Oscillometric pressure pulse waveforms: their current and prospective applications in biomedical instrumentation

J. JILEK*, M. STORK**
*Carditech, Culver City, California, USA
**Department of Applied Electronics and Telecommunications University of West Bohemia, Plzen, Czech Republic
jilekj@usa.net, stork@kae.zcu.cz

Abstract: The objective of this paper is to describe current uses of oscillometric pressure pulse waveforms and to introduce several prospective applications of the waveforms. A specialized system (Carditor) for acquisition, processing and display of waveforms is described. Carditor was used to acquire a database of oscillometric blood pressure waveforms from a wrist cuff. The following prospective methods are described: a) oscillometric blood pressure algorithms based on physiology, b) new method of blood pressure monitor testing based on a database of oscillometric waveforms and reference blood pressure measurement, c) determination of blood pressure and hemodynamics from oscillometric waveforms, d) wrist cuff method for acquisition of radial artery waveforms. An important feature of the described methods is that data can be acquired and processed automatically and no special skill is necessary to apply the cuff. Such feature makes a device utilizing these methods suitable for clinical and home environment.

Key-Words: Bioimpedance, blood pressure, hemodynamic, microcontroller, oscillometric waveforms, sensor.

1 Introduction

Studies of arterial pressure pulse date to the 19th century when Marey’s sphygmograph was introduced in 1860. The principle of vascular unloading was introduced in 1876 by Marey [1], who placed the forearm and the hand in a water-filled chamber to which a variable counter-pressure was applied.

A similar phenomenon was observed much later [2], when an air-inflated cuff was used. The point of maximal arterial pulsations in the cuff corresponded to true mean arterial pressure. Pulsations in the cuff are converted into oscillometric waveforms (OMWs) by a pressure transducer, an amplifier and a filter. The bottom trace in Figure 1 shows typical OMWs acquired during a gradual cuff deflation.

The most common application of OMWs is in automatic oscillometric BP monitors. OMW amplitudes have been the center of attention while OMW contours have not been studied extensively. Only a few applications of OMWs that reach beyond BP determination have been reported [3-4]. The lack of attention paid to OMW contours can be explained by the fact that the contours are variably distorted during gradual cuff deflation. The distortion is caused by partial occlusion of the artery under the cuff. Recent research [5] has shown that waveform contours are not distorted at cuff pressures lower than diastolic BP because the artery is free from occlusion at those cuff pressures. The undistorted waveforms can be used in applications where reasonably faithful representation of arterial pulse waveforms is required.

The authors developed a specialized data acquisition and processing system (Carditor) to acquire cuff pressures, oscillometric waveforms and finger photoplethysmographic (PPG) waveforms during a gradual cuff deflation procedure. Carditor was used to develop a database of waveforms and reference blood pressures.
2 Description of Carditor
Carditor (Fig 2) consists of a commercial wrist cuff, a prototype photoplethysmographic (PPG) finger transducer, a module containing pneumatic, pressure and electronic circuits, and a notebook computer with special software. Cuff pressure (CP) is converted into analog voltage by a pressure sensor. The analog voltage is amplified by an instrumentation amplifier and an operational amplifier. The amplified CP voltage is then separated into 2 channels. Analog signal from the PPG transducer is amplified and filtered. The analog signals are then digitized by a 12-bit A/D converter. Sampling rate is 11.8 mS. Gradual cuff deflation is controlled by a current-controlled valve. The module functions and communications with the notebook computer are controlled by special software. One data acquisition procedure lasts 30-40 seconds and is fully automatic.

Figure 2. Carditor – a system for acquisition and analysis of OMWs during a gradual cuff deflation. PPG is a finger photoplethysmographic transducer.

3 Characteristics of oscillometric blood pressure waveforms
Published studies of blood pressure OMWs have concentrated almost exclusively on amplitude changes during a gradual cuff deflation. Studies of OMW contours have been lacking. The authors have studied both the amplitudes and the contours of OMWs during gradual cuff deflation. Carditor was used to acquire cuff pressure, OMWs and PPG data. Reference systolic (SBPREF) and diastolic (DBPREF) pressure values were obtained from left-arm by auscultation with a mercury sphygmonanometer. Sequential measurements were used in order not to interfere with OMW acquisition.

