A Robust Bioimpedance Structure for Smartwatch-Based Blood Pressure Monitoring

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Abstract: One potential method to estimate noninvasive cuffless blood pressure (BP) is pulse wave velocity (PWV), which can be calculated by using the distance and the transit time of the blood between two arterial sites. To obtain the pulse waveform, bioimpedance (BI) measurement is a promising approach because it continuously reflects the change in BP through the change in the arterial cross-sectional area. Many studies have investigated BI channels in a vertical direction with electrodes located along the wrist and the finger to calculate PWV and convert to BP; however, the measurement systems were relatively large in size. In order to reduce the total device size for use in a PWV-based BP smartwatch, this study proposed and examined a robust horizontal BI structure. The BI device was also designed to apply in a very small body area. The proposed structure was based on two sets of four electrodes attached around the wrist. Our model was evaluated on 15 human subjects; the PWV values were obtained with various distances between two BI channels to assess the efficacy. The results showed that the designed BI system can monitor pulse rate efficiently in only a 0.5 × 1.75 cm² area of the body. The correlation of pulse rate from the proposed design against the reference was 0.98 ± 0.07 (p < 0.001). Our structure yielded higher detection ratios for PWV measurements of 99.0 ± 2.2%, 99.0 ± 2.1%, and 94.8 ± 3.7% at 1, 2, and 3 cm between two BI channels, respectively. The measured PWVs correlated well with the BP standard device at 0.81 ± 0.08 and 0.84 ± 0.07 with low root-mean-squared-errors at 7.47 ± 2.15 mmHg and 5.17 ± 1.81 mmHg for SBP and DBP, respectively. The result demonstrates the potential of a new wearable BP smartwatch structure.

Keywords: blood pressure; bioimpedance; pulse wave velocity; pulse transit time; wearable structure

1. Introduction

High blood pressure (BP) is dangerous for humans, especially for elderly people. BP control and monitoring are essential to avoid diseases such as heart attack, heart failure, and stroke. There are some existing noninvasive BP measurements that can be used at home; however, they require a cuff or they do not measure BP automatically. In order to develop a ubiquitous device that can measure BP continuously, pulse wave velocity (PWV) has been investigated [1]. PWV is the velocity of the blood traveling between two arterial sites. By measuring the pulse waveforms at two different sites, PWV values can be obtained using the ratio of the known distance and the pulse transit time (PTT) between two locations. Increasing BP level increases the PWV value and vice versa. As shown in Figure 1, on the basis of that relationship and under some assumptions, PWV can be utilized to estimate BP [2].
where $\Delta Z$ is the change in measured impedance, $Z_b$ represents the basal impedance of the segment. Thus, BI measurement has some notable aspects for BP measurement.

To measure the impedance waveform at the wrist, four electrodes are commonly placed above the radial artery in a vertical direction (Figure 2). This structure has shown a strong measured signal because most of the intensity of the electric current passes through the biological tissue. However, the vertical structure is relatively large in size [8,9]. In order to measure two pulse waveforms at a very short distance, this structure still requires a fairly large length. As shown in Figure 3, with the same distance between two BI channels, the horizontal structure shows an advantage in length compared to the vertical structure, which is suitable in size for a smartwatch. However, because the electric current does not fully pass through the biological tissue, the horizontal structure may yield a weak signal in some areas. With these aspects, this paper proposes to employ the horizontal structure at the wrist to calculate PWV values and compare those values to BP levels. In order to evaluate the potential of the proposed model, the horizontal BI structure was located in different body areas at the wrist. To assess the reliability and validity, some analytical parameters were measured and compared to the standard device.
(AD8429, Analog Devices, Norwood, MA, USA) was used. This IA excels at measuring tiny signals.

To detect a very small change in arterial impedance, an ultralow-noise instrumentation amplifier (IA) was used. The RC Wien Bridge network is combined with the positive feedback and has zero phase shift at one frequency. As a result, the output of the operational amplifier generates an oscillation waveform [10]. To detect a very small change in arterial impedance, an ultralow-noise instrumentation amplifier (IA) (AD8429, Analog Devices, Norwood, MA, USA) was used. This IA excels at measuring tiny signals with low input noise performance of 1 nV/√Hz and high common-mode rejection ratio. To amplify,
a 40-dB gain is required. To achieve wide input common-mode range and low power consumption, capacitively-coupled topology was applied at the IA input pins. After obtaining the small signal, the next stage is a lock-in amplifier (AD630, Analog Devices, USA) to separate a small, narrow-band impedance variation from the carrier signal at 100 kHz and interfering noise.

