Dual-Cuff Method Improves Accuracy of Blood Pressure and Hemodynamics Determination

JIRI JILEK\(^1\), MILAN STORK\(^2\)

\(^1\) Carditech, Culver City, California, USA
\(^2\) Dept. of Applied Electronics and Telecommunications/RICE Faculty of Electrical Engineering, University of West Bohemia, CZ

Abstract: This paper describes a method that uses two cuffs to improve accuracy of blood pressure and hemodynamics estimation. A specially designed dual-cuff experimental system was used to acquire and process data from the two cuffs. The arm cuff provided cuff pressures and cuff arterial pulse waveforms. The arm cuff pulse pressure waveforms were used to compute mean arterial pressure (MAP), systolic pressure (SBP) and diastolic pressure (DBP) values. The SBP and DBP values were computed with characteristic ratio method. Wrist cuff waveforms were used for the emulation of auscultatory measurement of SBP and for the determination of stroke volume. Stroke volume, heart rate, cardiac output, total peripheral resistance, and systemic arterial compliance were computed. The obtained dual-cuff blood pressure values were compared with values measured by the characteristic ratio arm cuff method. The computed hemodynamics variables were displayed numerically and graphically.

Key-Words: Blood pressure, hypertension, hemodynamics, cuff waveforms, dual-cuffs, quadrant

1 Introduction
Cardiovascular disease (CVD) is the leading cause of death in many countries. An important contributor to CVD is hypertension. Hypertension is a frequent reason for visiting a physician. Diagnosis and management of hypertension starts with an accurate blood pressure (BP) measurement.

Blood pressure measurement as used today started with the introduction of the sphygmomanometer by Italian physician Riva-Rocci in 1896 \([1]\). Riva-Rocci originally used wrist (radial artery) palpation to detect the pulse. The palpation method was later replaced by Korotkov \([2]\), who used a stethoscope to listen to sounds that were called Korotkoff sounds. Korotkoff sounds are caused by partial compression of the artery under the cuff. Partial artery compression causes the blood flow to be turbulent and the turbulence produces the sounds. The Korotkoff method for determining the systolic (SBP) and diastolic (DBP) pressures marked the beginning of the auscultatory method for blood pressure determination. The manual auscultatory method uses a sphygmomanometer (inflatable cuff and a manometer) and a stethoscope. With the stethoscope placed over the brachial artery, the cuff is slowly deflated. The SBP is determined as the point at which Korotkoff sound is first heard (phase I). The DBP is the cuff pressure (CP) at which the Korotkoff sounds are no longer heard (phase V). Blood flow at this point is no longer turbulent.

Automatic, electronic NIBP devices started appearing shortly after the introduction of microprocessors. In automatic auscultatory NIBP measurement, at least one microphone is used in place of a stethoscope to detect Korotkoff sounds. The microphone must be placed correctly over the brachial artery for proper function of the device. The need for external microphone was eliminated with introduction of the oscillometric method \([3]\). This method uses amplitudes of pulsations evoked in the cuff during gradual cuff deflation. Posey and Geddes \([4]\) determined that the point of maximum pulse amplitude was equal to mean arterial pressure (MAP). When cuff pressure was increased or decreased from the point of MAP, the pulse amplitudes decreased. Geddes later compared manual BP measurements with cuff pulse amplitudes \([5]\) and found that the SBP was frequently equivalent to the 50% of MAP amplitude on the ascending amplitude envelope slope. The point of DBP was found to be at about 80% amplitude on the descending envelope. This method is called the characteristic ratio method. Figure 1 shows cuff pressures (CP) and cuff pulse waveform (CPW) amplitude envelope during gradual cuff deflation. The waveforms appear well above the
Blood pressure is an important component of hemodynamics. Hemodynamics determine the flow of blood in the circulatory system. Clinical hypertension can be characterized by elevated MAP which equal to the product of cardiac output (CO) and total peripheral resistance (TPR).