A gradual cuff deflation procedure was divided into 4 segments. The following section describes oscillometric waveform amplitude and shape changes in each segment in terms of vascular unloading and blood flow. The finger PPG waveforms are shown and described to illustrate the changes in blood flow. Phases of Korotkoff sounds are mentioned where appropriate.

The SBPREF value indicates the approximate beginning of turbulent blood flow under the cuff and the DBPREF value indicates the approximate beginning of laminar blood flow under the cuff. Figure 1 shows typical OMW and PPG waveforms during a cuff deflation procedure.

Segment 1: Gradual cuff deflation from the beginning of the procedure to SBPREF.
OMWs are present because the radial artery pulsations are transmitted to the proximal side of the cuff’s bladder. The waveform amplitudes increase as cuff pressure is gradually lowered. No blood flow passes under the cuff, the PPG baseline is flat and Korotkoff sounds are not heard.

Segment 2: Gradual cuff deflation from SBPREF to the cuff pressure equal to mean pressure (MAP). Turbulent blood flow starts passing under the cuff into the vasculature of the hand. Phase I Korotkoff sounds are present. As more flow passes past the cuff, blood volume and pressure in the hand increase due to blocked venous return. The PPG tracing reflects rising volume and pressure in the hand by rising baseline and by increasing waveform amplitudes. When cuff pressure and arterial wall pressure are equal, the OMW amplitudes reach the maximum. The cuff pressure at this point is equal to MAP. The oscillometric waveform contours are distorted because of the continuing partial occlusion of the artery. Blood flow is still turbulent and Korotkoff sounds are present.

Segment 3: Gradual cuff deflation from MAP to DBPREF. The OMW amplitudes start decreasing with decreasing cuff pressures according to vascular unloading. Blood flow is still turbulent. Korotkoff sounds become muffled (Phase IV) when cuff pressure approaches the DBPREF value. The OMW contours continue to be distorted because the artery is still partially occluded. The PPG waveform contours are also distorted. When cuff pressure is at the DBPREF, the flow becomes laminar and Korotkoff sounds are no longer heard (Phase V). The artery under the cuff is free from occlusion and the OMW and PPG contours are no longer distorted.

Segment 4: Gradual cuff deflation from DBPREF to the end of the procedure. When cuff pressure is lowered below DBPREF, the artery under the cuff is free from occlusion, blood flow is laminar and the waveforms are not distorted. Korotkoff sounds are not heard. Lowering cuff pressure further decreases the OMW amplitudes according to vascular unloading. At some arbitrary cuff pressure the cuff is quickly deflated and the deflation procedure is terminated.

Study of OMW contours revealed an important observation: the OMW and PPG contours are distorted during most of the gradual cuff deflation, but at cuff pressures below DBPREF they are not distorted. The cuff
and the pressure transducer essentially form a pneumoplethysmograph [6]. PPG and OMW waveforms recorded at cuff pressure just below DBPREF are shown in Figure 3. Their contours are similar to those observed by other investigators [7-8].

Figure 3. Finger photoplethysmographic (PPG) waveforms (upper trace) and oscillometric waveforms (OMWs; bottom trace) acquired at the DBPREF value.

4 Current oscillometric methods for BP determination

The most common application of OMWs has been in noninvasive BP monitors. All BP monitors use software algorithms to determine BP values. The determination of oscillometric SBP and DBP values has been controversial. Geddes et al observed [9] that SBP values were frequently near the cuff pressure value at OMW amplitude of about 50% of maximal amplitude and diastolic values at 80% of maximal amplitude. This method of SBP and DBP determination is called “characteristic ratio method”. The values based on characteristic ratio method are, however, subject to a large inter-subject variability. The characteristic ratio method is not the only one used in oscillometric determination of SBP and DBP. Methods based on the change in the slope of amplitude envelope have been described. An article describing the function of an oscillometric BP device [10] claims that the device determines SBP as the point of the initial increase of the cuff pulsations. Another author [11] puts SBP on the minimal ascending slope of the amplitude envelope and DBP on the maximum slope of the descending amplitude envelope. The above algorithmic approaches result in differing SBP and DBP values [12]. The algorithms appear to have been developed empirically and the only universally recognized physiological principle is vascular unloading.