\[
Z = Z_b + dZ = R(K_a + V_S,K_b)
\]

(2)

2.2. Electrode Structures

A prototype horizontal structure for one BI channel is shown in Figure 5b. To demonstrate the potential for long-term monitoring, dry electrodes were employed using 3M™ conductive copper foil. At high frequency, due to the capacitor’s effects, the electrode equivalent circuit consists of the impedance associated with the electrode-skin interface \( R_d \) and polarization \( C_d \) in parallel. In particular, at 100 kHz, those values were 1.3 MΩ and 12 nF, respectively. Thus, the electrode-skin impedance is around 133 Ω at \( |R_d|/C_d| \leq 100 \text{ kHz} \) [11]. The electrode size was 5 × 5 mm². In order to improve the contact between the electrode and human skin, the layer thickness was chosen at 1 mm. The distances between the two voltage sensing electrodes and two current sensing electrodes were 25 mm and 45 mm, respectively. The distances between each pair of sensing electrodes are not equidistant because the arteries at the wrist are not in the center. The electrode dimensions were optimized to fit for the wrist size of all subjects so that the measurement site can produce good signals with the electrode location still near the arterial distribution area.

Those dimensions were designed to suit a normal wrist size and a smartwatch device. The electrodes were fixed on thin general silicone plastic. For a full structure, another channel was used. The distance between the two channels can be flexibly changed. The proposed structure was placed directly on the wrist using a flexible belt to allow stretchability.
2.3. Testing Protocols

To assess the reliability of the proposed structure, 15 human subjects without any history of cardiovascular disease were enrolled (age: 30 ± 5 years; gender: 9 males, 6 females; height: 165 ± 10 cm; weight: 60 ± 10 kg). The study includes three main experiments. First, only one BI channel was tested and validated with a continuous reference pulse sensor. Next, two BI channels were performed to assess PWV measurement at various distances. Finally, the distance between two BI channels was optimized and a prototype PWV-based device was designed and evaluated with a standard BP reference. The following tests were then conducted.

2.3.1. Performance Comparison to Commercial Pulse Sensor

A BI channel was placed in turn from 1 cm to 5 cm as described in Figure 5a with the bracelet line is the origin, while a reflected optical sensor RPS20 (Laxtha, Daejeon, Korea) was located at the index finger as a reference. All ipsilateral measurements were performed with the subject in a seated position with the arm resting on a table. For each subject, both BI and PPG waveforms were recorded over 20 s at various distances to provide five pairs of simultaneous pulse waveform measurements. To evaluate the performance of the proposed BI system, the correlation coefficients (r) and the signal-to-noise ratio (SNR) were calculated in comparison with those from the reference device. In addition, the ensemble impedance waveforms were displayed at different locations on the forearm, and the impedance variations were also computed.

2.3.2. Validation of PWV Measurement

To calculate PWV values, one BI channel was located at the 0-cm line and another channel was placed and moved sequentially from 1 cm to 5 cm. Thus, for each subject, five PWV values were obtained at the different distances between two channels. The waveforms were recorded over 20 s. Next, the PTT values were calculated, and finally, with each distance, PWV was computed.

Ideally, the PTT values are always positive. However, an erroneous transient delay time may still occur during real-time measurement. Negative PTT values can be obtained because of such factors as the effects of motion artifacts and unstable attachment between electrodes and skin. Therefore, the number of negative values must be quantified in order to evaluate the PTT estimation.

In this study, three types of PTT detection were employed to determine the best-performing type for PWV calculation with the fewest errors. As shown in Figure 6b, the peak, middle, and foot points of the impedance waveform were detected. The time intervals between peak-to-peak, middle-to-middle, and foot-to-foot of two waveforms were calculated to provide $PTT_{p-p}$, $PTT_{m-m}$, and $PTT_{f-f}$ values, respectively.

