulse wave). This is the PWTTHF. The aim of this study was to analyse the effect of cuff occlusion on PWTT, and using this information to improve the reliability of cuff-based indirect blood pressure (BP) measurement.

**Methods:** PWTT was measured with a home health monitoring device that inflates and deflates the cuff slowly (6 mmHg/s). The change in the arterial wall rigidity caused by cuff occlusion is different in the parts of the arterial section proximal and distal to the cuff. Accordingly, PWTT was divided into two parts: PWTT from the heart to the cuff (PWTTHC) and PWTT from the cuff to the fingertip (PWTTCF). Seven patients with various cardiovascular diseases (55–66 years old), seven healthy senior subjects (55–65 years old) and seven healthy young subjects (22–26 years old) were included in the research.

**Results:** Changes in PWTT characterise appropriately the effect of cuff occlusion on BP measurement. Cuff occlusion affected PWTTHC and PWTTCF differently; it increased the former and decreased the latter. Increased PWTTHC reflects a less rigid arterial wall, resulting in an underestimation of BP. The changes in PWTT values are person-specific and not group-specific (patient, healthy senior, and healthy youth).

**Conclusion:** Occlusion with the cuff is an excitation to the cardiovascular system, causing a temporary change in the dynamic properties of the arteries from the heart to the cuff. The change influences the result of indirect BP measurement. Arterial rigidity in the part proximal to the cuff can be characterized by PWTTHC, which provides different information about the arteries than the widely used PWTTHF.

## Izvleček

**Izhodišče:** Hitrost prenosa pulznega vala (*angl.* Pulse wave transit time: PWTT) pogosto uporabljamo za določanje dinamičnih lastnosti arterij. PWTT najpogosteje izračunamo kot časovni interval med najvišjo vrednostjo vala R na elektrokardiogramu (začetek pulznega vala) in porastom na fotopletizmogramu prsta (konec pulznega vala). To je PWTTHF (*angl.* PWTT heart-finger: PWTTHF). Namen te študije je bil raziskati vpliv zapore manšete na PWTT in s pomočjo teh informacij izboljšati zanesljivost posrednega merjenja krvnega tlaka z uporabo manšete.

**Metode:** PWTT smo merili z napravo za domačo uporabo, kjer se manšeta počasi napihuje in popušča (6 mmHg/s). Sprememba togosti arterijske stene, ki jo povzroči zapora manšete, je v delih arterije proksimalno in distalno od manšete različna. Glede na to je bil PWTT razdeljen na dva dela: PWTT od srca do manšete (*angl.* PWTT heart-cuff: PWTTHC) in PWTT od manšete do konice prstov (*angl.* PWTT cuff-finger: PWTTCF). V študijo je bilo vključenih sedem bolnikov z različnimi srčno-žilnimi boleznimi (starih od 55 do 66 let), sedem zdravih starejših oseb (55–65 let) in sedem zdravih mladih oseb (22–26 let).

**Rezultati:** Spremembe v PWTT ustrezno kažejo vpliv zapore manšete pri merjenju krvnega tlaka. Zapora manšete je vplivala na PWTTHC in PWTTCF različno: prvi se je povečal, drugi pa zmanjšal.

Povečana vrednost PWTTHC kaže na manj togo arterijsko steno, kar ima za posledico podcenjeno vrednost krvnega tlaka. Spremembe vrednosti PWTT so specifične za posameznika in niso specifične za skupino (bolniki, zdravi starejši in zdrave mlade osebe).

**Zaključek:** Zapora krvnega obtoka z manšeto vzburi srčno-žilni sistem, kar povzroči začasno spremembo dinamičnih lastnosti arterij v predelu od srca do manšete. Ta sprememba vpliva za rezultat posredne meritve krvnega tlaka. PWTTHC lahko določa arterijsko togost v delu proksimalno od manšete, kar zagotavlja drugačno informacijo o arterijah kot sicer pogosto uporabljeni PWTTHF.

