Arterial Pulsations in the Blood Pressure Cuff: Are They Hemodynamic Pulses or Oscillations?

J. Jilek, M. Stork

Abstract **—** Automatic monitors for the determination of blood pressure frequently use the oscillometric method. Amplitudes of arterial pulsations evoked in the cuff are evaluated by software algorithms in order to determine the systolic and the diastolic pressures. The arterial pulses in the cuff are commonly called oscillations. Almost no attention has been paid to the contours of these pulses. Our objective was to demonstrate visually and numerically that the contours of pulses in the cuff are hemodynamic arterial waveforms rather than oscillations. We designed and constructed an experimental notebook-based system for wrist cuff and finger photoplethysmograph data acquisition and processing. The contours of wrist cuff pulses acquired at the point of diastolic pressure were compared to radial artery pulses acquired by other methods. Visual and numeric comparison revealed that wrist cuff waveforms are closely related to other hemodynamic waveforms acquired invasively and non-invasively. Comparison with age related waveforms acquired by applanation tonometry revealed similar prolongation of upstroke time with age. Values of left ventricular ejection time computed from wrist cuff waveforms obtained from 12 volunteers were close to normal values (0.6%). Our conclusion was that the wrist cuff waveforms are not oscillations and that they belong in the family of hemodynamic waveforms. We proposed new, more accurate terms "cuff-pulse method" in place of "oscillometric method" and "cuff pulses" in place of "oscillations".

Keywords **—** Arterial pulsations, oscillations, wrist cuff, hemodynamic waveforms, cuff-pulse method, cuff pulses.

I. Introduction

MONITORS capable of automatic determination of systolic (SBP), mean (MAP) and diastolic (DBP) arterial pressures started appearing on the market in the nineteen seventies. Microprocessors facilitated algorithmic methods for the determination of SBP, MAP and DBP. One of the first descriptions of a microprocessor-based device using the so called oscillometric method appeared in 1978 [1]. Since then the oscillometric blood pressure (BP) monitors have dominated the market.

The oscillometric method is based on an early sphygmomanometer introduced by Marey in 1876 [2]. Marey placed the forearm and the hand in a water-filled chamber to which a variable counter-pressure was applied and pulsations were observed on the manometer. The counterpressure for maximum amplitude of these pulsations determined that the blood vessel walls were maximally relieved of tension during the cardiac cycle. Marey called the observed pulsations oscillations.

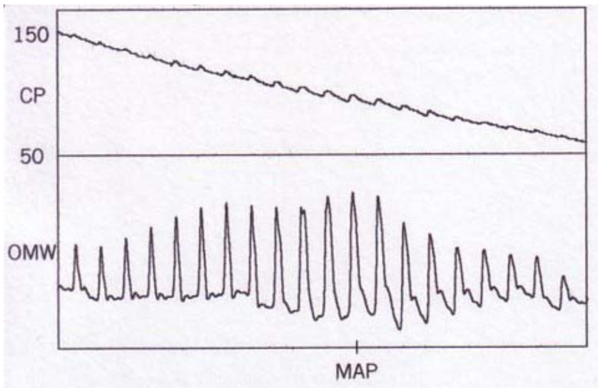

Figure 1. Cuff pressures (CP) and oscillometric waveforms (OMW) acquired during gradual cuff deflation.

Italian physician Riva-Rocci introduced in 1896 a modern sphygmomanometer using an air cuff and a mercury manometer [3]. He observed pulsations in the cuff and also called them oscillations. The terms oscillations and oscillometric waveforms have been accepted and used to this day. Posey and Geddes used the term oscillations in cuff pressure in the title of their article [4]. They related the point of maximal amplitudes of cuff pulsations to the mean arterial pressure (MAP). Figure 1 shows the cuff pressures (CP) and oscillometric waveforms (OMW) recorded during gradual cuff deflation from 150 mmHg to 60 mmHg. When the CP is gradually deflated, the waveform amplitudes initially increase until they reach the point of MAP and then the amplitudes decrease until the end of the procedure. There are no easily identifiable points on the OMW amplitude envelope that can determine the values of SBP and DBP. The only relatively easily identifiable point is the MAP. The Map corresponds to the maximal OMW amplitude.