\[ \text{MAP} = \frac{\text{CO} \times \text{TPR}}{80} \text{ [mmHg,l.min}^{-1}, \text{dyn.sec.cm}^{-5}] \] (1)

Elevation of MAP can be caused either by increased CO or by increased TPR. This relationship relates to the steady phenomena and it does not take into account the fact that blood pressure fluctuates about the MAP during the cardiac cycle. TPR is obtained by dividing MAP by CO.

\[ \text{TPR} = 80 \times \frac{\text{MAP}}{\text{CO}} \text{ [dyn, mmHg, L/min]} \] (2)

Cardiac output (CO) is obtained by multiplying stroke volume (SV) by heart rate (HR). Stroke volume is the amount of blood ejected into the aorta by left ventricle during each cardiac cycle.

\[ \text{CO} = \text{SV} \times \text{HR} \text{ [l.min}^{-1}, \text{ml, beats.min}^{-1}] \] (3)

More complete hemodynamic approach takes into account systemic arterial compliance (SAC) [5]. SAC influences systolic pressure (SBP), diastolic pressure (DBP) and pulse pressure (PP):

\[ \text{PP} = \text{SBP} - \text{DBP} \text{ [mmHg]} \] (4)

In the arterial system with decreased SAC, PP is higher for the same SV. The importance of arterial compliance has been recognized and its surrogate PP has been found [6] to be a significant risk factor of mortality in older people.

An estimation of systemic arterial compliance [7] is computed by dividing SV by pulse pressure (SBP - DBP).

\[ \text{SAC} = \frac{\text{SV}}{\text{PP}} \text{ [ml.mmHg}^{-1}, \text{ml, mmHg]} \] (5)

The described hemodynamic variables determine SBP, DBP and MAP. The most common essential hypertension is characterized by increased TPR. When CO is increased to abnormally high level while TPR stays the same, the result is hyperkinetic hypertension. Hyperkinetic hypertension occurs mostly, but not exclusively, in younger individuals. Isolated systolic hypertension (ISH) is characterized by increased SBP and normal or decreased DBP due to decreased SAC and increased TPR [8]. ISH occurs mostly in older individuals.

## 2 Problem Formulation

The oscillometric method of NIBP determination has become very popular. Elimination of an external microphone made oscillometric BP monitors easier to use at the cost of decreased accuracy. It can be seen in Figure 1 that the SBP and DBP points are not easily determined from the cuff pressure waveforms (CPW) amplitude envelope. The points of SBP and DBP depend on the amplitude envelope slopes. The slopes are, however, variable. One of the important factors affecting the slopes is arterial compliance [9]. A number of studies questioned the accuracy and reliability of the oscillometric method [10]. The manual auscultatory method of BP measurement is still considered by the healthcare establishment to be the gold standard of NIBP measurement [11]. Unfortunately, even the manual auscultatory BP measurement is not error-free. The impact of human error on BP measurement is a well described and substantial problem. Human errors include rapid cuff deflation, incorrect stethoscope positioning, incorrect cuff selection, inadequate rest period, digit bias, poor observer concentration, and lack of repeated measurements. Automatic BP monitors remove some, but not all, human errors and they introduce other errors. Incorrect cuff selection causes errors even in automatic devices. Cuff too small causes incorrectly high BP values and a cuff too large causes low BP values [12].

Wrist cuff BP monitors typically use cuff width of about 6 cm that results in under-cuffing of many
patients with wrist circumferences larger than 17 cm [13].

Accurate BP determination is crucial from a public health standpoint. A systematic error of underestimating BP 5 mmHg would mean that millions of persons who would benefit from treatment for hypertension would be mislabeled as having high normal BP. A systematic error in the opposite direction could misclassify millions of people as high normal rather than hypertensive [11].

A device that provides more accurate and reliable BP measurement together with determination of hemodynamics is highly desirable.