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## 1. Introduction

Non-invasive methods are widely used to determine the momentary value of systolic (SBP) and diastolic blood pressure (DBP) (1). However, the momentary value is not necessarily appropriate, as many internal and external factors influence the actual value of BP (2). Cuff placement and size (3) as well as stress level (4,5) play an important role. There are several causes of beat-to-beat changes in SBP (6). Beat-to-beat variation in the BP of a relaxed 24-year-old male in sitting was measured with a wrist tonometer (COLIN CBM7000, Colin Corporation, Japan). In seven seconds, his BP dropped from 152/83 to 137/68 mmHg (7). Similarly, the fluctuation in SBP while resting in a supine position may reach 20 mmHg within an 8-minute interval (8). Momentary SBP/DBP values alone, provided by cuff-based measurement, do not characterize BP well. Information about the rigidity of the arteries would greatly enhance the assessment of the cardiovascular system.

The oscillometric blood pressure measurement (BPM) method (9,10,11) is widely used as it does not require extra sensors, and only cuff pressure (CP) has to be recorded and processed. The method basically determines the mean arterial pressure (MAP), thus the calculated SBP and DBP values may have a margin of error that is too high (12). Oscillometric blood pressure monitors can be checked with simulators (13). Arterial stiffness and pulse pressure have a substantial impact on accuracy. As a result, the reliability of the method is better in persons with normal BP and is questionable in those with cardiovascular diseases, especially those with arrhythmia or rigid arteries. Cardiologists approach the SBP and DBP values of automated BPM with reservation. The assessment of arterial rigidity would improve the accuracy of oscillometric BPM as well as other cuff-based methods. Pulse wave velocity (PWV) and pulse wave transit time (PWTT) can be used for assessment as they depend on arterial rigidity.

Mukkamala *et al.* (2015) surveyed (14) the PWTT-based cuffless (without a cuff) methods for BP measurement. They concluded that PWTT can be used to effectively monitor BP if smooth muscle contraction and viscous effects are negligible, aging and disease do not alter arterial elasticity, and wave reflection interference is absent.

A photoplethysmographic (PPG) signal is often used to aid the assessment of the cardiovascular system and the detection of SBP. Using slow inflation, pulsation in the PPG signal recorded at the fingertip ceases when CP exceeds SBP. During slow deflation pulsation restarts when CP drops below the momentary value of SBP (15). Jobbágy (2010) reported (16) that the momentary value of SBP during deflation ($SBP_{defl}$) is usually lower than SBP; the difference between SBP and $SBP_{defl}$ is greater the longer the total occlusion of the artery lasts. Buxi *et al* (2015) surveyed (17) the application of PWTT in ambulatory blood pressure measurement (BPM). Alan and Murray (2003) analysed (18) the age-related changes in the PPG pulse shape. Pilt *et al* (2014) suggested (19) a PPG signal waveform index to detect increased arterial stiffness. PWTT can be calculated by measuring electrocardiographic (ECG) and PPG signals. The majority of the reviewed methods measure PPG signals at the fingertip.

Occluding the artery with a cuff often alters SBP and DBP; the measurement method itself influences the parameter to be measured. The resulting deviation is not constant even in the same person.

The aim of this study was to analyse the changes in PWTT during cuff-based BPM to examine the effect of cuff occlusion. A further aim was to determine if changes in PWTT are group-specific (e.g. young – senior, patients – healthy subjects) or rather person-specific.

## 2. Materials and Methods

To achieve the aim of the study, measurements were taken in healthy subjects and patients with cardiovascular diseases to analyse the effect of occlusion during BPM.

### 2.1. Subjects

All subjects gave their written consent. The research was performed in accordance with the Declaration of Helsinki, and the study protocol was approved by the Scientific and Research Committee of the Hungarian Medical Research Council (permission nr: 230–100/2006–1018EKU). A total of 1600 recordings were taken. The changes in SBP and DBP have been analysed previously (20). A subset of the recordings was re-evaluated to study the effect of cuff occlusion. The results are reported in this paper.

Seven patients (age 55–66 years; 4 females and 3 males) with various cardiovascular diseases (all underwent open chest cardiac surgery) used a home health monitoring device (HHMD) in their homes for four months. They are referred to as the patient group (PG). Seven healthy senior subjects (age 55–65 years; 5 females and 2 males) were also tested. They are referred to as the healthy senior group (HSG). Seven healthy young subjects participated in the test as well (age 22–26 years; 2 females and 5 males). This group is referred to as the healthy young group (HYG).

The BP of each person in the PG, HSG, and HYG was measured with the HHMD several times (for subjects in PG 60…120 times, in HSG and HYG: 15…50 times). Adhering to the basic statistic rules to avoid biasing, group statistics were calculated using the first BPM of each person taken with the HHMD.

Several recordings were taken from a senior male (SM1, not belonging to HSG) during two measurement series with ten years in between. In 2006, SM1 was 55 years old and had mild hypertension without any treatment. Antihypertensive medication was initiated in 2009. The second measurement series for SM1 was taken in 2016. The aim of including SM1 in the research was to evaluate the difference between PWTTHF and PWTTHC.

## 2.2. Pulse wave transit time

The velocity of the pulse wave progressing through the arteries depends on blood pressure (21), as defined by the Moens-Korteweg equation [1], [2], [3],

$$PWTT = \frac{L}{\sqrt{\frac{Eh}{\rho d}}} \qquad [1]$$

$$E = E_0 e^{\alpha BP} \qquad [2]$$

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

where E is the Young's modulus of the arterial wall ($E_0$ is the value at a given $BP_0$), h is the thickness of the arterial wall, d is the inner diameter of the artery, ρ is the blood density, α is a constant, and L is the distance between the heart and the fingertip. Many attempts have been made to make use of PWTT (usually from the heart to the fingertip, PWTTHF) during BPM. BP changes can be estimated based on changes in PWTTHF even without using a cuff (22,23). However, BP calculated from PWTTHF has an unacceptable level of error. The reason is that the dynamic parameters of the arterial wall are not constant. In equation [3] we should consider $E_0$ as a variable. PWTT-based cuffless monitoring of BP requires calibration so frequently that it makes the method practically useless for quantitative measurement (22). These methods are applicable to monitor changes in BP. Laurent *et al.* (1994) showed (24) that the elastic modulus of the radial artery did not increase in patients with essential hypertension. They also demonstrated that the arterial tree is not homogeneous, and the medium-sized radial artery does not behave like the elastic, large common carotid artery.

Systole can be divided into two periods: an isovolumetric and an auxotonic period (25). The former ends when the pressure in the left ventricle exceeds the diastolic pressure in the aorta. Calculating PWTT from the QRS complex in the ECG signal until the next local minimum of the PPG signal also includes the time of the isovolumetric contraction and the electromechanical delay (the two together are known as the pre-ejection period, or PEP). When determining changes in PWTT, the constant portion of PEP is subtracted and only the fluctuating portion distorts the calculated values. Payne *et al.* (2006) found (26) that over a 1-min resting period the standard deviation/mean of PEP was 5.2/69 ms (twelve healthy men, mean age 22 years).

## 2.3. The home health monitoring device (HHMD)

The HHMD (20) was developed at the Department of Measurement and Information Systems, Budapest University of Technology and Economics, for BPM at home by patients with cardiovascular diseases. The HHMD inflates and deflates the cuff slowly according to the following protocol (see Figure 1). During the first 24 s the cuff is completely deflated. Recording of ECG and PPG signals (both in infrared (IR) and near infrared (NIR)) start at t = 0 s. Inflation starts at t = 24 s and

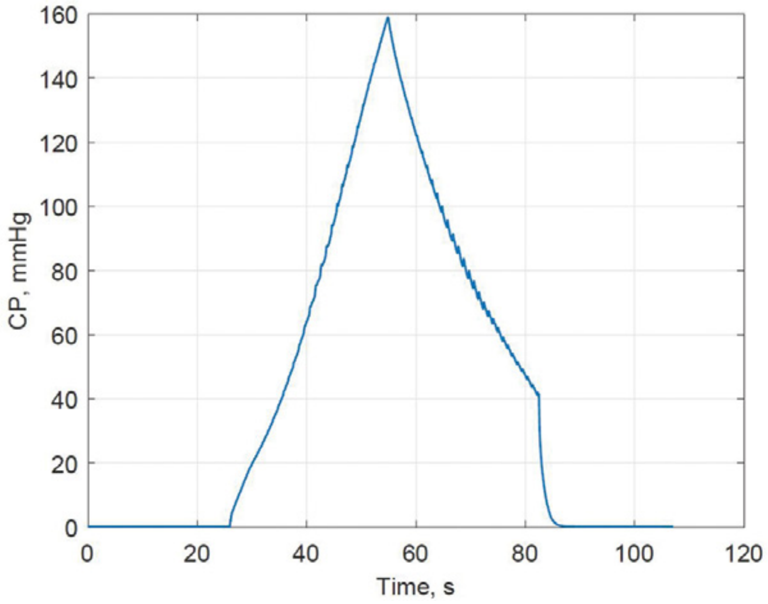

**Figure 1:** The CP(t) protocol applied in HHMD.

lasts until the maximum CP is reached at 160 mmHg, which is supposed to be higher than the SBP of all persons tested with the pilot version of HHMD. Should the HHMD detect SBP at a lower CP, inflation is terminated. Slow deflation lasts until the CP reaches 40 mmHg, which is supposed to be lower than the DBP of all tested persons. At this point, a valve opens and the CP abruptly drops to 0 mmHg. Recording of ECG and PPG signals continues for a further 24 s. The pressure change rate is approximately 6 mmHg/s during both inflation and deflation. The actual value depends on the strength and tone of the patient's upper arm and how tightly the cuff is wrapped around it. The HHMD records the ECG signal in the Einthoven I lead and the PPG signal from the index finger. The signal-to-noise ratio of the ECG signal is increased by body surface potential driving. The circuitry is the same as the one used for the DRL (driven right leg) method (27) but it is realised by a second electrode under the right palm. Either a transmission- or a reflection-type PPG sensor is used at the fingertip. The CP, AC-coupled ECG and PPG signals are sampled at 1 ksample/s, each using a 12-bit analog-to-digital (A/D) converter.

**Table 1:** Intergroup comparison of PWTT parameter changes with occlusion characterised by the nonparametric Kruskal-Wallis test. The test shows that the three groups (PG, HSG, and HYG) do not differ significantly regarding the changes during BPM.

| PWTT parameters | Chi square | p |
|---|---|---|
| PWTTHF | 7.02 | 0.0298 |
| PWTTHC | 1.28 | 0.5282 |
| PWTTCF | 1.09 | 0.5796 |

## 2.4. Measurement of PWTT

The occlusion with the cuff divides the arterial section from the heart to the fingertip into two parts. Accordingly, PWTTHF should also be divided into two parts: from the heart to the cuff (PWTTHC) and from the cuff to the fingertip (PWTTCF). See equation [4].

$$\mathrm{PWTTHF} = \mathrm{PWTTHC} + \mathrm{PWTTCF} \qquad [4]$$

PWTTHC extends from the QRS complex in the ECG signal – t(QRS) – until the arrival of the pulse wave to the cuff, t(PWC), where t represents time. The shape of the cuff pressure pulse changes from person to person and also depends on the actual cuff pressure (28); it must be taken into account while determining t(PWC). t(PWC) is determined from the CP(t) function. The most frequently applied method is to use a highpass filter and then find the maximum values of the first derivative. This method has been found to be error-prone, especially during inflation and when CP is between DBP and SBP. For more than 3500 heartbeats analysed, the ratio of false positives was found to be 5 %. We augmented this method by detrending CP(t) for each heart cycle separately. Instead of using a high-pass