5 Algorithms for SBP and DBP determination based on physiology

A study of 32 subjects [5] conducted by the authors showed that blood flow under the cuff alters OMWs in a predictable manner. The central objective of the study was to formulate and test a specific hypothesis. The hypothesis states that the slope (S2) of OMW amplitude envelope between the SBPREF and MAP (Figure 2) is less steep than either the slope (S1) of OMW envelope at above- SBPREF cuff pressures or the slope (S3) of OMW envelope between MAP and DBPREF. The decrease of S2 is caused by blood flowing under the cuff and into the hand’s vasculature. A hand cooling experiment was conducted in order to illustrate that changes in blood flow alter slope S2. The cooling experiment increased the slope S2 from −0.023 to −0.059.

The study results supported the hypothesis and the conclusion that blood flow under the cuff and in the hand is an important variable affecting OMW amplitudes and contours. An SBP algorithm capable of detecting the point of transition from S1 to S2 should be less sensitive to the changes of OMW envelope slopes. Observations of OMW and PPG waveform contours at cuff pressures above and below DBPREF revealed a transition from distorted to undistorted contours. A DBP algorithm capable of recognizing the transition from distorted to undistorted OMW contours should be less sensitive to changes of OMW envelope slopes.

The issue of accuracy is becoming increasingly important as many healthcare institutions rely heavily on automatic BP devices. Published algorithms show disagreements and device manufacturers consider their algorithms proprietary and keep them secret [13]. This makes verification of accuracy difficult.

6 A new method of BP monitor testing based on a database of OMWs and reference BP values

An investigator or a device developer who wants to study oscillometric methods needs a reasonably large database of waveforms and reference BP measurements. Manufacturers of oscillometric BP devices must have such databases in order to conduct their development efficiently. These databases are, however, proprietary. General principles of acquisition and use of databases of physiological waveforms are described in the Association for the Advancement of Medical Instrumentation Technical Information Report [14]. The report stresses the necessity to test algorithmic functions of digital devices with real
physiological data. Properly documented databases are needed for such testing. The authors introduced [15] and further developed [16] the concept of a database of OMWs and reference BP values. The concept is based on acquisition of oscillometric data and reference BP values. The process is similar to the process used by the guidelines for monitor validations. Cuff pressures and OMWs are acquired by a data acquisition system during a gradual cuff deflation procedure. Reference BP values are obtained by a stethoscope and a sphygmomanometer in a sequential manner. Each completed procedure is stored and documented. Validation guidelines requirements for the range of BPs and arm circumferences can be followed during the database development. The database concept has 2 major advantages over currently used validations and testing of oscillometric BP monitors:

1. The database needs to be developed only once and it can then be used repeatedly to test oscillometric BP algorithms and to develop new ones.
2. Oscillometric BP monitors could be equipped with interfaces allowing database OMWs to bench-test performance. Such testing is not presently possible. The expensive BP monitor validations as performed today could be eventually eliminated.

8 Blood pressures and hemodynamics derived from OMWs.
Oscillometric BP waveforms are suitable for BP determination and the OMWs acquired at or below DBP are suitable for further analysis. The authors developed software that is used in the Carditor system to determine BPs and hemodynamics [3,25]. Carditor performs an oscillometric BP test and then acquires OMWs for determination of left ventricular ejection time (LVET) and stroke volume (SV). After a test, subject’s weight and height are manually entered and stroke volume is adjusted for body surface area. Carditor’s SV value was calibrated by comparing its value with SV obtained by bioimpedance. Data from the database used for the development of the system were used to compare the hemodynamic values estimated by the system with the values obtained from literature [26-28]. Data from a group of men and women (age 17-76) were used for comparison. The comparison results are shown in Table 1.