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J. Jilek is with the Carditech, Culver City, California, USA (e-mail: jilekj@usa.net).

M. Stork is with the Regional Innovation Centre for Electrical Engineering,, University of West Bohemia, Univerzitni 8, Plzen, 30614 CZ., (phone: 420-377634243, fax: 420-377634202, e-mail: stork@kae.zcu.cz).

The term oscillometric method was derived from the term oscillations. Almost all descriptions of the oscillometric method in scientific and commercial literature use the term oscillations. Amplitudes of these oscillations in the cuff are used for algorithmic determination of the systolic, diastolic and mean pressures. Several differing algorithmic methods have been reported [5]. According to Geddes [6], SBP corresponds to the point of 50% of maximal amplitude on the ascending slope of the amplitude envelope. DBP value corresponds to 80% of maximal amplitude on the descending slope of the amplitude envelope. Algorithms used in commercial BP monitors are generally considered intellectual property and they are kept secret. It is, however, very likely that the commercial algorithms are also based on evaluation of OMW amplitudes.

Little attention has been paid to the contours of the OMWs. Exceptions are the author's previously published articles on the oscillometric method [5,7]. The term oscillometric waveforms rather than oscillations was used and contours of the waveforms were studied. The observations revealed that the waveforms elicited in the wrist cuff were similar to radial arterial waveforms acquired noninvasively by other methods.

Simultaneously acquired finger photoplethysmo-graphic waveforms and wrist cuff waveforms [7] exhibited similar characteristics. Photoplethysmographic hemodynamic waveforms have been used in research studies [8] and in clinical instruments, such as pulse oximeters. Second derivative of the photoplethysmographic waveforms obtained from the finger revealed usefuful information about cardiac cycle. Radial artery waveforms acquired by applanation tonometry have been used in conjunction with a transfer function for estimation of central aortic pressure. Applanation tonometry uses a pencil-shaped transducer that is applied by a trained operator to a suitable location on the wrist and held in place for the duration of the test. Applanation tonometry noninvasive radial waveforms also appeared to be similar to wrist cuff waveforms.

The objectives of this study were:

- To examine arterial pulses in the wrist cuff and to show visually and numerically that they are arterial waveforms rather than oscillations and that they are similar to arterial waveforms acquired by other methods.
- To propose more accurate terminology for the cuff-pulses and for the method utilizing these pulses. Accurate terminology is important for understanding of the underlying physiological principles.
- To point out potential applications of properly acquired wrist cuff waveforms. The wrist cuff radial waveforms can be acquired automatically at the end of blood pressure measurement. The potential wrist cuff waveform applications are similar to applications of radial waveforms obtained by other noninvasive methods.

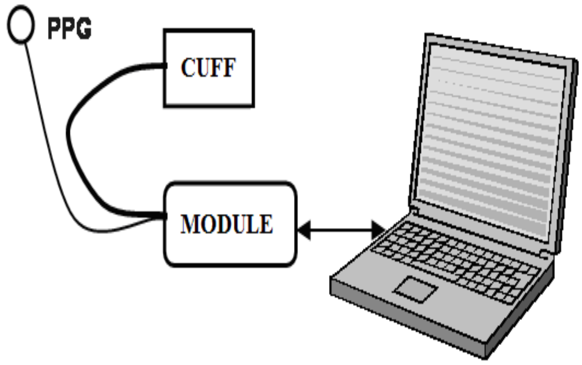

Figure 2. The system for acquisition of wrist-cuff and finger PPG waveforms.

II. METHODS

Instrumentation

A specialized experimental system for acquisition and evaluation of cuff pressures and waveforms was used in the study. The system (Figure 2) consists of a notebook computer, a module with pneumatic and electronic circuits, a commercial wrist cuff (Omron) and an experimental finger photoplethysmograph (PPG). The notebook controls all pneumatic and electronic functions of the system via USB interface.

Block diagram of the module is in Figure 3. The module consists of a pneumatic valve (Valve), a miniature air pump (M), a pressure sensor, an amplifier and filter, a 12-bit A/D converter, and a microcontroller.

