DISSERTATIONES PHYSICAE UNIVERSITATIS TARTUENSIS

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CONTINUOUS NON-INVASIVE BLOOD PRESSURE MEASUREMENT: COMPARATIVE AND METHODOLOGICAL STUDIES OF THE DIFFERENTIAL SERVO-OSCILLOMETRIC METHOD

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CONTENTS

LIST OF ORIGINAL PUBLICATIONS

I. Jagomägi, K., Talts, J., Raamat, R. and Länsimies, E., 1996, Continuous non-invasive measurement of mean blood pressure in fingers by volume-clamp and differential oscillometric method. *Clinical Physiology*, **16**, 551–560.

II. Raamat, R., Jagomägi, K. and Talts, J., 2000, Different responses of Finapres and the oscillometric finger blood pressure monitor during intensive vasomotion. *Journal of Medical Engineering & Technology*, **24**, 95–101.

III. Jagomägi, K., Raamat, R. and Talts, J., 2001, Effect of altering vaso-activity on the measurement of finger blood pressure. *Blood Pressure Monitoring*, **6**, 33–40.

IV. Raamat, R., Jagomägi, K., Talts, J., Länsimies, E., Jurvelin, J. and Kolari, P., 2001, Continuous mean arterial pressure measurement in the fingers: the influence of local arm cooling. *Medical & Biological Engineering & Computing*, **39**, 584–589.

V. Jagomägi, K., Raamat, R., Talts, J., Länsimies, E. and Jurvelin, J., 2003, Portapres and differential oscillometric finger blood pressure changes during deep breathing test in the assessment of BRS index. *Clinical Physiology and Functional Imaging*, **23**, 9–13.

VI. Raamat, R., Jagomägi, K., Talts, J., Toska, K. and Walløe, L., 2001, Recording of short-term finger blood pressure changes induced by an arterial occlusive thigh cuff: comparison between the modified oscillometric and Finapres techniques. *Physiological Measurement*, **22**, N13–N18.

VII. Raamat, R., Talts, J., Jagomägi, K. and Länsimies, E., 1999, Mathematical modelling of non-invasive oscillometric finger mean blood pressure measurement by maximum oscillation criterion. *Medical & Biological Engineering & Computing*, **37**, 784–788.

VIII. Raamat, R., Jagomägi, K., Talts, J., Toska, K. and Walløe, L., 2003, Beat-to-beat measurement of finger arterial pressure pulse shape index at rest and during exercise. *Clinical Physiology and Functional Imaging*, **23**, 87–91.

IX. Talts, J., 2004, Estimation of the finger arterial pressure-volume relationship and blood pressure waveform from photoplethysmographic signals. *Proceedings of the Estonian Academy of Sciences. Engineering*, **10**, 137–147.

X. Talts, J., Raamat, R. and Jagomägi, K., 2004, Dynamic arterial compliance during successive handgrips. *Proceedings of the International Federation for Medical and Biological Engineering*. On CD, **6**, article 496, 4 pages.

Comment on participation

Author's research has been an essential part of all these publications. In all experiments he was responsible for data acquisition and primary processing. The experimental setup and writing of publications I–VIII were done as team-work.

1. INTRODUCTION

Classical methods for measuring arterial blood pressure (BP) non-invasively are based on the detection of hemodynamic phenomena occurring in a collapsing artery under the effect of an external occlusive cuff. Among these methods, there are mainly two techniques most widely used and accepted in clinics at present: one is the auscultatory method and the other the oscillometric technique originally designed and described by Marey more than a century ago.

Marey established that the arterial wall had a maximum compliance at the equilibrium point of pressures, when the cuff pressure was nearly equal to the mean intra-arterial pressure (IAP). At this pressure level the arterial wall performs rhythmic oscillations of maximum amplitude. This principle, called 'vascular unloading technique', is now widely used in various types of indirect blood pressure measurement devices.

A conventional oscillometric sphygmomanometer records a number of pulse oscillations while the cuff pressure falls from suprasystolic to subdiastolic pressure. Routine measurement needs 30–40 seconds to obtain a result. This intermittent measurement is not sufficient when the arterial pressure is highly variable or when fast BP changes are recorded. Another drawback of this instrument is that the occlusive cuff on a large artery cannot be applied for a long period of time.