3 Problem Solution

The authors developed an experimental dual-cuff system that can provide more accurate BP measurements and hemodynamics determination. The system is an improvement over the earlier version described previously [14]. The early version employed small wrist cuff 6 cm wide with resulting decreased accuracy of BP measurement.

Figure 2. Block diagram of the dual-cuff system module. USB cable connects the module to a notebook computer.

The dual-cuff system consists of a compact module with pneumatic and electronic circuits, two detachable cuffs (arm and wrist), and a notebook computer that is connected to the module via a USB cable.

Block diagram of the main module with cuffs is in Figure 2. The two pneumatic and analog circuits for the cuffs are similar. Air pumps inflate the cuffs and cuff deflation is controlled by the valves. Piezoelectric pressure transducers (pr.xducer) provide analog signal that is amplified, filtered, and separated into two channels. One channel provides cuff pressure and the other channel provides amplified cuff-pressure waveforms. The resulting analog signals are digitized in the submodule. Analog-to-digital conversion is 12-bit, 85 conversions/sec operation. The digitized data are converted into USB format and made available to the notebook. The notebook contains special software that controls the module’s functions and receives four channels of digitized data. We designed the specialized software as Windows-based multifunction system that performs data acquisition and processing functions. The function used in this study is “Dual-cuff”.

Figure 3. Wrist (WW) and arm (AW) cuff waveforms. The values of CP and SBP are in mmHg.

The dual-cuff function uses auscultation. When CP is gradually lowered, Korotkoff sounds and pulse waves appear downstream past the arm cuff at CP just below SBP. Korotkoff sound frequencies are not detected by the wrist cuff – the pulse waves are. Pulse waves travel downstream along the brachial, radial, and digital arteries. Radial pulse waves are detected in a pre-inflated wrist cuff. The appearance of wrist cuff waveforms (WW) can be observed in Figure 3. At CP approximately 140 mmHg the arm cuff wave (AW) is present but the wrist cuff wave (WW) is not. When CP is lowered to SBP, the WW is present simultaneously with the AW and first Korotkoff sound can be heard. SBP in Figure 3 is equal to 133 mmHg. As CP is lowered further, the WW amplitudes rapidly increase while AW amplitude increases are much smaller. The value of SBP can be determined from the onset of WW amplitudes automatically and more accurately.
than from AW amplitudes. In the example in Figure 3 the value of SBP determined by the oscillometric method is equal to 118 mmHg.

Table 1 shows results obtained from ten volunteers in sitting position. The values were computed from the same set of CP, WW and AW data acquired during gradual arm cuff deflation. The WW data were acquired at expected CP values below the point of DBP. The CP was held at that pressure during the entire procedure. The values of wrist systolic BP (WSBP) were computed automatically with an algorithm developed by the authors. The algorithm computes the WSBPs as CP at the first occurrence of a WW waveform.

Table 1. Mean values of wrist method SBP (WSBP), arm cuff SBP (ASBP), mean difference (d) and standard deviation of d (SD). Sample size n=10. All values are in mmHg.

<table>
<thead>
<tr>
<th>WSBP</th>
<th>ASBP</th>
<th>Mean d</th>
<th>SD (d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>142.3</td>
<td>136.4</td>
<td>5.9</td>
<td>9.62</td>
</tr>
</tbody>
</table>

The values of arm cuff SBP (ASBP) were computed automatically with an amplitude ratio algorithm developed by Geddes [5]. The algorithm determines SBP as cuff pressure at the point of 50% of maximal AW amplitude. Mean difference between mean WSBP and ASBP was 5.9 mmHg and standard deviation SD was 9.62 mmHg. The largest positive difference was 18 mmHg and largest negative difference was 12 mmHg.

Figure 4. Wrist cuff waveforms (WW) and arm cuff waveforms (AW) at arm cuff pressures near diastolic pressure point (DBP).