Figure 5. (a) Various locations of the BI channel placed at the wrist for the validation; (b) the electrode dimensions applied in this study.
To quantify the quality of the PTT detection extracted from the individual beats of the BI waveforms at various distances, a detection ratio (DR) was calculated. For a full recording, DR is defined as the ratio between the number of positive PTT values and the total number of PTT values. In other words, DR will be 100% if the recording has no negative PTT values. However, DR does not reflect the magnitude of the measured PTT or PWV values. With $N$ as the total number of beats, DR can be obtained by

$$\text{DR} = \frac{1}{N} \sum_{i=1}^{N} \{\text{PTT}_i \geq 0\}$$

To process the waveform, a band-pass filter ($f_{\text{pass}} = 0.5$–10 Hz) was applied to smooth the signal and reduce the noise as the first step. The low cutoff frequency was selected to eliminate the undesirable signals due to motion artifacts, whereas the other frequency was designed to remove the high-frequency noise and interference. Next, first-order and second-order differentiators were applied to generate the derivative BI waveforms. An automatic beat detection was then performed to detect the three points of the BI waveform: the peak, middle, and foot points. Finally, three types of PTT detections were computed. The average PTT with and without negative values over 20 s was used to calculate PWV for further analysis.

### 2.3.3. Validation of BP Estimation

The standard BP monitoring system Oscar 2 (SunTech Medical, Morrisville, NC, USA) was used as a reference. The proposed device was located at the wrist while the reference device was placed on the upper arm. All measurements were performed with the subject in a seated position with both devices held over the chest area for the best comparison and to prevent errors from the change due to hydrostatic pressure. Both systolic BP (SBP) and diastolic BP (DBP) from the BP reference device were recorded, while the average PTT without errors (negative values) over 20 s was used to calculate the PWV value. All those values were analyzed and evaluated for correlation coefficient and root-mean-squared-error (RMSE) to assess the estimated BP values from the designed device.

To perturb the BP levels, a handgrip exercise was employed. The validation protocol included six sessions. Each session was conducted for 2 min. First, each subject was instructed to relax for 10–15 min to record a baseline BP. Next, the increasing BP values were recorded after the subject...
performed the handgrip exercise. After that, the remaining sets alternated between recovery periods and handgrip exercises were performed to provide a total of six pairs of BP measurements from the reference device and PWV from the proposed design.

3. Results

3.1. Validating the Pulse Waveform and Pulse Rate

Figure 7 shows the ensemble average of BI waveforms at various distances from 1 to 5 cm away from the origin line at the wrist. It can be seen that the BI waveform is more stable for short distances, such as 1, 2, and 3 cm. The other areas achieved significant variation, which is manifested in the large standard deviation (SD). Moreover, the measured waveforms at those areas were lower in amplitude in comparison with the other areas nearer the origin. The actual impedance variations of all areas were computed as shown in Table 1. It is obvious that increasing distances decreased the impedance variations. At 1 cm, the measured impedance is greatest at 325.8 mΩ, whereas the minimum impedance change is 67.2 mΩ at 5 cm.

![Figure 7. Ensemble average of BI waveforms at various locations.](image)

Table 1. Impedance variation, signal-to-noise ratio (SNR) of BI measurement, and correlation coefficients of pulse rate against the commercial device under different location of forearm.

|        | 1 cm         | 2 cm         | 3 cm         | 4 cm         | 5 cm         |
|--------|--------------|--------------|--------------|--------------|--------------|
| \(dZ\) (mΩ) | 325.8        | 275.8        | 238.5        | 143.9        | 67.2         |
| SNR (dB) | 12.65 ± 2.87 | 10.99 ± 1.27 | 10.82 ± 2.99 | 7.75 ± 2.12  | 6.88 ± 2.27  |
| \(r\)    | 0.97 ± 0.03  | 0.98 ± 0.02  | 0.93 ± 0.08  | 0.84 ± 0.09  | 0.82 ± 0.1   |

As shown in Figure 8, the SNRs obtained with the proposed system are nearly equal to those values from the reference device, at approximately 11 dB at 2 cm and 3 cm. The BI system achieved even higher SNR at 1 cm. However, with the areas away from the wrist, the BI measurements obtained 37% lower SNRs at approximately 7 dB at 4 cm and 5 cm.
Table 1. Impedance variation, signal-to-noise ratio (SNR) of BI measurement, and correlation coefficients of pulse rate against the commercial device under different location of forearm.

| Distance (cm) | $dZ$ (mΩ) | SNR (dB) ± SD | Correlation Coefficient (r ± SD) |
|--------------|------------|---------------|----------------------------------|
| 1            | 325.8      | 12.65 ± 2.87  | 0.97 ± 0.03                      |
| 2            | 275.8      | 10.99 ± 1.27  | 0.98 ± 0.02                      |
| 3            | 238.5      | 10.82 ± 2.99  | 0.93 ± 0.08                      |
| 4            | 143.9      | 7.75 ± 2.12   | 0.84 ± 0.09                      |
| 5            | 67.2       | 6.88 ± 2.27   | 0.82 ± 0.1                       |

Figure 8. SNR values of the commercial device and the proposed BI measurements at various locations.