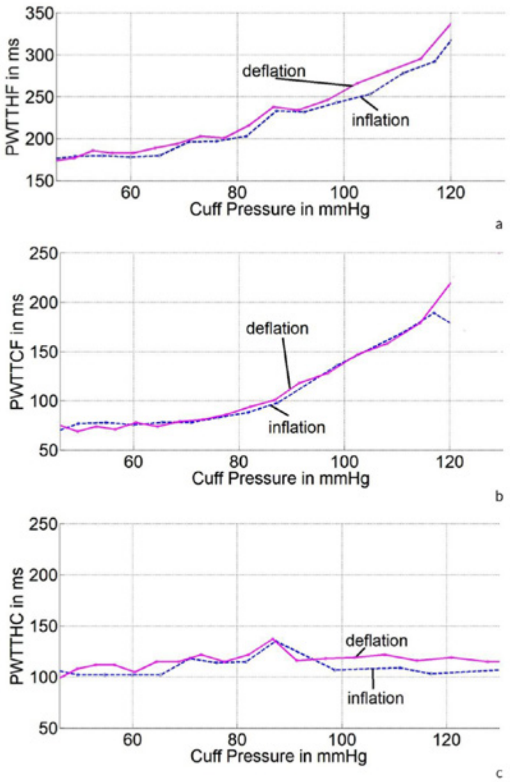

**Figure 2:** The PWTT vs. CP curves of a senior healthy male HSM1 (typical curves for the HSG) during slow inflation and deflation: (a) from heart to fingertip, (b) from cuff to fingertip, and (c) from heart to cuff. (SBP = 122 mmHg) The longer transit times during deflation result from the decreased rigidity of the brachial artery caused by cuff occlusion. The difference between inflation and deflation in PWTTHF is caused mainly by the difference in PWTTHC.

filter, a straight line was subtracted from the CP(t) separately for each heart cycle. The straight line was fitted to the beginning and endpoint of each heart cycle in CP(t), as defined by the consecutive zero values of dCP(t)/dt. This reduced the ratio of false positives to 0.2 %. PWTTCF extends from t(PWC) to the arrival of the pulse wave to the fingertip, t(PWF). The t(PWF) value was determined by the next local minimum value in the PPG signal following the corresponding t(QRS) in the ECG signal.

PWTT was calculated for each heart cycle during indirect BPM using the CP profile of the HHMD. t(PWC) can be determined while CP is greater than 30 mmHg. When CP < 30 mmHg, the pulse wave arriving to the cuff results in an oscillometric amplitude too small to be reliably detected. When CP exceeds SBP, the pulse wave does not pass through the occluded artery; thus, PWTTHF and PWTTCF cannot be calculated. Contrary to PWTTCF and PWTTHF, PWTTHC can be calculated when CP > SBP, with no upper limit for CP.

The effect of occlusion is characterised by the change in PWTT. PWTTHF, PWTTHC, and PWTTCF were averaged over four consecutive heartbeats to reduce the effect of breathing. During inflation, the four values right after CP = 40 mmHg, and during deflation, the four values right before CP = 40 mmHg, were averaged. The ratio of the average value during deflation to the average value during inflation was calculated for PWTTHF, PWTTHC, and PWTTCF for each person in the three groups (PG, HSG, and HYG) and for the two measurement series of SM1.

## 2.5. Statistical analysis

The non-parametric Kruskal-Wallis test was used to test the null hypothesis that the data in two or three groups come from distributions with the same median. The alternative hypothesis is that not all samples come from the same distribution. The result of the non-parametric

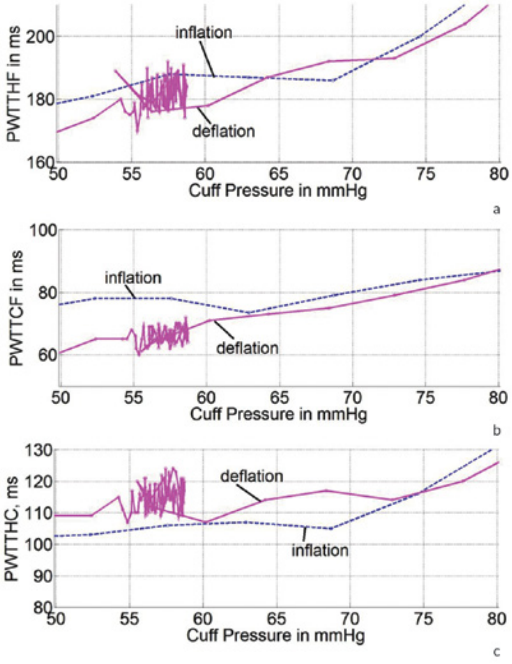

**Figure 3:** PWTT values for HSM1 during inflation and deflation. Deflation was stopped for 60 s at CP = 60 mmHg. (a) PWTTHF, (b) PWTTCF, and (c) PWTTHC. The change in arterial wall rigidity caused by the cuff occlusion is not identical along the artery from the heart to the cuff. The change remains present even after CP drops below DBP.

test was further pairwise analysed to check if the estimated two group means are significantly different. The confidence level was set to 95 % (alpha = 0.05). Two group means are significantly different if their intervals with a given confidence are disjoint; they are not significantly different if their intervals overlap. The *kruskalwallis* and *multcompare* functions of the data analysis program Matlab (29) 2007b (The Mathworks Inc., Natick, MA, USA) were used.

## 3. Results

Figure 2 shows the PWTT vs. CP curves of a healthy senior male (HSM1, belonging to the HSG). The curves shown are typical for the HSG. PWTT values change as a function of CP. PWTTHF and PWTTCF increase with CP. PWTTHC increases to a maximum value around the MAP and then decreases. The PWTTHF vs. CP curve during deflation is slightly above the curve obtained during inflation. The PWTTCF vs. CP curve is about the same during inflation and deflation. The longer PWTTHF values during deflation derive from the longer PWTTHC values.

Recordings were also taken while applying a modified CP vs. time profile. Deflation was stopped at approximately 60 mmHg for 60 s (a very low, 0.05 mmHg/s deflation was still present). Figure 3 shows the results for HSM1 (typical curves for the HSG). The change caused in the arterial rigidity by cuff occlusion is not identical along the artery from the heart to the fingertip. The changes in PWTT values caused by complete occlusion with the cuff remain present for a while, even when CP < DBP. While holding the CP at approximately 60 mmHg, the PWTTHF values are slightly below the values measured during inflation at CP = 60 mmHg. PWTTCF values are likewise below the values obtained during inflation, while PWTTHC values are above those obtained during inflation. Fluctuations in PWTT values are caused by breathing.

Data sets are illustrated using box-and-whisker plots showing quartiles. The PWTTHF values of the three groups during slow inflation (before complete occlusion) at CP = 40 mmHg are given in Figure 4. The CP must be small enough to modify the PWTT values only slightly compared to CP = 0 mmHg. At the same time the CP must be high enough to make possible the detection of the pulse wave arrival to the cuff. The changes (values at CP = 40 mmHg during deflation over the values at CP = 40 mmHg during inflation) in PWTT values of the

**Table 2:** Difference in PWTT values before (PWTTHF0I) and during inflation (PWTTHFI, PWTTHCI, PWTTCFI) for a senior male subject between 2016 and 2006. Lower and upper limits for the true mean differences of the two-measurement series are given, calculated with post-hoc tests following the nonparametric Kruskal-Wallis test (alpha = 0.05). The test shows that the differences in PWTTHF0I and PWTTHFI are not significant while PWTTHCI increased and PWTTCFI decreased significantly.

| Difference in | Chi-square | p | lower limit (5 %) of diff. | upper limit (95 %) of diff. |
|---|---|---|---|---|
| PWTTHF0I | 1.2548 | 0.2626 | -2.70 | 9.90 |
| PWTTHFI | 1.0331 | 0.3094 | -3.03 | 9.57 |
| PWTTHCI | 12.0033 | $5.31 \times 10^{-4}$ | 4.84 | 17.43 |
| PWTTCFI | 7.7247 | 0.0054 | -15.23 | -2.63 |

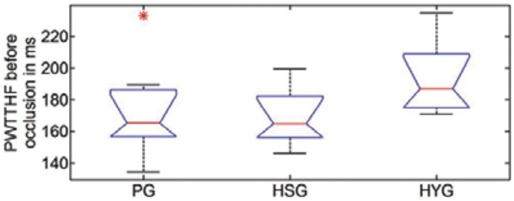

**Figure 4:** PWTTHF values before occlusion at CP = 40 mmHg. There are no significant differences between PG, HSG and HYG.

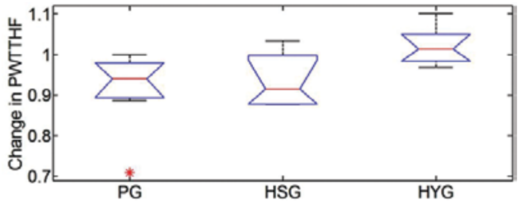

**Figure 5:** The occlusion with the cuff has no unidirectional effect on PWTTHF. Value during deflation over value during inflation at CP = 40 mmHg. There are no significant differences between PG, HSG and HYG.