The determination of DBP using wrist cuff waveforms is more difficult than determination of SBP. The WWs and AWs appear contiguously from the point of SBP to the end of BP test. DBP determination has to rely on subtler waveform changes, Figure 4 shows WW and AW waveforms from CP equal to 93 mmHg to below the point of DBP. Examination of the wrist waveforms reveals distortions at cuff pressures above DBP. These distortions are two-fold. The diastolic segments have flattened bottoms and the amplitudes of these WWs are smaller than those at and below the point of DBP. The WW distortions are, however, variable just as the WW amplitudes and the contours themselves are variable. An algorithm for automatic DBP determination using wrist cuff waveforms has not been yet developed. Instead, visual examination of WW waveform contours was used to determine WDBP values. The point of DBP (WDBP) was determined as CP at which the WW distortions are no longer present.

Table 2. Mean values of wrist method DBP (WDBP), arm cuff DBP (ADBP), mean difference (d) and standard deviation of d (SD). Sample size n=10. All values are in mmHg.

<table>
<thead>
<tr>
<th>WDBP</th>
<th>ADBP</th>
<th>Mean d</th>
<th>SD (d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>81.1</td>
<td>78.8</td>
<td>3.2</td>
<td>4.62</td>
</tr>
</tbody>
</table>

The results in Tables 1 and 2 show the differences between the wrist cuff and arm cuff blood pressures. The WSBP and ASBP differences are larger than the differences between the WDBP and ADBP. The reason for the larger SBP differences is the slope of the amplitude envelope (see Figure 1). The slope of the envelope from the point of SBP to the point of MAP is much less steep than the slope from DBP to MAP. These slopes are not fixed, but the SBP to MAP slope change will produce larger measurement difference than the DBP to MAP slope [13]. The wrist cuff wave method does not depend on the slope. It is similar to the auscultation method with Korotkoff sounds. It depends only on the appearance of wrist cuff waveforms for SBP and on the disappearance of wrist waveform distortions for DBP. Blood pressures and hemodynamic variables are computed by software developed by the authors. Blood pressure values computed from the arm cuff are used for computation of MAP, TPR, PP, and SAC.
Formulas (1), (2), (4) and (5) were used. The value of SV is computed from the wrist cuff waveforms. The waveforms obtained from the wrist cuff at cuff pressure near the point of DBP have been shown to be similar to radial waveforms obtained by other methods [15,16]. More accurate values of SBP, DBP and MAP result in more accurate hemodynamic variable values. The value of SV is not affected, but the values of MAP, TPR, PP, and SAC are. For example, mean value of PP from formula (4) obtained from the wrist cuff is 61.2 mmHg and the value from the arm cuff is 57.6. Mean value of SAC obtained from formula (5) with SV=80 ml is equal to 1.31 ml for wrist cuff values and 1.38 ml for arm cuff values.

The computed blood pressure and hemodynamic variables are displayed on the computer screen as numeric values and as a “quadrant” graphic format (Figure 5). The quadrant shows the relationships of CO, TPR and SAC. TPR and SAC are graphically represented by small rectangles that move together on the vertical axis according to the value of CO. TPR and SAC rectangles are positioned on the horizontal axis according to their values. The right side of the quadrant represent normal values and the left side represent hypertension. Left ventricular ejection time (LVET) is presented only numerically because it does not have a direct relationship to the other hemodynamic variables.

4 Conclusion
The presented dual cuff method promises improved accuracy of BP determination and determination of hemodynamic variables. The results and conclusions of this study are preliminary. Development of an algorithm for automatic determination of DBP is under way. Larger population studies are needed to establish the reliability of the presented methods.

ACKNOWLEDGMENT
Milan Stork’s participation was supported by the European Regional Development Fund and Ministry of Education, Youth and Sports of the Czech Republic under project No. CZ.1.05/2.1.00/03.0094: Regional Innovation Centre for Electrical Engineering (RICE). M. Stork is with the Regional Innovation Centre for Electrical Engineering, University of West Bohemia, Univerzitni 22, Plzen, Czech Republic.

References:


