Digital Blood Pressure Estimation with the Differential Value from the Arterial Pulse Waveform

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Abstract – In this study, we proposed the new method to estimate the blood pressure with the differential value of the digital arterial pulse waveform and BP relation equation. To get the digital arterial pulse waveform, we designed and implemented the arterial pulse waveform measurement system acquires from the digital air-pressure sensor device and transmits to the smartphone app through the Bluetooth communication. The acquired digital arterial pulse waveforms are classified as hypertension group, normal group, and hypotension group, and we can derive the average differential value between the highest point and lowest point of a single waveform of individuals along with the group. In this study, we found the functional correlation between the blood pressure and differential value as a form of BP relation equation through the regression process on the average of differential value and blood pressure value from a tonometer. The Experimental results show the BP relation equation can give easy blood pressure estimation method with high accuracy. Although this estimation method gives somewhat poor accuracy for the diastolic, the estimation results for the systolic show the high accuracy more than 90% compare to the commercial tonometer.

Keywords: Digital arterial pulse waveform, Blood pressure measurement, Differential value, BP relation equation, Non-Kortokoff method

1 Introduction

The blood pressure measurement is a sort of the basic medical treatment and the blood pressure is one of the most important biomedical signals of one’s health status. Therefore, every medical staff always measures and checks a patient’s blood pressure and health status at the hospital. There are two traditional methods to measure a patient’s blood pressure so called the Kortokoff’s method and the oscillometric method. These methods have been used for a long time on lots of medical devices, and still adopted on the current electronics tonometer [1]. But the Kortokoff-type tonometer attacks the arteries and veins by high pressure until blocking the blood current, it would hurt the blood vessels. This is why the traditional methods have a great drawback that cannot be applied to a patient repetitive or continuous blood pressure measurement [2]. Therefore, we need a Non-Kortokhoff blood pressure measurement method that can measure the blood pressure continuously without blocking the blood vessel.

1.1 Aim of the continuous blood pressure measurement

In many cases, hypertensives or pregnant women have to measure or monitor the blood pressure variation 24-hours continuously. Since the traditional Kortokoff-type tonometer has to block the blood current completely and release the vessel slowly, many trials cause a serious damage to the patient’s artery or vein and make some dangerous hemorrhage in many cases. So we have to take continuous blood pressure measurement with a non-Kortokoff method not to press the blood vessel. If we can try to measure the blood pressure without heavy press on the vessel, we can check the blood pressure over 24-hours and more continuously [3]. In this study, we measured the arterial pulse waveform that represents the continuous pressure variation of the blood current in the artery by using the digital sensor unit and smartphone app, and composed the blood pressure estimation algorithm with the differential value of the arterial pulse waveform. With this method, we don’t have to block the artery or to press the vessel deeply that can take a long time period blood pressure measurement.

1.2 Arterial pulse waveform measurement

The arterial pulse waveform from a digital sensor unit can be described as two types of waveform, integral waveform and differential waveform. The differential waveform shows the series of the blood pressure variation per unit time and the integral waveform shows the series of the blood pressure value itself as time flows. Figure 1 shows the same blood pressure variation with the differential waveform (a) and integral waveform (b) respectively.

Since blood pressure is the pressure value of blood current directly oppresses the vessel, the integral waveform has more advantages than differential waveform to find out...
the relation between the blood pressure and arterial pulse waveform. Therefore, we adopted the integral type digital sensor unit that can produce a series of the digital signal in a form of the integral waveform that can be used to estimate the blood pressure value such as systolic and diastolic.

The remaining part of this paper is organized as follows: Section 2 describes the related works and studies concerned with the proposed method; in Section 3 we defined the relation between the arterial pulse waveform and blood pressure and in Section 4 we provide the experimental environment that carries the proposed method; Section 5 contains analysis of the proposed method including blood pressure relation equation, blood pressure estimation, and its experimental evaluations; the paper is concluded with some summarizing remarks and further studies in Section 6.

2 Related works

The blood pressure measurement has been studied by lots of researchers through various ways of the method for a long time. Most of the studies have been concentrated on the advance method based on the traditional Kortokoff’s method or oscillometric method and its applications rather than focused on a new method development. In general, blood pressure can be checked the blood current pressure in the artery with non-invasive way from the outside of blood vessel. Some Japanese researchers had studied a kind of non-invasive method that can measure the blood pressure from the blood vessel inside [4]. Another research studied on the remote technique to monitor the patient’s blood pressure and health status through the wrist-banded type sensor device [5]. Although the existing wrist-type tonometer based on the oscillometric method still oppresses the artery of the wrist by using the air-cuff at every blood pressure measurement trial, the electronics sensor based non-invasive methods measure the blood pressure with the pressure value from the sensor unit [6]. Since non-invasive method could not guarantee the accuracy within the acceptable error range, there are still many oscillometric method based electronics tonometer supported by digital techniques. Many types of research on the u-Healthcare area are interested in the Zigbee, Bluetooth and WiFi wireless communication environment that can connect the electronics healthcare devices to the smartphone, smart pad and smartwatch [7, 8, 9]. But these approaches has been tried to measure the blood pressure directly with the digital sensor. This way eventually has a kind of limitation on the method that has no other considering factors besides the pressure parameter. In this paper, we proposed the blood pressure estimation method with the arterial pulse waveform generated by the blood current in the artery by using digital sensor without oppressing the blood vessel and focused on the evaluation of its effectiveness.

3 Relation between the blood pressure and arterial pulse waveform

The arterial pulse is a kind of impact pulse generated by the heart beat and has closely related to the blood pressure, the pressure of the blood impact to the blood vessel [10]. If we assume there is always the same external pressure parameters such as the atmosphere or the pressure on the skin outside the artery, the amplitude of an arterial pulse waveform would be increased or decreased along with the blood pressure. So, if we find out the relation between the amplitude of the arterial pulse waveform and actual blood pressure, we can easily calculate the real blood pressure by measuring the amplitude of the arterial pulse waveform.

3.1 The differential value

The differential value of an arterial pulse waveform can be defined as the difference between the highest point and lowest point in a single waveform \( W_i \) from the continuous arterial pulse waveform \( W \). It can be represented as \( \Delta P_i \), the same value as the difference between the \( S \) point and \( P \) point as shown in Figure 2. In a case of the continuous arterial pulse measuring, there are so many waveforms in the consecutive arterial pulse waveform data. So, we can get the differential values as many as the number of waveforms.

![Figure 2 Differential value \( \Delta P_i \) from waveform \( W_i \)](image)

The arterial pulse waveform has various amplitudes and shapes in detail according to the individuals. Therefore, the differential value also has lots of different values also. In this study, we analyzed the relation between the differential value and blood pressure and researched the blood pressure estimation method through the differential value.

3.2 Relation between the blood pressure and arterial pulse waveform

Most of the arterial pulse waveform have almost the same shape for every patient but has a little difference among the detail shapes. The main characteristics of an arterial pulse waveform are the period, linear curve shape and a differential value of each pulse. The period of a waveform corresponds to the pulse count [11], and linear curve shape is concerned with the heartbeat and status of the artery [12]. The differential value of the waveform would be concerned with the blood pressure, but there is no research or report about the exact relation between two factors. In this study, we had investigated various types of volunteer and found out the typical pattern of the arterial pulse waveforms as shown in Figure 3. It shows that there are distinct differences of the differential value among the waveform types. In the clinical case of blood pressure, systolic pressure has more important than diastolic pressure. In general, a hypertensive has higher
systolic pressure than normal person’s systolic pressure average, and a hypotension patient has a tendency to lower systolic pressure than normal person’s systolic average [13]. Therefore, if we can find out the relation between the differential value and the systolic pressure or diastolic pressure, we can estimate the blood pressure with the differential value from one’s arterial pulse waveform.

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3.3 Blood pressure relation deduction

To determine the relation between the differential value of the arterial pulse waveform and blood pressure, we have to know what kind of relation between the measured blood pressure from the tonometer and the differential value. To examine the relation, we measured the blood pressures and amplitude of waveforms from many volunteers and deducted the relation equation through regression process. If there is a sort of functional relation between the differential value and the real blood pressure as a result of regression, we can make the BP(Blood Pressure) relation function (1), (2) correspond to the differential value as follows:

\[
\text{Systolic (AP)} = \text{Reg(Systolic avg, AP avg)} \quad (1)
\]

\[
\text{Diastolic (AP)} = \text{Reg(Diastolic avg, AP avg)} \quad (2)
\]

\(\text{AP avg} \) : Average of \(\text{AP}_i, i = 0, \ldots, n\)

\(n\) : number of peaks \(W_i\) in \(W\)

\(\text{Systolic avg}\) : Average systolic value of a volunteer

\(\text{Diastolic avg}\) : Average diastolic value of a volunteer

To calculate the \(P_{avg}\) and \(\text{Systolic}_{avg}\), we need lots of clinical data on systolic pressures and arterial pulse waveforms. In this study, we designed and implemented the experimental environment for blood pressure measurement, and gathered systolic pressures and arterial pulse waveforms from 3-kinds of samples: hypertensives, normal persons, and hypotension patients.

4 Experimental environments

4.1 Measurement environment

The arterial pulse waveform measurement system is composed of a digital sensor unit, Bluetooth communication network, and smartphone app. The digital sensor unit has air pressure sensor enclosed in a non-press round-type cuff that can detect the pressure variation from outer vessel [14]. The air pressure sensor can output the pressure variation as an integral form of signal that can help measuring the arterial pulse waveform directly. The round-type cuff includes air pressure sensor, Bluetooth communication module that can transmit the digital sensor output values to a specific smartphone, and battery module as shown in Figure 4. The arterial pulse waveform data measured through the digital sensor unit from the wrist vessel is transmitted to the smartphone through the Bluetooth module in the cuff and saved in the smartphone memory while showing the waveform on the screen via the smartphone app.

![Figure 4 implemented arterial pulse measurement system](image)

Table 1 Environment parameters

<table>
<thead>
<tr>
<th>System Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampling Rate</td>
<td>120Hz</td>
</tr>
<tr>
<td>ADC Resolution</td>
<td>20 bit (8bit downsampling)</td>
</tr>
<tr>
<td>Sensor Type</td>
<td>Integral Output</td>
</tr>
<tr>
<td>Initial Sensor Pressure</td>
<td>852 mmHg</td>
</tr>
<tr>
<td>Bluetooth Protocol</td>
<td>2.1+EDR</td>
</tr>
</tbody>
</table>

4.2 Measurement of the differential value

The arterial pulse waveform measurement system converts the waveform data into the differential value \(\Delta P_k\).
and finally conducts the average of differential value $\Delta P_{avg}$ as shown in Figure 5.

$$\Delta P_{avg},$$ the average of differential values $\Delta P_k$ from the arterial pulse waveform of individual volunteer, can be used as input data for building the BP relation equation and can be applied to calculate the systolic pressure.

In this experiment, all volunteers are categorized into three independent groups. All members in Group#1 participated in the experimental data collection to get the BP relation equation. Group#2 and Group#3 participated in the experiments for estimating blood pressure by using BP relation equation. Table 2 shows numbers of volunteers and samples in each group. Group#1 samples were picked from the college students in a class. Group#2 and Group#3 samples were picked from the college men and college women in another class respectively. Each sample was categorized as hypertension that has the systolic pressure over 130mmHg, normal between 105mmHg and 130mmHg, hypotension under 105mmHg.

<table>
<thead>
<tr>
<th></th>
<th>Hypertension</th>
<th>Normal</th>
<th>Hypotension</th>
<th>Total Volunteers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group #1</td>
<td>11</td>
<td>32</td>
<td>11</td>
<td>54</td>
</tr>
<tr>
<td>Group #2</td>
<td>4</td>
<td>12</td>
<td>10</td>
<td>26</td>
</tr>
<tr>
<td>Group #3</td>
<td>8</td>
<td>17</td>
<td>4</td>
<td>29</td>
</tr>
</tbody>
</table>

For each volunteer, we attempted 5 times for arterial pulse waveform measurement and 3 times for tonometer alternatively. All measurement tried with 5 minutes interval. In the experiment, we used two brands of tonometer. One is OMRON101 wrist type electronics tonometer, and another is MEDITEC desk type electronics tonometer. For each volunteer, we tried tonometer measurement 3 times, twice with OMRON101 and once with MEDITEC.

The most important thing on every trial is the fact that the sensor has to oppress the skin on the artery with constant initial sensor pressure during the measurement. But it is very difficult to constant the initial sensor pressure all over the measurement process. Therefore, we had to discard all break-away data over 10% of initial sensor pressure on Table 1, and should take 5 effective arterial pulse waveform data within the unavoidable bandage per individual for deducing the BP relation equation. At the same time, for more precise blood pressure estimation, we also deduced another BP relation equation with data those have 5% of initial sensor pressure variation range and performed extra experiments if this equation can enhance the blood pressure estimation precision or not.

## 5 Experiment results and analyses

### 5.1 BP relation equation

To get the BP relation equation, we first had to measure the average differential values $\Delta P_{avg}$ from each volunteer’s arterial pulse waveform data and average systolic pressures $Systolic_{avg}$ with tonometer for all samples in Group#1. Next, we run the regress process by using Microsoft Excel for all $Systolic_{avg}$ and $\Delta P_{avg}$ and conducted the first-order regression function as equations (3), (4). Figure 6 shows the regression graphs for systolic pressures vs differential values.

\[
\text{Systolic}(\Delta P_{avg}) = Systolic_{angle} \times \Delta P_{avg} + Systolic_{offset} \quad (3)
\]

\[
\text{Diastolic}(\Delta P_{avg}) = Diastolic_{angle} \times \Delta P_{avg} + Diastolic_{offset} \quad (4)
\]

![Figure 6 Regression graphs for systolic vs $\Delta P_{avg}$ at 10% and 5% initial sensor pressure error range](image)

Table 3 shows the regression results of $Systolic_{angle}$, $Diastolic_{angle}$, $Systolic_{offset}$ and $Diastolic_{offset}$ for all volunteers in Group#1. The $Systolic_{angle}$ and $Systolic_{offset}$ show almost the same value at the case of 10% and 5% of initial sensor pressure breakout bandage within 0.05 of standard deviation. Therefore, we can estimate the systolic pressure by using the BP relation equation with over 95% of accuracy. Otherwise, the standard deviation for diastolic has not affordable values, the estimation results would be unreliable.
Table 3 Results of regression for BP relation function for 10% and 5% initial sensor pressure error range

<table>
<thead>
<tr>
<th>Factors</th>
<th>Value</th>
<th>St. deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10%</td>
<td>5%</td>
</tr>
<tr>
<td>Systolic_angle</td>
<td>0.5843</td>
<td>0.6300</td>
</tr>
<tr>
<td>Systolic_offset</td>
<td>100.150</td>
<td>99.084</td>
</tr>
<tr>
<td>Diastolic_angle</td>
<td>0.3617</td>
<td>0.4414</td>
</tr>
<tr>
<td>Diastolic_offset</td>
<td>71.380</td>
<td>63.224</td>
</tr>
</tbody>
</table>

5.2 Blood pressure estimation results

To make sure of the reliability and usability of the BP relation equation (3) and (4), we have to validate the precision of the BP relation equation. Therefore, we extracted the differential values $\Delta P_i$ from the arterial pulse waveform data for the samples in Group#2, calculated the average differential value $\Delta P_{avg}$, and estimated the systolic pressure and diastolic pressure corresponded to the $\Delta P_{avg}$. Figure 7 and Figure 8 show the analysis results of the differences between the tonometer and blood pressure estimation with $\Delta P_{avg}$ for Group#2 and Group#3 by using BP relation equation at 10% initial sensor pressure variation range.

The analysis results show that systolic pressure estimations for Group#2 and Group#3 have less than 10% errors. Otherwise, diastolic pressures have unreliable maximum 66% error rate. It was already expected at the stage of the regress function of the BP relation equation for the diastolic pressure. Though the BP relation equation has high reliability for the systolic pressure, it has also unacceptable standard deviation for the diastolic pressure and expected the high error on experimental estimation.

Figure 8 shows that estimation results for Group#3 have lower precision than Group#2. It can explain the fact that the blood pressures of the college women were lower than the college men, and overall blood pressure distribution skews at hypotension. Therefore, Group#3 has remarkable estimated diastolic pressure error than Group#2.

Figure 9 shows the systolic pressure estimation accuracies for Group#2 and Group#3 at 10% initial sensor pressure variation range and at 5% variation range. Both two cases, though the BP relation equation is almost the same, the accuracies of the estimated systolic pressures are somewhat different, especially for the hypertension case. This result shows that accuracy of the estimated systolic pressure depends on how to sustain constant initial sensor pressure. Therefore, a technique to make the constant initial sensor pressure all over the measurement process is very important to enhance the systolic pressure estimation accuracy. As the experimental results on systolic pressure estimation, although the blood pressure estimation method with the proposed differential value from the arterial pulse waveform has nice estimation accuracy on the systolic pressure, but has poor performance on diastolic pressure. If there are more volunteers, we also can get more accurate
regression function for BP relation equation. But it can enhance the BP relation equation only for systolic pressure estimation, not for the diastolic pressure estimation. Therefore, the proposed blood pressure estimation method can be used effectively to estimate the systolic pressure. Moreover, the initial sensor pressure should be sustained constantly and it is very difficult to contact the sensor on the skin with constant pressure. But if we can reduce the variation of the initial sensor pressure, we can also reduce the error between the estimated systolic pressure and tonometer and enhance the precision of the blood pressure estimation method.

6 Conclusions

This paper proposed a new blood pressure estimation method by using a differential value from one’s arterial pulse waveform and BP relation equation. The BP relation equation deduced from the regression function between blood pressure measured by the tonometer and differential value measured with the digital sensor unit. As the experimental results with the BP relation equation, although the diastolic pressure estimation has a little bit poor performance, but the systolic pressure can be estimated with over 90% accuracy.

This work has very high possibility to open a new approach for non-Kortokoff-type continuous blood pressure measurement with the BP relation equation and the digital measurement system. But this method should be more precise to have the low error less than 5% compared to a commercial tonometer for clinical blood pressure measurement method. To make this, we have to get more precise BP relation equation through more experimental trials. Moreover, we need to solve many technical problems in maintaining the initial sensor pressure during the experiment to get more precise differential value through stable arterial pulse waveform measurement. Therefore, we will improve the BP relation equation and enhance the stable, non-Kortokoff-type digital arterial pulse waveform measurement system at further research.

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8 References