The notebook controls inflation and deflation of the cuff and acquisition of data. Operation of the system starts with cuff inflation to about 30 mmHg above expected SBP and the CP is then gradually decreased to the level below DBP. Cuff pressure is converted to analog voltage by pressure sensor (piezoresistive bridge type, range 0-250). The analog voltage is amplified by an instrumentation amplifier and filtered by a low-pass filter with cutoff frequency of 35 Hz. The pressure voltage and the cuff pulse waveforms are digitized by a 12-bit A/D converter.The A/D converter operation is controlled by the microcontroller. Sampling rate is 11.6 mS.

Specialized software developed by the authors performs acquisition of waveforms and corresponding cuff pressures, waveform display, computations of waveform amplitudes, and computation of other pertinent variables. SBP, PP, DBP, heart rate (HR), stroke volume (SV), left ventricular ejection time (LVET), total peripheral resistance (TPR), and systemic arterial compliance (SAC) are automatically computed at the end of the data acquisition procedure. A graphic quadrant concept was developed for easy visualization of hemodynamic variables.

Wrist-cuff radial artery waveforms are used in this study because they can be compared with radial (wrist) waveforms acquired by other methods. Waveforms in Figures 5 and 6 were acquired with the described system from volunteers in the sitting position. Waveforms in Figure 4 were obtained from another study.

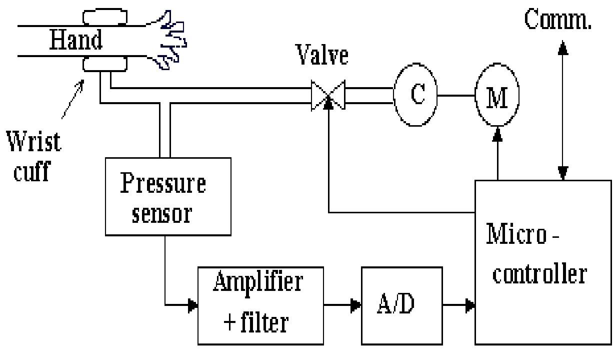

Figure 3. Block diagram of the module

Visual waveform comparison

Oscillations are well known from physics to be periodic motion back and forth over the same path. Oscillations can be either mechanical (a pendulum) or electronic (an oscillator). Many types of electronic oscillations exist. Electronic oscillations are typically generated by oscillators. Their contours range from sinusoidal to triangular, square or other shapes.

On the other hand, pulsations in the arterial system originate in the heart. When the heart's left ventricle contracts, it ejects blood into the aorta. The resulting pressure pulse then travels through the arterial bed. The pressure pulses can be picked up by a sensor and they can be converted into arterial waveforms by various methods. The waveforms are typically identified by the method and by the anatomical site. Waveforms generated by a pressure system with a catheter are called invasive radial waveforms if the site is radial artery. Waveforms obtained noninvasively are identified as plethysmographic if obtained with a plethysmograph, or tonometric if obtained with a tonometer.

Cardiac cycle of the left ventricle can be observed on the radial artery pressure pulse waveforms in Figure 4. The top trace represents radial artery waveforms obtained invasively [9] and the bottom trace shows radial waveforms obtained noninvasively by applanation tonometry .During early systole the velocity of blood flow is represented by the initial upstroke of the pulse waveform from the bottom threshold up. The peak of the invasively obtained pressure waveforms corresponds to the systolic blood pressure. In late systole the velocity of flow slows and the resulting pressure decrease is reflected by a downturn of the pulse waveform contour. The end of systole is marked by closure of aortic valve. A short dicrotic wave on the descending slope reflects closure of aortic valve. The dicrotic wave also marks the end of the left ventricular contraction. The remaining segment of the arterial waveform represents the diastolic portion of cardiac cycle. The end of the diastolic segment corresponds to the diastolic pressure. It should be noted that peripheral arterial pulse waveforms are only approximations of pressures and time intervals as measured in the ascending aorta. Wave reflections and arterial compliance are two major factors affecting arterial pulses [10, 11].

