Dual-cuff System for Improved Determination of Blood Pressures and Hemodynamics

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Abstract: Accurate measurement of blood pressure (BP) is important for diagnosis and treatment of hypertension. Noninvasive BP measurements performed manually or automatically are subject to errors. We developed an experimental system that uses two cuffs in order to improve accuracy of noninvasive BP measurement. The system consists of a compact module with pneumatic and electronic circuits, two detachable cuffs (arm and wrist), and a notebook computer connected to the module via a USB cable. The notebook’s special software controls the module’s functions and receives four channels of digitized data. We designed the specialized software as a Windows-based multifunction system that performs automatic determination of BP and hemodynamics. Dual-cuff BP function uses the wrist cuff as a substitute for a stethoscope for improved accuracy. The wrist cuff is also used for computation of hemodynamics.

Key-Words: Blood pressure, hemodynamics, microcontroller, cuff-pulse waveforms, sensor.

1 Introduction
High blood pressure (BP) is a major public health issue, affecting millions of individuals in the world. Control of BP begins with accurate measurements [1] leading to appropriate diagnosis and treatment decisions. Even minor errors in BP measurement can misclassify many individuals. Conventional BP measurement uses a sphygmomanometer and a stethoscope. The observer inflates the cuff to a pressure higher than the anticipated systolic blood pressure (SBP). Cuff pressure is then slowly reduced and the observer listens for the first appearance of Korotkoff sounds and the cuff pressure is noted as the SBP. The observer then waits for the disappearance of Korotkoff sounds. The cuff pressure at that point is equal to the diastolic pressure (DBP).

The impact of human error on blood pressure measurement is a well-described and substantial problem [2]. Use of automated devices rectifies some but not all of these problems. Automatic BP monitors are used widely in healthcare institutions and in homes. The most widely used upper-arm and wrist BP monitors use pulses in the cuff to determine SBP and DBP values. Upper-arm monitors are the most prevalent type but wrist monitors are gaining popularity with home users.

The cuff-pulse (oscillometric) method uses pressure pulse waveforms (PWs) evoked in the cuff during gradual cuff deflation (Fig. 1) [3]. The PW amplitudes increase with decreasing cuff pressure (sections S1,S2) until they reach the point of mean arterial pressure (MAP) and then the amplitudes decrease (Section S3) until the end of the procedure. The transition point between the sections S1 and S2 is the point of SBP.

Cuff-pulse BP monitors utilize PW amplitudes to algorithmically determine blood pressures. Some algorithms have been published, but commercial algorithms are not usually revealed by the device manufacturers [4]. Published algorithms differ in their approaches. Some algorithms use PW amplitude ratios while other algorithms use changes in the PW amplitude envelope slope or sudden changes in PW amplitudes. These algorithms have been developed...
empirically. One published algorithm [5] uses the cuff pressure at 50% of maximal PW amplitude (PWmax) as the point of SBP and (80%) of PWmax to determine DBP. Another published algorithm [6] uses ratio of 40% for SBP and 60% for DBP. This type of algorithm is called "characteristic ratio" algorithm. Commercial algorithms are considered intellectual property and are kept secret. Different algorithms inevitably result in different BP values and their empirical nature results in unpredictable errors. In spite of errors attributed to the manual BP measurement, the manual method remains the "gold standard".

Several years ago we developed a system that attempted to improve accuracy of systolic pressure determination with a finger photoplethysmograph (PPG) [7]. The results were promising, but the method had several disadvantages, specifically the need for a finger PPG and poor signal-to-noise ratio when the patient’s fingers were cold. Further research led to the development of a system that uses two cuffs.

2 Description of the system
The 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.

- **Dual-cuff test** – uses both the upper-arm and wrist cuffs. The arm cuff is used to acquire brachial cuff pressure pulses and the wrist cuff is used in a manner similar to a stethoscope; appearance of wrist-cuff pulses indicates SBP. SBP, MAP and DBP values are also determined by a commonly used ratiometric method from the arm cuff pulses.
- **Wrist-cuff test** – uses only wrist cuff pulses. Blood pressures and hemodynamics are determined from wrist waveforms and body area.
- **Show waveforms** – shows waveforms from both cuffs or only from wrist cuff.
- **Show Quadrant** (wrist test only) – shows hemodynamics numerically and graphically.
- **Store test** – stores all raw data and subject name in a numbered file.
- **Get test** – gets raw data from disc file and performs computations.
- **Variables** – shows important computed variables.
- **Test directory** – shows test (file) numbers and subject names.

![Figure 2. Block diagram of the dual-cuff system module. USB cable connects the module to a notebook computer.](image)

Block diagram of the module with cuffs is in Fig. 2. The two pneumatic and analog circuits for the cuffs are similar. Pumps inflate the cuffs and cuff deflation is controlled by the valves. Piezoelectric pressure transducers (pr.xdcr) 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 the following functions:

- **Dual-cuff test** – uses both the upper-arm and wrist cuffs. The arm cuff is used to acquire brachial cuff pressure pulses and the wrist cuff is used in a manner similar to a stethoscope; appearance of wrist-cuff pulses indicates SBP. SBP, MAP and DBP values are also determined by a commonly used ratiometric method from the arm cuff pulses.
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![Figure 3. Wrist waveforms (WW) and arm waveforms (AW) obtained simultaneously. Systolic pressure (SBP) is the point of WW appearance.](image)
3 Results of tests

Waveforms acquired during dual-cuff test are shown in Figure 3. The upper trace shows waveforms from the wrist cuff (WW) and the lower trace shows waveforms from the arm cuff (AW). The appearance of the WW indicates SBP. In the test shown in Figure 3 the SBP measured by WW appearance was 174 mmHg and the SBP determined by ratiometric method was 159 mmHg.

Figure 4. Graphic and numeric results of a wrist cuff test.

Figure 5. Waveforms (WW) acquired from wrist cuff at DBP level.

The computed blood pressure and hemodynamic variables are displayed on the computer screen as numeric values and as a “quadrant” graphic format (Fig. 4). The quadrant shows the relationships of cardiac output (CO), total peripheral resistance (TPR), and systemic arterial compliance (SAC). 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. Abnormal values (usually accompanied by hypertension) are located in the left half. In the example (Fig. 4) the values 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 5 shows waveforms acquired from wrist cuff at the cuff pressure 78 mmHg, just below DBP level of 81 mmHg. The results are shown in Tables 1 and 2. The range of SBP values was 117 - 141 mmHg. The range of DBP values was 68 – 89 mmHg. Mean reference pressure values: SBP =131 mmHg, MAP=95 mmHg, DBP=79 mmHg.

All the S2 slopes are less steep than the S1 slopes regardless of blood pressure values. Most of S3 slopes are steeper than S2 slopes. Mean slope values: S1=0.125, S2=0.056, S3=0.093.

Table 1. Measured and computed blood pressure data from 10 subjects in sitting position. All values are in mmHg.

<table>
<thead>
<tr>
<th>Subject</th>
<th>SBP&lt;sub&gt;REF&lt;/sub&gt;</th>
<th>MAP</th>
<th>DBP&lt;sub&gt;REF&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>131</td>
<td>99</td>
<td>89</td>
</tr>
<tr>
<td>2</td>
<td>132</td>
<td>89</td>
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<td>3</td>
<td>138</td>
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</tr>
<tr>
<td>10</td>
<td>143</td>
<td>95</td>
<td>81</td>
</tr>
<tr>
<td>Means</td>
<td>131</td>
<td>95</td>
<td>79</td>
</tr>
</tbody>
</table>

The notebook controls all pneumatic and electronic functions of the system via USB interface. Specialized software performs acquisition of waveforms and corresponding cuff pressures, waveform display, and computations of waveform amplitudes and derived variables. The system is capable of evaluating either standard single cuff pressures or dual-cuff pressures. Dual-cuff BP measurement is more accurate. Dual-cuff method uses the wrist cuff as blood flow pulse sensing device in a manner similar, but not identical, to a stethoscope as used in the traditional BP measurement. The wrist cuff is inflated to a near-DBP pressure and blood flow pulse modulates the cuff pressure. Figure 5 shows brachial cuff OMWs and wrist cuff waveforms (WCWs). The algorithm for SBP determination detect the onset of WCWs.
A standard commercial brachial cuff 12 cm wide and a 6 cm wide wrist cuff were used to obtain reference BP values. Reference SBP value was obtained first with the system in dual-cuff mode. The OMWs and the corresponding cuff pressures were obtained from the brachial cuff.

Ten volunteers were tested in the sitting position with both cuffs positioned at heart level. The values of MAP were determined as cuff pressure at the point of maximum OMW amplitude. Software routine developed by the authors was used to compute the values of MAP.

Table 2. Computed values of slopes S1, S2 and S3.

<table>
<thead>
<tr>
<th>Subject</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.213</td>
<td>0.056</td>
<td>0.154</td>
</tr>
<tr>
<td>2</td>
<td>0.062</td>
<td>0.046</td>
<td>0.13</td>
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<tr>
<td>3</td>
<td>0.11</td>
<td>0.03</td>
<td>0.09</td>
</tr>
<tr>
<td>4</td>
<td>0.21</td>
<td>0.081</td>
<td>0.055</td>
</tr>
<tr>
<td>5</td>
<td>0.073</td>
<td>0.072</td>
<td>0.059</td>
</tr>
<tr>
<td>6</td>
<td>0.11</td>
<td>0.043</td>
<td>0.087</td>
</tr>
<tr>
<td>7</td>
<td>0.18</td>
<td>0.048</td>
<td>0.082</td>
</tr>
<tr>
<td>8</td>
<td>0.11</td>
<td>0.085</td>
<td>0.083</td>
</tr>
<tr>
<td>9</td>
<td>0.092</td>
<td>0.058</td>
<td>0.1</td>
</tr>
<tr>
<td>10</td>
<td>0.091</td>
<td>0.045</td>
<td>0.088</td>
</tr>
<tr>
<td>means</td>
<td>0.125</td>
<td>0.056</td>
<td>0.093</td>
</tr>
</tbody>
</table>

4 Discussion
The described dual-cuff system expanded and improved functions of an earlier version of the system [8] that used only a wrist cuff. The dual-cuff system offers more complete evaluation of blood pressures and hemodynamics. The use of an arm cuff is a standard method of BP determination and the use of wrist cuff to determine SBP values is an improvement over the ratiometric method used in most monitors. The amplitude ratio algorithms are not true physiological methods. The amplitude ratios for SBP and DBP are based on statistics and they assume that the amplitude envelope slopes are even. The example in Fig. 3 showed SBP value determined with dual-cuff as 174 mmHg. The arm-cuff ratiometric method showed SBP = 159 mmHg. The error in the ratiometric determination appears to be due to uneven slope S1 of the amplitude envelope (Fig. 1). Such errors of measurement have been reported [9] and they appear to be one of the reasons for the continuing use of manual BP measurement as a “gold standard” [1].

Quadrant hemodynamic representation in Figure 4 facilitates better visualization of the interplay of hemodynamic variables and their movement from a “good” part of the quadrant (right side of the quadrant) to the “bad” side (left side of the quadrant) in hypertension. The hemodynamic variables TPR (total peripheral resistance), SV (stroke volume), CO (cardiac output), and SAC (systemic arterial compliance) determine blood pressure (BP) values. High CO with high TPR results in increased BP level. High SV with low SAC results in increased pulse pressure (PP). Manipulation of the independent variables either with lifestyle modification or with medication is easier with their values known and with their graphic representation. Hemodynamically directed management of resistant hypertension has been shown to improve outcome when compared with empiric “expert” hypertension management [10].

Hemodynamics play an important role in pregnancy. Cardiac output in pregnancy is increased 30 – 40% over pre-pregnancy level. It is important in managing pregnancy hypertension to use drugs that do not decrease cardiac output. Decreased cardiac output could compromise the fetus [11].

Finally, it should be noted that the waveforms acquired from the wrist cuff at or below DBP level (Figure 5) can be used in a manner similar to the waveforms obtained with radial tonometry [12, 13, 14]. The arm and wrist cuffs are shown in Figure 6.

Wrist cuff method has the advantage of automatic data acquisition where trained observer is not required as is the case with radial tonometry. Radial pressure waveforms have been used for estimation of aortic augmentation index (AI) and more accurate estimation of aortic pressure [15]. The example of dual-cuff blood pressure measuring is shown in Figure 7.

Figure 6. Example of 2 different width cuff used for measuring.
5 Conclusions
The described experimental dual-cuff system for improved BP measurement and for determination of hemodynamics is easy to use and its BP and hemodynamics determination are fully automatic. Unlike other, more expensive systems used in a laboratory environment, the dual-cuff system can be used in a clinic or a home.

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References