Table 1. Mean values estimated by Carditor and values obtained
From literature. MAP=mean arterial pressure, HR=heart rate, SV=stroke volume, CO=cardiac output, TPR=total peripheral resistance.

<table>
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<tr>
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<th>MAP (mmHg)</th>
<th>HR (bpm)</th>
<th>SV (ml)</th>
<th>CO (l/min)</th>
<th>TPR (mmHg)</th>
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<tr>
<td>Carditor (n=41)</td>
<td>107</td>
<td>70 76</td>
<td>5.3</td>
<td>1615</td>
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<tr>
<td>Guyton</td>
<td>-</td>
<td>-</td>
<td>5.35</td>
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<tr>
<td>Richardson</td>
<td>- 70-75</td>
<td>65-75 4.9-5.3</td>
<td>- 5.35</td>
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<td>De Simone (n=544)</td>
<td>- 68</td>
<td>81 5.5</td>
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The ease of use and low cost could make Carditor useful in applications where other methods may not be justified in terms of cost and complexity of operation. A number of investigators published studies demonstrating the utility of hemodynamic measurements and the effects of antihypertensive drugs [21]. Hemodynamically directed antihypertensive therapy has been used successfully by several investigators. The usefulness of serial hemodynamic measurements in resistant hypertension was recently studied and the results showed superior blood pressure control when compared with expert clinical judgment.
Hemodynamically directed therapy of hypertension in pregnancy was conducted in other studies [23]. Carditor’s BP and hemodynamics functions appear to be ideally suited for hemodynamically directed antihypertensive therapy.

9 Wrist cuff method for acquisition and analysis of radial arterial waveforms

A growing number of investigators study radial arterial waveforms in order to obtain information about structural and functional changes of the arterial system and about wave reflections. Applanation tonometry of the radial artery is the prevalent method of obtaining the waveforms. Tonometry requires observer training in order to obtain correct waveforms. Misapplication of the probe can result in distorted waveforms. This disadvantage limits the use of the method. Studies of radial waveforms have been conducted [24-25] and substantive changes in waveform contours in subjects of different ages were found [8]. Waveform contours of the young subjects showed prominent fluctuations. With advancing age the fluctuations become less distinct, the peaks rounded, and waveform amplitudes increased. Central aortic pressure (CAP) is the determinant of cardiac loading and perfusion and it impacts importantly on cardiovascular function. Knowledge of CAP values presents a valuable addition to current noninvasive techniques. CAP is not identical to peripheral arterial pressure. Brachial and radial pressure waveforms are augmented by arterial wave reflections that are superimposed on the original pressure waveform. Estimation of CAP has been made possible by methods based on measurement of peripheral blood pressures and by mathematical transformation of radial tonometry pressure waveforms [26]. A study by Millasseau et al [27] showed that CAP can be estimated from the radial waveform and peripheral BP values using a simple formula.

Radial artery waveforms can be obtained from a wrist cuff (Figure 5). The advantage of the wrist cuff method is that no training is required to acquire the waveforms. The cuff is applied in the manner identical to the application of wrist blood pressure cuff. The authors acquired wrist cuff waveforms from young, middle age, and elderly volunteers with the Carditor system. Waveform acquisition procedure was fully automatic and lasted about 20 sec. Wrist cuff radial waveforms acquired by Carditor (Fig 5) showed changes in contours and amplitudes with age that were similar to the changes in waveforms acquired by radial tonometry [8].

10 Conclusion

Oscillometric blood pressure waveforms are currently used almost exclusively for BP determination. The authors developed several innovative ways of utilizing OMW properties that have the potential to improve noninvasive BP measurement and to estimate hemodynamic variables. An important advantage of these innovations is that data can be acquired, processed and displayed automatically and no special skill is necessary to apply the cuff. Such advantage makes a device utilizing these innovations suitable for clinical and home environment.

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References