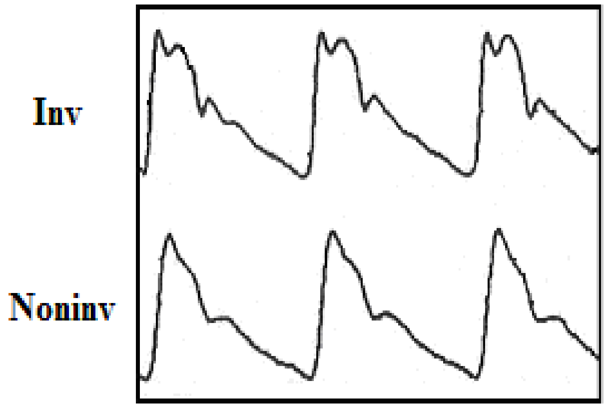

Figure 4. Radial artery pressure waveforms acquired invasively (Inv) and noninvasively by applanation tonometry (Noninv).

Oscillometric methods for noninvasive blood pressure determination evaluate amplitudes of arterial pulses elicited in the cuff [5]. Wrist cuff pressure pulse waveforms acquired during the descending portion of the gradual cuff deflation are in Figure 5. The waveforms at cuff pressures above DBP are distorted because the radial artery is fully or partially occluded by the cuff and blood flow under the cuff is turbulent [7]. Korotkoff sounds can be registered with a stethoscope during the turbulent flow segment of the gradual cuff deflation. When cuff pressure (CP) is lowered to pressures equal to or below DBP, the artery is no longer occluded and the waveforms are not distorted. When observed from right to left (increasing CP), the waveform amplitudes rise but they maintain the same contours until the point of DBP is reached. At CP above DBP the waveform contours start changing (observe the dicrotic wave) and they are variably distorted until the beginning of the BP measurement.

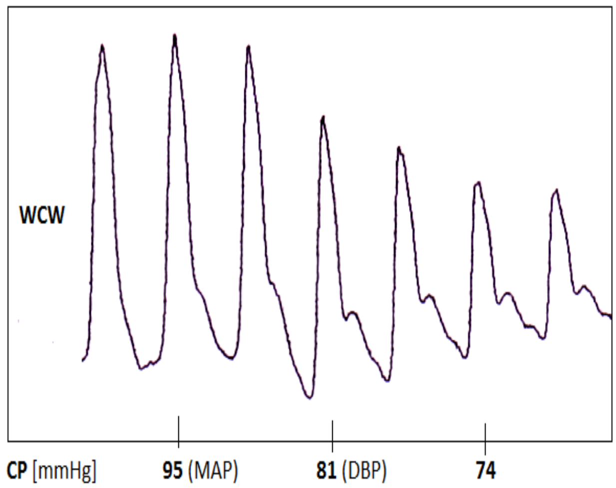

Figure 5. Wrist cuff waveforms (WCW) obtained at cuff pressures near DBP.

Waveforms acquired from a wrist cuff (WCW) and from a finger photoplethysmograph (PPG) are in Figure 6. The waveforms were recorded simultaneously near the end of a gradual cuff deflation at cuff pressure just below the point of DBP. The wrist cuff waveforms and the finger PPG waveforms are similar but not identical. The small differences are due to the fact that the waveforms were acquired from two different locations on the arterial tree. The photoplethysmographic waveforms were recorded from the finger (digital artery) and the wrist cuff waveforms were recorded from the radial artery.

As described above, the waveforms acquired at or below the point of DBP are not distorted by the compression of the artery and they are suitable for comparison with arterial waveforms obtained by other methods. Wrist cuff waveforms in Figures 4 and 5 were compared with arterial waveforms acquired invasively, and noninvasively by applanation tonometer (Figure 4) and by finger photoplethysmograph (Figure 6). The important arterial waveform segments are rapid systolic upstroke, late-systolic downturn, dicrotic wave, and diastolic segment. Rapid systolic upstroke lasts approximately from the onset to the peak of the waveform. Late-systolic downturn lasts approximately from the peak to the dicrotic wave. Left ventricular ejection time (LVET) is the sum of rapid systolic upstroke and late systolic downturn. Diastolic segment lasts from the dicrotic wave to the onset of the next systolic upstroke.