These shortcomings can be overcome by the application of some recently developed finger BP monitors, which are able to estimate arterial BP in every cardiac cycle and can be used in long-lasting measurements.

Finapres monitor follows the idea of the volume-clamp method ("dynamic unloaded arterial wall technique"). In the closed-loop mode the finger photoplethysmographic (PPG) signal is kept stable, and as a result, the cuff pressure continuously equals the intra-arterial pressure. Systolic (P_s), diastolic (P_d) and mean (P_m) blood pressure values for every cardiac cycle can be estimated from a full arterial pressure wave.

The differential oscillometric monitor also contains a servosystem to control the pressure in the finger cuff. Unlike Finapres in which the counterpressure rapidly follows the intra-arterial pressure wave, in the differential servo-oscillometric instrument the cuff pressure tracks the mean value of the arterial pressure pulse in every cardiac cycle, changing stepwise during the diastole. Oscillations from two cuffs on adjacent fingers at slightly shifted pressures are used as input signals for the automated system. Since values of P_m are measured on the beat-to-beat basis, it is possible to track the mean blood pressure dynamics.

The differential oscillometric method, being a new modification of oscillometric blood pressure measurement, was originally introduced at the University of Tartu. However, despite its good perspectives this method is still not widely used in clinical practice and scientific research. Reasons are an absence of validation studies of this new method, an unsatisfactory theoretical basis regarding influences from peripheral vasoactivity and unsolved problems in methodology.

This thesis is a summary of the author's work in the field of oscillometric blood pressure measurement, focusing on the research and development of the novel differential servo-oscillometric method. In the first section, the properties of the differential servo-oscillometric BP measuring method are investigated under various physiological conditions applying a volume-clamp BP monitor as a reference. Special attention is paid to the changing peripheral vascular tone.

In the second section, the results of comparison are used to improve the performance of the differential servo-oscillometric method and enhancing its range of application. The research involves the development of a theoretical basis for analysing factors influencing the oscillometric blood pressure measurement. Feasibility of the differential servo-oscillometric method in the estimation of the dynamic arterial compliance is also studied. Reconstruction of the arterial pressure waveform from PPG signals is included.

2. REVIEW OF LITERATURE

2.1. Short history of cuff-based methods for blood pressure measurement

In case of indirect blood pressure estimation, instead of the actual BP some other physical parameter, which is related to BP, is measured. For this purpose, for instance, force to deform an artery, pulse wave propagation time in arterial system or plethysmographic signal can be used.

Among these parameters there is one, which is naturally expressed by the same units as BP. Basch showed that the pressure required to occlude the lumen of an artery was equal to the pressure within the vessel plus the pressure required to overcome the rigidity of its wall [1]. As the rigidity of arteries was small, the occlusion pressure was a good estimate of IAP. Using limb-occluding cuffs Marey discovered principles of oscillometry and Riva-Rocci introduced a group of BP measurement principles based on tracking the signals distal to cuff, from which the Riva-Rocci / Korotkoff method has remained a golden standard for many years.

Marey used a liquid-filled occluding chamber sealed around the subject's arm. He found that intra-arterial pulsations were transmitted to the liquid. While increasing the applied counterpressure, pressure oscillations first increased, but began to decrease beyond certain pressure level. He assumed that the counterpressure was equal to the arterial pressure at the moment of maximal oscillation and called this condition "unloading the arterial wall" [2].

This principle of non-invasive measuring of BP by applying cuff pressure to obtain an unloaded condition of the arterial wall was afterwards called Marey's principle, and the maximum oscillation criterion is known as Marey's criterion.

2.2. Traditional intermittent measurement on the brachial artery (auscultatory and oscillometric methods)

Traditional non-invasive BP measurement by the auscultatory (Korotkoff) or oscillometric method usually takes 30–40 seconds to obtain results after slow cuff deflation from suprasystolic to subdiastolic pressure.

The auscultatory method, introduced by Korotkoff [3], uses characteristic sounds that appear distal to the occluding cuff to estimate P_s and P_d. Despite a long history and wide practical use, the origin of the Korotkoff sounds still remains controversial. Some authors consider that both blood flow phenomena and the transmission of sonic vibrations from the artery produce the sounds [4, 5]. Drzewiecki proposes that the sound is caused by a nonlinear distortion of the brachial pulse [6]. The cavitation hypothesis has also been presented [7]. The Korotkoff sound method tends to underestimate P_s and overestimate P_d. However, certain subject groups, such as the hypertensives or elderly, can compound these errors [8].