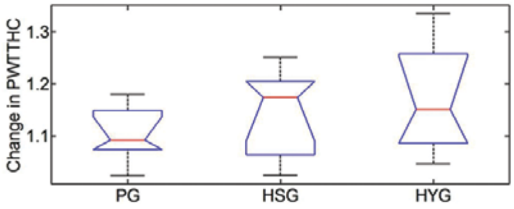

**Figure 6:** The occlusion with the cuff increases PWTTHC for all subjects. Value during deflation over value during inflation at CP = 40 mmHg. There are no significant differences between PG, HSG and HYG.

three groups (PG, HSG, and HYG) are given in Figure 5 (PWTTHF), Figure 6 (PWTTHC), and Figure 7 (PWTTCF). PWTTHC values at CP = 40 mmHg during slow inflation (before complete occlusion) are given in Figure 8 for the PG, HSG, and HYG.

The median *PWTTHF before occlusion* in the HYG is longer than that of the HSG and PG (Figure 4). In Figures 4 and 5 there is one outlier in the PG (marked by an *). The outlying data belong to a patient with an artificial heart valve that affected her PWTT values. Nevertheless, the nonparametric Kruskal-Wallis test did not find the distribution of the values for the HYG to be significantly different from the HSG and PG (chi-square = 0.7482, p = 0.6879).

The nonparametric Kruskal-Wallis test was also completed for the *changes* in PWTTHF (Figure 5), PWTTHC (Figure 6), and PWTTCF (Figure 7) values for the three groups (PG, HSG, and HYG). Table 1 shows these results. With regard to the change in PWTTHF, the HYG seems to be different from the HSG and PG. However, further pairwise comparison of the change in PWTTHF, PWTTHC, and PWTTCF revealed that the three groups do not differ from each other significantly; the 5 % – 95 % interval for all pairwise differences includes the value 0. Thus, the initial hypothesis, that the values of the tested groups originate from the same distribution, cannot be rejected. The changes caused by occlusion are not group- but person-specific, and help characterise the state of the brachial artery.

According to the Kruskal-Wallis test, the results for the HYG were significantly different from the HSG and PG with regard to the PWTTHC before (Figure 8, chi-square = 10.9013, p = 0.0043) and after (chi-square = 12.7671, p = 0.0017) complete occlusion. The pairwise differences between the HYG and PG, and HYG and HSG were confirmed by post-hoc tests.

Fifteen measurements were taken from SM1 within a single month in 2006 and again in 2016. Table 2 shows these results. The PWTT values in the table were analyzed using the non-parametric Kruskal-Wallis test followed by post-hoc tests. PWTTHFoI is the value before starting inflation (at CP = 0 mmHg), while PWTTHFI, PWTTHCI, and PWTTCFI are parameters measured during slow inflation at CP = 40 mmHg.

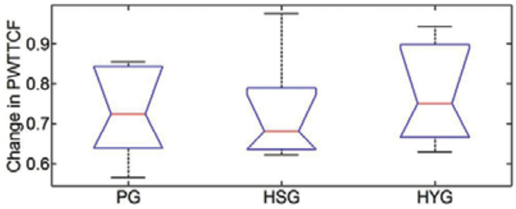

**Figure 7:** The occlusion with the cuff decreases PWTTCF for all subjects. Value during deflation over value during inflation at CP = 40 mmHg. There are no significant differences between PG, HSG and HYG.

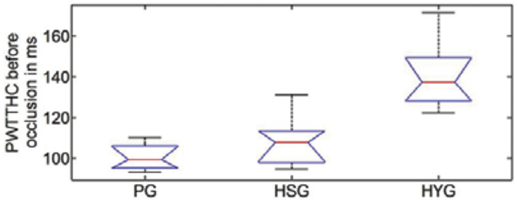

**Figure 8:** PWTTHC before occlusion at CP = 40 mmHg. HYG significantly differs from PG and HSG.

The fifteen values of each parameter measured in 2016 and in 2006 were compared. Although in 2016 SM1 was ten years older than he was in 2006, the antihypertensive medication increased the PWTTHC (and decreased PWTTCF) significantly. There was no significant change in PWTTHF. These results confirm that PWTTHC is more informative than the widely used PWTTHF.

## 4. Discussion

In the paper we have shown that the occlusion with the cuff changes the dynamic properties of the brachial artery. The change is different in the parts of the arterial section proximal and distal to the cuff. The dynamic property of the proximal part can be characterised by PWTTHC.

The general measurement of PWTTHF showed no unidirectional change resulting from complete occlusion (value during deflation over value during inflation at CP = 40 mmHg) for the three groups (Figure 5). There were some subjects whose PWTTHF increased (mainly in the HYG) while the PWTTHF of other subjects decreased (mainly in the PG and HSG) as a result of occlusion. However, PWTTHC increased and PWTTCF decreased for each subject tested in each group. An increase in PWTTHC corresponds to a less rigid brachial artery, which causes the underestimation of BP.

The non-parametric method for testing whether samples of two or three groups originate from the same distribution requires the inclusion of a single BPM from each subject to avoid biasing. The weakness of applying this procedure in this research is that the parameters of a person exhibit variation. For each subject in PG and HSG the coefficient of variation (CV) was lower for the PWTTHC than for the PWTTCF. The mean and standard deviation of CV was 0.077 ± 0.04 (PG) and 0.065 ± 0.024 (HSG) for the PWTTHC, while these values were 0.141 ± 0.056 (PG) and 0.222 ± 0.085 (HSG) for the PWTTCF. These values validate the introduction of PWTTHC.

The relationship between BP and PWTTHF has been studied by several research groups. Marcinkevics *et al.* (2009) found (30) that the PWTTHF-BP relationship was unique for each individual tested. There is a common understanding that SBP has a stronger impact on PWTTHF than DBP. The reported agreement between SBP values measured by BPM devices and those calculated on the basis of PWTTHF varies between ± 10.9 mmHg (31), ± 17 mmHg (26), and ± 19.8 mmHg (32,33), with a correlation between 0.6 and 0.99. PWTT can be used as an indicator for qualitative changes in SBP but it does not support quantitative assessment.

A potential clinical application would be the measurement of PWTTHC in parallel with cuff-based BPM. This service could be integrated into simple oscillometric devices. The value of PWTTHC can warn the operator if the occlusion with the cuff substantially changes the momentary SBP/DBP, and also indicate an increase in the rigidity of the brachial artery even in the early phase.

## 5. Conclusion

The main achievement of the present study is the introduction of PWTTHC, which provides different information about the cardiovascular system than the widely used PWTTHF.

Occlusion with the cuff is an excitation to the cardiovascular system, causing a temporary change in the dynamic properties of the arteries from the heart to the cuff. It influences the result of indirect BPM; a temporarily less rigid arterial wall results in the underestimation of BP. The temporary change in the rigidity of the artery lasts for minutes; thus, a second cuff-based measurement within five minutes following complete occlusion is likely to give lower SBP/DBP values.

## 6. Study limitations

In total, in this study 1100 BPMs taken from seven patients and 14 healthy subjects were analysed. However, further tests involving more patients are required to validate the clinical applicability of the PWTTHC. Further research is needed to devise a more accurate BPM calculation, taking into account the pre-occlusion value of PWTTHC and the increase that occurs during BPM, to compensate for the change in BP caused by the occlusion.

## 7. Acknowledgment

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## 8. List of abbreviations

| | |
|---|---|
| AC | alternating current |
| A/D | analog to digital |
| BP | blood pressure |
| BPM | blood pressure measurement |
| CP | cuff pressure |
| CV | coefficient of variation |
| DBP | diastolic blood pressure |
| DRL | driven right leg |
| ECG | electrocardiographic |
| HHMD | home health monitoring device |
| HSG | healthy senior group |
| HSM1 | a healthy senior male in HSG |
| HYG | healthy young group |
| IR | infrared |
| MAP | mean arterial pressure |
| NIR | near infrared |
| PEP | pre-ejection period |
| PG | patient group |
| PPG | photoplethysmographic |
| PWTT | pulse wave transit time |
| PWTTHC | PWTT from the heart to the cuff |
| PWTTHF | PWTT from the heart to the fingertip |
| PWTTCF | PWTT from the cuff to the fingertip |
| PWV | pulse wave velocity |
| SBP | systolic blood pressure |
| SBPdefl | SBP during deflation |
| SM1 | a senior male person, not belonging to HSG nor to PG |
| t(PWC) | the time instant when the pulse wave arrives to the cuff |
| t(PWF) | the time instant when the pulse wave arrives to the fingertip |
| t(QRS) | the time instant of the R peak in the ECG signal |

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