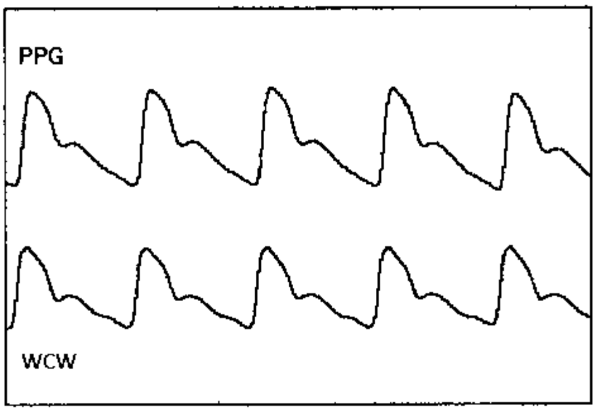

Figure 6. Wrist cuff waveforms (WCW) and finger photoplethysmograph (PPG) waveforms were recorded simultaneously.

Wrist cuff and finger PPG waveforms in Figure 6, and radial artery waveforms in Figure 4 exhibit similar characteristics. Systolic upstroke, late-systolic downturn, dicrotic wave, and diastolic segment can be easily identified on all of them.The waveforms are not, however, identical. The reasons for differences in contour shapes are numerous and they include location on the arterial tree [10] arterial compliance [11] wave reflections, and subject’s age. Kelly [12] observed that waveforms obtained with applanation tonometry from radial arteries of young subjects had much more pronounced dicrotic notch, faster upstroke and lower amplitudes than in older subjects.

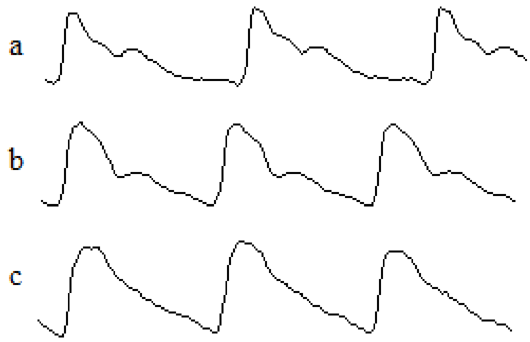

Figure 7. Age related waveforms obtained from wrist cuff: (a) 22 years old female, (b) 51 years old male, (c) 70 years old female.

Similar age differences can be observed on the wrist cuff waveforms in Figure 7. Upstroke of waveform obtained from a young subject (a) is shorter and amplitude is lower than that of older subjects (b,c). Lower amplitudes in young subject are due to higher arterial compliance of young arteries. More details can also be observed on the descending segment of young subject waveforms while older subject waveforms are more rounded and the details are obliterated.

TABLE I
Mean values of variables HR, AMPL, UT computed for 3 age groups.

Age	HR [bpm]	AMPL [pasc]	UT [mSec]
< 30	69	594	102
35-60	77	715	134
> 60	66	1197	162

Numerical waveform comparison

Age differences were observed on tonometric radial waveforms [11, 12] and on wrist cuff waveforms obtained by the authors (Figure 7). Some of the age differences can be quantified. Upstroke time (UT) and amplitude (AMPL) were computed by the authors using wrist waveforms obtained from 12 volunteers. Four volunteers were younger than 30 years, four were between 35 and 60 years and four were older than 60 years. The UT values were obtained by computing the time from the onset of the waveform to the waveform peak. The values of AMPL were obtained by computing the amplitude from the waveform onset to the waveform peak. Heart rates (HR) were computed by computing the intervals between waveform onsets and converting the intervals into heart rates. Reasonably comparable heart rates are necessary because upstroke intervals are heart rate dependent. The results are in Table 1. Waveform amplitudes (AMPL) are smaller and upstroke times (UT) are shorter in young subjects (< 30) than in older subjects. The results in Table 1 are in agreement with findings of other investigators [11, 12].

Some important values of left ventricular ejection time (LVET) are in Table II. The values of LVET in Table II were obtained by computing the time interval from the onset of the wrist cuff waveform to the nadir of the dicrotic wave. Heart rates were computed by determining the time intervals between waveforms and converting them into heart rate values. Values of LVET determined by the system were compared with normal values developed by Weissler [13]. The LVET values obtained from non-pregnant women in sitting position were very close to normal values obtained by Weissler. The values obtained from non-pregnant women in supine position were 9% longer than normal values and values from pregnant women in sitting position were also 9% longer than normal values. The prolongation of LVET in supine position and in pregnancy is caused by increased stroke volume [14]. The values in Table 2 indicate that LVET determination from wrist cuff waveforms is in agreement with normal values and with predicted physiological changes. Values of LVET are to some extent heart rate dependent but it was not possible to obtain lower HR values for pregnant women because heart rates in pregnant women are significantly higher than in nonprgnant women. In spite of this deficiency the LVET values in pregnant women were higher than in nonpregnant women.

TABLE II
Left ventricular ejection time (LVET) values (in milliseconds) obtained with the system (n=12). HR=heart rate, LVET=left ventricular ejection time.

	HR BPM	Measured LVET MS	Normal LVET MS	Change [%]
Non-pregnant (sitting)	72	299	297	+0.6
Non-pregnant (supine)	66	335	306	+9
Pregnant (sitting)	80	313	283	+9

III. Discussion

The visual and numerical waveform comparisons above indicate that contours of arterial pulses elicited in the wrist cuff exhibit close similarities to arterial waveforms obtained by other methods. It can then be concluded that wrist cuff pulse contours are arterial hemodynamic waveforms rather than oscillations and that they belong in the family of arterial hemodynamic waveforms.

The term arterial waveforms is used consistently when contours of arterial pulsations along the arterial tree are described in literature [7, 8, 9]. The terms for methods used to acquire these waveforms are specific, such as radial applanation tonometry or finger photoplethysmography. Also, the terms describing the waveforms are specific unlike the terms oscillations and oscillometric method.

New, more accurate terms for arterial pulses in the cuff and for blood pressure determination method are needed [15, 16, 17]. The terms cuff-arterial pulses or cuff-arterial waveforms are appropriate for arterial pulses elicited in the cuff. The term oscillometric method currently in use is not accurate because it implies the term oscillations and it is non-specific and it can be misleading. New term cuff-pressure pulse method reflects the fact that the method involves arterial pulses elicited in the cuff. Physiologically correct terminology removes confusion that can arise from the use of the incorrect terms oscillations in the cuff and oscillometric method. Correct terminology is also important for all biomedical workers who use arterial waveforms. They need to understand what physiological phenomena they deal with. Clinical engineers and technicians need to know at least the rudimentary physiological waveforms and their origins. Correct terminology helps to avoid errors that can arise from misunderstood physiological concepts.

Visual examination of the wrist cuff waveforms can be utilized for detection of certain abnormalities in their configuration and in their rhythm [9]. Rounded contours (Figure 7) may indicate premature aging of the arteries, slow upstroke could indicate change in contractility of the left ventricle, and abnormal left ventricular ejection time can also point to a change in contractility. Examination of the OMW envelope (Figure 1) can help detect missing or irregular beats that can cause errors in BP measurement.

Wrist cuff arterial pulse waveforms appear to be suitable for improved BP determination and for applications beyond BP determination. Hemodynamic variables such as stroke volume (SV), cardiac output (CO), total peripheral resistance (TPR) and systemic arterial compliance (SAC) together with blood pressure make global hemodynamics more complete at much lowered cost [18,19,20]. Examples of such application are in Figures 8 and 9. The computed blood pressures and hemodynamic variables are displayed on the computer screen as numeric values and as a “quadrant” graphic format. The quadrant shows the relationships of cardiac output (CO), total peripheral resistance (TPR), and systemic arterial compliance (SAC). Values of TPR and SAC are graphically represented by small black rectangles and they move together on the vertical (CO) axis according to the value of CO. TPR and SAC rectangles are positioned on the horizontal axis according to their values. Higher SAC and lower TPR values move the rectangles to the right. Normal values of TPR and SAC are displayed graphically in the right half of the quadrant Fig 8). Abnormal values (usually accompanied by hypertension) are located in the left half. In the example (Fig.

9) the blood pressures and other hemodynamic variables are determined from a hypertensive subject (SBP= 198 mmHg). The value of CO is near normal and the values of TPR (2173 dyn) and SAC (1 mL) are abnormal.

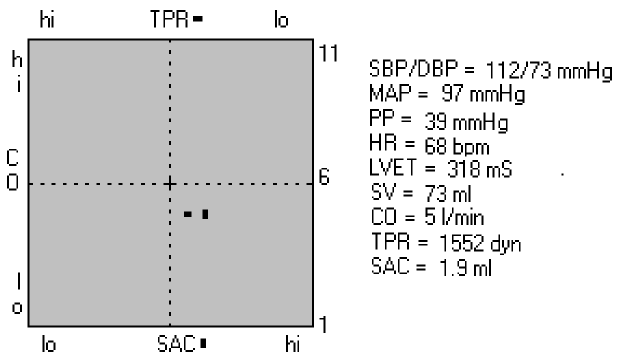

Figure 8. Graphic and numerical results of a normal wrist cuff test.

Additional numerical values shown to the right of the quadrant are SBP, DBP, pulse pressure (PP), heart rate (HR), mean arterial pressure (MAP), left ventricular ejection time (LVET), and stroke volume (SV). The values of CO, SAC and TPR are also shown numerically. The quadrant together with numerical values allow quick, easy evaluation of the hemodynamic state of the patient.

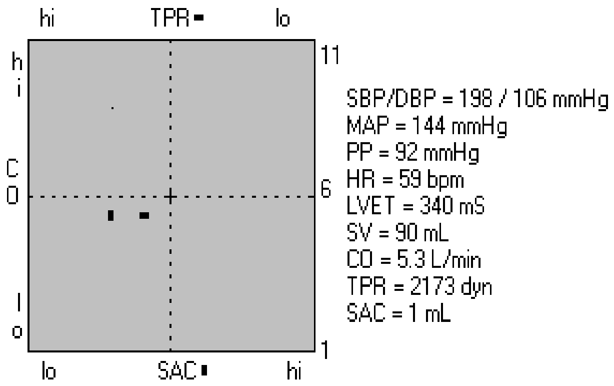

Figure 9. Graphic and numerical results of an abnormal wrist cuff test.

Wrist cuff arterial waveforms are also potentially suitable for waveform analysis similar to that of applanation tonometry [21, 22]. It is, however, important to acquire the wrist cuff waveforms at cuff pressures at or below the point of DBP.

An important application of radial pressure waveforms is the determination of aortic AI. AI is usually calculated as the ratio of aortic augmentation pressure and overall aortic pressure. Aortic AI is highly predictive of cardiovascular mortality [11]. Increased aortic AI increases the load presented to the left ventricle. The brachial or radial arterial pressures do not represent the load accurately. Application of a transfer function allows the determination of aortic AI and facilitates synthesis of the aortic pressure waveform. Accuracy of the transfer function depends on high frequency information. The transfer function shows inter-subject variability of aortic AI and its accuracy has been questioned. A recent report [7] showed that aortic AI can be derived from the radial waveform without use of a mathematical transfer function. Such approach is suitable for waveforms acquired by the wrist cuff method because the air in the wrist cuff is likely to dampen high frequencies. Computation of aortic AI from the wrist cuff waveforms is currently under investigation. Another potential application of wrist cuff method is computation of "oscillatory" arterial compliance [12]. Oscillatory compliance reflects changes affecting central aortic pressure.

Wrist cuff waveforms can also be used to improve detection of SBP. A dual-cuff system developed by the authors [23] uses an arm cuff and a wrist cuff. The wrist cuff is used to detect the onset of blood flow that occurs when cuff pressure is lowered to just below SBP level. The arm cuff waveforms and cuff pressures are used to determine the SBP and the DBP values by oscillometric ratiometric method. This method is commonly used in commercial oscillometric BP monitors. Ratiometric method does not determine BPs directly. It is based on the statistical assumption that the SBP and DBP values are located on statistically predictable points of the OMW amplitude envelope. Errors caused by this approximation appear when the OMW amplitude envelope slopes change. Such slope changes can be caused by changes in arterial compliance [24]. The dual cuff system determines the value of SBP more directly in a manner similar to that of the classical method using a stethoscope and a sphygmomanometer. Waveforms acquired during dual-cuff test are shown in Figure 10.

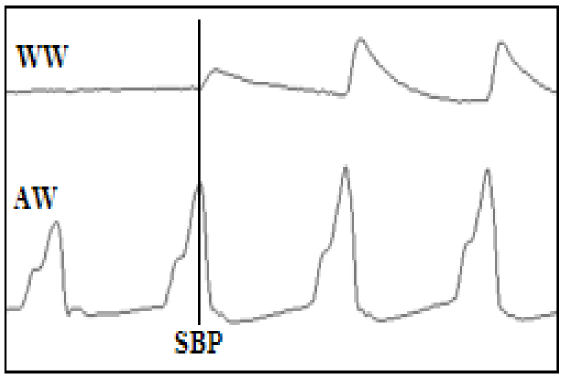

Figure 10. Wrist waveforms (WW) and arm waveforms (AW) obtained simultaneously. Systolic pressure (SBP) is the point of WW appearance.

The upper trace shows waveforms obtained from the wrist cuff (WW) at approximate cuff pressure at the point of DBP. The lower trace shows waveforms from the arm cuff (AW). Note that both WWs and AWs are heavily distorted due to the fact that the brachial (arm) artery is compressed. The first appearance of the WW indicates SBP similarly to the stethoscope method that determines the point of SBP when Korotkoff sounds first appear. In the test shown in Figure 10 the SBP measured by WW appearance was 174 mmHg and the SBP determined by a conventional oscillometric method was 159 mmHg. The result indicates an error made by the oscillometric method due to the fact that the ascending slope of the OMW amplitude envelope changed.

IV. Conclusions

The presented visual and numerical comparison of wrist cuff arterial hemodynamic waveforms with arterial waveforms obtained by other methods indicate that the cuff waveforms belong in the family of arterial hemodynamic waveforms. They can be used for blood pressure determination, for waveform analysis and for estimation of hemodynamic variables. The proposed new terms cuff arterial pulse and cuff-pressure pulse method are specific and they reflect the fact that pulses elicited in the cuff are of the arterial hemodynamic character. The results and conclusions of this study are preliminary. More studies simultaneously comparing wrist cuff waveforms with other, more established methods are needed.

Acknowledgment

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Mr. Jiri Jilek received MSEE degree from University of Southern California (USC), Los Angeles . From 1972 to 1981 worked as research engineer at USC-Medical Center, Los Angeles, in the field of instrumentation for perinatal medicine. Research projects included a method for evaluation of fetal heart rate variability and an on-line system for evaluation of fetal heart rate patterns. From 1989 to 1997 worked as research engineer at Drew University of Medicine and Science, Los Angeles. Projects included development of an experimental system for evaluation of maternal cardiovascular parameters and data acquisition from fetal monitors. From 1997 to 2007 worked at King-Drew Medical Center, Los Angeles as a senior R&D engineer. He has also worked as an independent engineering consultant. Research projects included processing of digital arterial waveforms, development of a system for noninvasive evaluation of blood pressures and hemodynamics, and a new method for bench-testing of blood pressure monitors. Mr. Jilek published numerous journal and conference papers. He is a member of the Association for Advancement of Medical Instrumentation

(AAMI) sphygmomanometer and blood pressure committees.

Mr. Milan Stork received the M. Sc degree in Electrical Engineering from the Technical University of Plzen, Czech Republic at the Department of Electronics in 1974 and Ph. D degree in automatic control systems at the Czech Technical University in Prague in 1985. In 1997, he became an Associate Professor at the Department of Applied Electronics and Telecommunication, faculty of Electrical Engineering on University of West Bohemia in Plzen, Czech Republic and full professor in 2007. He has numerous journal and conference publications. He is member of editorial board magazine ‘‘Physician and Technology’’. His research interests include analog/digital systems, signal processing and biomedical engineering, especially cardiopulmonary stress tests systems.