The oscillometric method estimates P_m by the maximum oscillation criterion. P_s and P_d can be also determined by observing oscillations during cuff deflation. The height-based criterion identifies P_s and P_d when oscillations reach a fixed or variable percentage of the maximum oscillations. The slope-based criterion applies the derivative of the oscillation amplitude curve with respect to cuff pressure. The maximum and minimum of this derivative denote P_s and P_d, respectively [8, 9]. A promising alternative to oscillation amplitude based algorithms is the pulse wave shape analysis [10]. Pattern recognition algorithms [11] and neural network technique [12] have also been used for BP estimation. Generally, there is no generic oscillometric technique, and different brands of oscillometric recorders use different algorithms [13].

Validation standards

An increasing variety of BP measuring methods and devices necessitated the development of standard protocols for testing them. The two most widely used have been developed by the British Hypertension Society (BHS) [14] and by the Association For The Advancement Of Medical Instrumentation (AAMI) [15].

Criteria for the fulfilment of the AAMI protocol require that the test device must not differ from the mercury standard by a mean difference greater than 5 mm Hg or by standard deviation greater than 8 mm Hg. The BHS protocol requires that the test devices must give at least 50% of readings within 5 mm Hg and 75% within 10 mm Hg with the two methods (grade B). Experience has demonstrated that the conditions demanded by the protocols are extremely difficult to fulfil. The European Society of Hypertension (ESH) protocol gives rationalized and simplified validation procedures without losing the merits of the much more complicated earlier protocols [16, 17]. The evaluation protocol is divided into separate sequential phases, each having own criteria.

2.3. Continuous (beat-to-beat) arterial blood pressure measurement on the finger arteries

Traditional oscillometric and auscultatory devices allow BP to be assessed once every few minutes, and this intermittence results in the lack of detection of a rapid change. This shortcoming can be avoided by continuous BP measurement. The availability of a continuous measuring device can also dramatically improve the reliability of measurement [18, 19]. Continuous BP measurement has started to provide an opportunity to examine the pathologic role of other characteristics of blood pressure, such as abnormalities of the diurnal rhythm, short term variability [13] and baroreflex sensitivity [20].

In case of a continuous indirect measurement by the external pressure the latter has also to be applied continuously. If cuffs are used around the extremity, the counterpressure will either decrease or stop the venous outflow, thus causing venous congestion and as a result, limiting the duration of a continuous measurement. The duration of occlusion without causing any considerable discomfort to the patient is longer when a peripheral point, e.g. finger is used for the measurement.

2.3.1. Volume-clamp method

Marey's unloading technique with unloading at a mean arterial pressure was extended by Peñaz who introduced the dynamic unloading of pulsatile blood pressure [21]. He used an inflatable finger cuff incorporating a built-in photoelectric plethysmograph. The cuff pressure was changed by a fast servocontrol system to keep plethysmographic signal at a constant level, called setpoint. Since the arterial wall is unloaded dynamically, the changes in arterial pressure are followed by changes in external pressure, and arterial pressure waveform is estimated by measuring cuff pressure.

The setpoint must be determined during calibration procedures. A criterion for setpoint determination, proved to work well, was proposed by Wesseling. His software expert system Physiocal readjusts the setpoint at regular intervals to compensate possible changes in vasomotor tone in the finger arterial wall [22]. The volume-clamp method with Physiocal setpoint adjustment is implemented in Finapres and Portapres devices.

A large number of studies have compared finger pressure, obtained by Finapres technology, with IAP or with non-invasive but intermittent BP measurements. An overview analysis, compiling results of 43 publications, found average differences between the finger and reference pressures ranging from –48 to 30 mm Hg for P_s, from –13 to 25 mm Hg for P_m and from –20 to 18 for P_d. The weighted accuracy among these studies was –0.8 ± 11.9 mm Hg for P_s, –1.6 ± 7.6 mm Hg for P_m and –1.6 ± 8.3 mm Hg for P_d [23].

Another analysis of results of 20 publications [24], found that an average bias (IAP-Finapres) was 2.2 ± 12.4 mm Hg for P_s, 2.1 ± 8.6 mm Hg for P_m and –0.3 ± 7.9 mm Hg for P_d. Both of analyses conclude that Finapres can provide an accurate estimate of P_m and P_d. Inaccuracy of P_s may have a physiological explanation.

Nevertheless, for some persons and for specific experimental conditions associated with peripheral vasoconstriction or vasodilatation a noticeable difference between the directly and indirectly measured blood pressure values has been detected [25–27]. Several experimental studies [28–30] have indicated the necessity of avoiding cold hands during Finapres measurements.

Some problems for finger BP measurements are connected with the peripheral measuring site. In several circumstances, finger pressure might physiologically differ from radial and even more from brachial artery pressure. Blood flow is accompanied by the pressure gradient, and in case of narrow arteries and/or high flow it can be significantly high. The reflection of pulse wave at arterial branching points and arterioles causes amplification of the peripheral pulse wave.

To make the comparison of finger pressure to brachial artery pressure more meaningful, two additional procedures were applied. First, a mathematical filter to compensate pulse wave distortion and second, a "return to flow" calibration to calibrate the measured finger blood pressure level with a reference to brachial arterial pressure (BAP). The effects of these procedures are studied in [31]. Before corrections differences (finger BP-BAP) were –3.2 ± 16.9 mm Hg for P_s, –13.0 ± 10.5 mm Hg for P_m and 8.4 ± 9.0 mm Hg for P_d. After corrections differences between the reconstructed and actual BAP were found 3.7 ± 7.0 mm Hg for P_s, 0.7 ± 4.6 mm Hg for P_m and 1.0 ± 4.9 mm Hg for P_d, i.e. all within AAMI criteria.

These improvements have been implemented in a newer device Finometer. Implication of the monitor has demonstrated its usefulness when recording of relative acute and longer-term changes in cardiovascular function [32, 33].

Peñaz's vascular unloading principle has also been implemented in other groups [34–36].

2.3.2 Differential oscillometric method

To obtain beat-to-beat values of the finger arterial BP, an oscillometric monitor was designed at the University of Tartu by Vello Reeben and Maria Epler [37, 38]. Instead of measuring the pressure corresponding to the comparatively even maximum of the oscillations in one cuff, it measures the arithmetical mean of the two biased counterpressures. This differential modification of Marey's principle has several advantages:

1) When splitting the counterpressure into two biased cuff pressures, the working points on the oscillometric curve may be shifted from a comparatively even maximum region to its steepest sides, so that the curve of differences will go through zero quite abruptly.
2) As two signals at different counterpressure levels are obtained simultaneously, there is no need to compare successive pulses and, thus, information about BP changes is obtained for every heartbeat.

3) Several inevitable accessory modulations of the amplitudes of the oscillations affect both differential channels equally, and consequently, their impact is eliminated.

The servosystem controls the level of counterpressures in two cuffs with a constant pressure difference between them, trying to equalize the oscillations, i.e. to keep the difference of pulses at zero. Pulses were obtained pneumatically, and in order to increase the signal to noise ratio, only systolic parts of pulses were used.

The differential oscillometric BP monitor was further improved at the University of Tartu. In the modified version it is possible to determine the gain factor for the servo system, and, as a result, achieve the values of mean BP readings that are more accurate and without delay [39].

2.4. Factors, affecting oscillometric blood pressure measurement

Maximum oscillation criterion

A large number of experimental in vivo and in vitro studies, concerning the relationship between arterial pressure and the counterpressure for maximum oscillations, have confirmed that maximum oscillations occur when the mean cuff pressure is approximately equal to the mean arterial pressure [40–44]. Some theoretical studies of recent years, [45, 46], however, have shown that non-invasive estimates of BP (including P_m measurement) can be influenced by the arterial wall properties, BP pulse amplitude and pulse shape. Some clinical investigators have also reported differences between the results of the individual invasive measurement of P_m and the corresponding values estimated by the maximum oscillation criterion [47].

Pulse shape index

In order to facilitate the determination of mean arterial pressure using non-invasive techniques, many studies have been performed applying coefficients like the pressure pulse shape index [46], pressure form factor [48], arterial pressure waveform coefficient k_a [49] and pressure constant k [50, 51]. Despite a variety in symbols applied to characterise arterial pressure waveforms, all the listed coefficients express the same content as pressure pulse shape index k_{pulse}, which is defined as $k_{pulse} = (P_m - P_d) / (P_s - P_d)$. From this equation a formula to calculate the mean arterial pressure can be derived: $P_m = P_d + k_{pulse} \cdot P_{pulse}$, where P_{pulse} is pulse pressure. The most commonly used procedure for larger arteries (e.g., *a. brachialis* and *a. radialis*) is the application of the pressure pulse shape index value of 1/3. In this case the formula becomes a well-known "standard" approximation $P_m = P_d + 1/3 \cdot P_{pulse}$. This equation has been included in physiological textbooks [52] and is frequently used in clinical practice [12, 53, 54]. Whether the "one-third" formula can validly be applied to distal vascular beds under various experimental conditions is not sufficiently known.

Pressure-volume (P-V) relationship

Nonlinear response of the arterial wall to transmural pressure (TP) changes serves as a basis for several non-invasive blood pressure estimation methods. However, although the nonlinearity is practically always present, the result of BP measurement can be influenced by mechanical properties of the vessel wall. Information on the behaviour of the artery is of great importance for the correct interpretation of results in indirect blood pressure measurement.

On the other hand, data about vascular properties have an independent prognostic value. It has been revealed that an elevated level of arterial blood pressure usually originates from an increase in the arterial wall stiffness and peripheral vascular resistance. The "compliance" of an artery has been considered a useful tool in the evaluation of cardiovascular disease [55, 56].

To determine mechanical properties of peripheral arteries, a simultaneous recording of the arterial BP and volumetric signal is needed. Invasive technique [57], volume-clamp method [58] or tonometry [59] can be used for BP waveform registration. Volume changes can be recorded by applying impedance plethysmography [60], photoplethysmography [61, 62], pneumoplethysmography [11], ultrasonic [63] or laser techniques [64]. Responses to an external pressure vibration have also been applied to an analysis of biomechanical characteristics of arteries [65, 66].

Owing to the viscoelastic properties of the arterial wall, the original recordings of P-V characteristics show a shape of a hysteresis loop and are different for static and dynamic measurements [67].

In mathematical studies the arterial wall P-V curve is usually modelled by using exponents [46] or arctangent function [68]. Neural network system identification technique has also been used [69].

The slope of the P-V curve is known as vascular compliance $C = dV/dP$. Since the relationship is nonlinear, the compliance is related to local transmural pressure. Tanaka et al. [70] have carried out compliance measurements at constant TP= 40 mm Hg. Some authors prefer an unloaded situation when TP=0 [65].

Practically the compliance is often estimated using the formula $C = \Delta V / \Delta P$, and maximal differences occurring during one cardiac cycle are used. Since the instantaneous slope of the P-V diagram can vary remarkably even during one cardiac cycle, this approach is an approximation. Alternative methods with smaller differences in pressure, generated e.g. by vibration [65, 71, 72] are more exact.

If the volumetric signal is obtained using PPG, the compliance formulas can be modified in accordance with assumptions about light absorption in tissue and blood. Because of light scattering Lambert-Beer's law doesn't hold exactly.

Tanaka [73] uses Lambert-Beer's law approximation, and Cejnar [74] found that the inverse function gave a better data fit to experimental results.

Knowledge or assumptions concerning how pressure pulses are transformed into volumetric pulses can be used to reconstruct continuous BP. Oscillometric pulses generated at a low constant pressure are similar to BP pulses. This principle serves as a basis for the constant cuff oscillometric measurement method [75]. The arterial BP is estimated continuously, using pre-determined calibration factors, but since at high positive TP the slope of the P-V diagram is quite low, measurement by this method is very sensitive to motion artefacts. If the cuff pressure is higher (until TP = 0), the slope of the P-V diagram is higher too, but due to nonlinearity the shapes of pressure and volumetric signals can be remarkably different, making reconstruction via linear transformation inaccurate.

Concluding the review of non-invasive blood pressure measurement, it should be pointed out that there is a growing need for a non-invasive blood pressure monitoring technique. The leading members of the European Society of Hypertension have persistently in their presentations and review articles emphasised an importance of non-invasive beat-to-beat pressure monitoring. It is commonly accepted that proper assessment of variability of blood pressure can come only from the analysis of continuous recordings. Continuous measurement will provide us with a deeper insight into the physiology and pathophysiology of cardiovascular regulation.

New perspectives in this field have been offered by the volume-clamp method through use of photoplethysmographic finger cuffs. The volume-clamp recordings are compared to intra-arterial or intermittent measurement in many publications. At the same time the recently developed differential oscillometric method has not been sufficiently compared to existing blood pressure measuring methods.

A few theoretical studies have demonstrated that several factors can influence the oscillometric blood pressure measurement. The knowledge about these factors for fingers needs to be extended for better interpretation of finger blood pressure estimation.

As to the arterial P-V relationship or compliance, these characteristics are mostly obtained from simultaneous recordings of pressure and volume changes. There have so far been no attempts to derive an arterial P-V relationship and BP waveform only from volumetric signals.

The addressed problems remain topical and need further investigation.

3. AIMS OF THE PRESENT STUDY

The main objective of this study was to investigate the differential oscillometric method for non-invasive blood pressure measurement.

The specific aims of the study were:

1. To compare the differential oscillometric device to the volume-clamp monitor under various physiological conditions, paying special attention to the changing peripheral vascular tone, known to present the most challenging condition for the finger BP measurement.
2. To find out whether the differential oscillometric device is able to track rapid short-term changes in blood pressure.
3. To model the finger mean blood pressure measurement applying the maximum oscillation criterion.
4. To develop an algorithm for deriving an arterial P-V relationship and BP waveform from volumetric signals.
5. To estimate beat-to-beat changes in the finger arterial compliance during light physical exercise.

4. REVIEW OF PUBLICATIONS

4.1. Comparison between the volume-clamp and differential oscillometric methods

When investigating properties of particular measurement principle or device, it is preferred to exclude possible sources of disturbing factors. When testing a finger BP monitor, the use of a reference finger BP monitor eliminates discrepancies connected with the measurement site. In a series of studies we compared beat-to-beat readings of P_m in various physiological conditions using two different and independent methods for continuous non-invasive finger BP measurement, viz. the differential oscillometric method and the volume-clamp method. The originally developed differential oscillometric monitor UT9201 (University of Tartu) and the volume-clamp instrument Finapres (Ohmeda, USA) or Portapres (TNO, Netherlands) were used in these experiments.

In publication I we studied seven male and six female healthy volunteers at room temperature at rest, head-up tilting and deep breathing. Difference between the values (UT9201- Finapres) at rest was +1.1 ± 5.5 mm Hg, during head-up-tilting –0.5 ± 6.9 mm Hg and during deep breathing +3.6 ± 7.7 mm Hg. In all situations the obtained differences were less than ± 5 mm Hg, which is generally accepted as the clinically meaningful value of differences (errors).

It is well known that the BP values, obtained in peripheral arteries (fingers or toes) are much more affected by the changing vascular tone than values obtained in central arteries. As this phenomenon seemed to be the most responsible for low frequency dynamic discrepancies between readings of the two compared devices, we investigated an influence of spontaneous and provoked vasomotions in the finger arteries during a series of experiments. The studies were conducted under different temperature conditions for the subjects. The degree of peripheral vasoconstriction was established by recording skin blood flow with a laser Doppler instrument. The results of these studies appeared in publications II–IV.

In publication II, two different techniques for non-invasive beat-to-beat finger arterial blood pressure monitoring are compared in 6 healthy volunteers during local hand heating from 21°C to 38°C. For time episodes without vasoconstriction no systematic difference in the readings of P_m of the two monitors was registered (the difference was 0.3 ± 0.3 mm Hg). For the episodes with vasoconstriction the difference was statistically significant (6.7 ± 2.0 mm Hg). The difference and the laser Doppler signal were found to be inversely correlated, with the correlation coefficient varying from –0.28 to –0.67.

In publication III differential oscillometric and volume-clamp methods are compared in 8 subjects during intensive vasomotion at room temperature 22–23°C. The study demonstrated that changes in BP were similarly tracked by the two monitors, except during the episodes with peripheral vasoconstriction.

Difference between the instruments for all simultaneously recorded P_m values in episodes without vasoconstriction was 0.7 ± 1.8 mm Hg and in episodes with vasoconstriction 10.6 ± 5.6 mm Hg.

In publication IV, we studied two different techniques in 14 healthy volunteers during arm local cooling to 17°C. A difference, estimated before cooling, was –1.5 ± 1.1 mm Hg. This difference, being less than 5 mm Hg, can clinically be considered not meaningful. The results obtained by the two devices under condition of arm intensive cooling revealed a systematic disagreement in the continuously recorded P_m. After a 30-second period of cooling, the group-averaged difference, calculated as a change from the baseline, reached 8.8 ± 6.3 mm Hg.

In all three previous publications (II–IV), complementing each other in covering the research area of spontaneous and provoked vasoconstrictions, we noticed a relatively good agreement between the devices except in the episodes with intensive vasomotion. A disagreement between the monitors is supposed to be caused by a tendency of the volume-clamp method to underestimate and of the oscillometric method to overestimate finger mean blood pressure in condition of peripheral vasoconstrictions.

In publication V, instead of comparing the direct BP values, we opposed the baroreflex sensitivity indices (BRS) being estimated on the basis of readings obtained by the two monitors. Our results indicate that P_m can be used as a substitute for P_s in an estimation of BRS from the amplitude of oscillation in BP and pulse interval during deep breathing. This innovation is believed to improve the reliability of the estimation of BRS since an integrated parameter like P_m can be more precisely estimated than a peak value like P_s. We also found that the differential oscillometric monitor can be used with sufficient confidence to study short-term responses in P_m, e.g. those provoked by the deep breathing test.

Physiological activities in previous publications, although covering quite a large scope of modulations in P_m, can be regarded as mild sources for cardiac modulation, causing only relatively slow changes in P_m. In publication VI we examined faster processes. The "thigh cuff" method allows achieve rapid systemic BP changes in response to step changes in total peripheral resistance. The provoked short-term changes in P_m were similarly tracked by both devices. An agreement between the methods was better for P_m rise than fall. The group-averaged difference did not exceed 1.2 mm Hg after cuff successive inflation, but yielded 3.8 mm Hg after cuff successive deflation.

4.2. Studies on the methodology of the differential oscillometric method

Although it has been commonly accepted and it can be read in the textbooks of physiology that in majority conditions the peak of the cuff oscillation envelope corresponds to the mean intra-arterial pressure, our theoretical research demonstrated that the maximum oscillation criterion does not uniquely estimate the mean arterial pressure, and a considerable shift of the maximum point of oscillations (more than 20 mm Hg) may occur (publication VII). The derived analytical error equation allows the calculation of that shift, depending on the arterial pressure pulse amplitude as well as on the difference between the arterial pressure pulse shape index and the arterial pressure-volume (P-V) curve shape index. As the oscillometric devices are widely used in BP monitoring, we expect the theoretical supplement made by us to be valuable in improving the accuracy of BP measurement in many applications.

Study on the finger arterial pressure shape index is presented in publication VIII. We aimed to test whether the usual value of 0.33 of the pressure shape index for the brachial artery can validly be applied to finger vascular beds under various experimental conditions. We established that in the fingers of young healthy persons in supine position formula $P_m = P_d + 1/3\ (P_s - P_d)$ gives an adequate approximation for rest and low intensity exercise and slightly underestimates the actual finger mean BP during moderate exercise and recovery.

A method for an estimation of the arterial P-V curve is presented in publication IX. Differently from the preceding works, we derived the P-V relationship using photoplethysmographic (PPG) signals without BP measurement. Basis for the method rests on the fact that the shape of PPG waveforms varies remarkably depending on the counterpressure applied. The nonlinear relationship and blood pressure waveform were estimated by coupling waveform changes to counterpressure values.

Publication X reports results of the beat-to-beat compliance measurement at a constant transmural pressure during a light physical exercise. Pressure pulses were measured by Finapres and volume pulses by the UT9201 monitor. We conclude that Finapres combined with the UT9201 monitor can be used in estimating rapid changes in the dynamic compliance of finger arteries. For better interpretation, a registration of instantaneous compliance $C(t)$ should be recommended instead of applying the methodology of beat-to-beat measurement $C = \Delta V / \Delta P$, where ΔP is the arterial pulse pressure.

5. CONCLUSIONS

1. The study demonstrated that the peripheral vascular tone differently influences the originally developed differential oscillometric monitor (UT9201, Tartu) and the commercially available volume-clamp technique (Finapres, Ohmeda). A disagreement between the devices is assumed to be connected with the origin of the methods and is caused by the tendency of the volume-clamp method to underestimate, as well as the tendency of the oscillometric method to overestimate finger mean blood pressure under the conditions of peripheral vasoconstrictions.
2. The ability of the differential oscillometric monitor to track rapid short-term changes was demonstrated by applying a special "thigh cuff" technique permitting to introduce rapid systemic blood pressure changes as responses to gradual changes in peripheral resistance.
3. Mathematical modelling of the oscillometric measurement revealed that the maximum oscillation criterion does not accurately estimate the mean arterial pressure as has commonly been accepted. An error between the true mean blood pressure and its estimate depends on the arterial pressure pulse amplitude, as well as on the difference between the arterial pressure pulse shape index and the arterial pressure-volume curve shape index.
4. An algorithm is proposed to derive an individual nonlinear arterial P-V relationship and BP waveform from PPG signals recorded at different cuff pressure levels. This approach makes it possible to extend the scope of the oscillometric blood pressure measurement adding new valuable information to the existing opportunities.
5. Our experimental study to estimate beat-to-beat changes in the finger arterial compliance during light physical exercise demonstrated that the application of the methodology of beat-to-beat measurement at fixed transmural pressures can be influenced by the changing pulse pressure amplitude.

It can be concluded that new experimental and theoretical knowledge about the differential oscillometric finger blood pressure measurement method has been obtained. The results are important for understanding the properties of the method and also for extending its possibilities.

SUMMARY IN ESTONIAN

Pidev mitteinvasiivne vererõhu mõõtmine: diferentsiaalse servo-ostsillomeetrilise meetodi võrdlevad ja metodoloogilised uuringud

Käesolev töö on pühendatud vererõhu kaudse pideva mõõtmise ühe variandi, diferentsiaalse ostsillomeetrilise meetodi uurimisele.

Sellel meetodil töötavat seadet ei olnud enne võrreldud teiste, laiemalt levinud sõrmelt vererõhku mõõtvate seadmetega. Võrdlevad uuringud näitasid perifeersete veresoonte toonuse erinevat mõju diferentsiaalsele ostsillomeetrilisele vererõhumonitorile (UT9201, Tartu) ja ruumalalukustuse põhimõttel töötavale seadmele (Finapres, Ohmeda). Tulemuste lahknevuse põhjus on arvatavalt põhimõtteline, ruumalalukustuse meetodi kalduvus alahinnata ja ostsillomeetrilise meetodi kalduvus ülehinnata sõrme keskmist vererõhku perifeerse vasokonstriktsiooni tingimustes.

Diferentsiaalse ostsillomeetrilise monitori võimekust jälgida kiireid lühiajalisi vererõhumuutusi on demonstreeritud kasutades erilist "reiemanseti" meetodit, mis võimaldab tekitada kiireid vererõhumuutusi reaktsioonina perifeerse takistuse hüppelistele muuutustele.

Ostsillomeetrilise mõõtmise matemaatiline modelleerimine näitas, et vastupidiselt levinud arvamusele ei ole maksimaalsete ostsillatsioonide kriteeriumi alusel hinnatud keskmise vererõhu väärtus alati õige. Tekkiv viga võrreldes tegeliku keskmise vererõhuga sõltub arteriaalse pulsirõhu suurusest ja pulsilaine kujuteguri ning arteriaalse rõhu-mahu sõltuvuse kujuteguri vahest.

Esitatud on algoritm arteriaalse P-V sõltuvuse ja vererõhulaine kuju määramiseks erinevatel mansetirõhkudel registreeritud fotopletüsmograafiliste signaalide alusel. Kasutades leitud mudelit on võimalik hinnata patsiendi arteriseina omadusi, nt. dünaamilist arteriaalset venitatavust. Eksperimentaalne töö dünaamilise arteriaalse venitatavuse leidmiseks pulsimahu ja pulsirõhu alusel näitas, et sellise meetodi puhul on tulemus mõjutatud pulsirõhu muutustest ja seetõttu tuleks eelistada venitatavuse hetkväärtuse mõõtmist või tuletamist.

Töö põhitulemuseks on Tartu Ülikoolis välja töötatud diferentsiaalse ostsillomeetrilise vererõhu mõõtmise meetodi omaduste eksperimentaalne ja teoreetiline uurimine ning meetodi kasutusvõimaluste laiendamine.

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