The group average correlation coefficients for estimating pulse rate from the proposed system against the commercial device at various distances are shown in Table 1. The BI system showed strong correlations ranging from 0.82–0.98 versus the reference. The plot of estimated versus reference pulse rate values from both devices for all subjects is shown in Figure 9. A strong correlation at 0.98 for estimating pulse rate was obtained.

Figure 9. Correlation plot of estimated pulse rate (PR) from the proposed structure against the commercial device at various locations.

3.2. Structure Optimization Results

The average DR of PTT detections at different distances between two channels can be seen in Figure 10. All types of PTT detections tended to obtain lower DR with increasing distance. The results showed that $PTT_{p-p}$ yielded the highest DR, while $PTT_{f-f}$ achieved the lowest DR for all distances compared to the other detections. Those values were 99 ± 2.24%, 99.25 ± 2.07%, 94.78 ± 3.73%, 80.03 ± 4.84%, and 62.9 ± 2.85% for $PTT_{p-p}$ from 1 to 5 cm, respectively. Peak-to-peak PTT detection provided 4.9%, 7.1%, and 24.7% higher in DR than middle-to-middle PTT detection;
those values were 11.9%, 9.6%, and 32.6% higher compared to foot-to-foot PTT detection at 1 cm, 3 cm, and 5 cm, respectively.

Figure 10. Detection ratio of three types of PTT detections at various locations.

Figure 11 shows histograms of measured PTT values for a subject over 20 s and the group average PWV with and without PTT errors. With errors, increasing distances increased PWVs. At 4 cm and 5 cm, it can be seen that the negative PTTs degraded the average PTT values, resulting in higher PWVs compared to normal. After eliminating the PTT errors, the computed PWVs are within the normal physiological range. It can be seen that negative PTTs is meaningless for the mean PWV values and should be eliminated. The average PWVs without error were 6.15 ± 0.78 m/s, 5.94 ± 0.75 m/s, 6.28 ± 0.48 m/s, and 6.85 ± 0.5 m/s from 2 cm to 5 cm, respectively. The changes in resulting PWVs were not significant at those distances. However, at 1 cm between the two channels, the PWV value was 3.87 ± 0.39 m/s, which is lower than that of the other distances.

Figure 11. (a–e) Distribution of measured PTT at various distances over 20 s; (f) PWV with and without PTT errors at various distances.
3.3. Correlating between the Estimated PWV and Standard BP Device

From the results of the proposed system at various distances for estimating PWV, the distance between the two channels was optimized. All distances showed good estimated PWV values except 1 cm. On the other hand, only 1 cm and 2 cm resulted in high DR and strong SNR. Therefore, the study was designed to validate the proposed structure at 2 cm between the two channels with the standard BP device. Figure 12 shows the prototype PWV-based BP device with a horizontal structure and BP reference monitoring. The designed smartwatch includes necessary modules such as the display part, controller, battery, and wireless communication. The size of the design is approximately $35 \times 35 \times 25 \text{ mm}^3$.

![Figure 12. Prototype of the designed PWV-based BP smartwatch at the wrist with the BP standard device located on the upper arm.](image)

Table 2 shows the high correlation coefficient between PWV and both BP levels. The group average coefficients were $0.81 \pm 0.08$ and $0.84 \pm 0.07$ for SBP and DBP, respectively. Three representative subjects with different coefficients are shown in Figure 13.

| Subject | Reference SBP (mmHg) | Reference DBP (mmHg) |
|---------|----------------------|----------------------|
| Subject 15 | $r = 0.77$ | $r = 0.75$ |
| Subject 7  | $r = 0.86$ | $r = 0.83$ |
| Subject 3  | $r = 0.97$ | $r = 0.98$ |

![Figure 13. Representative correlation plots between calculated PWV and reference BP.](image)
Table 2. Group average correlation coefficients and root-mean-squared-errors (RMSEs) between estimated systolic BP (SBP) and diastolic BP (DBP) from the proposed device and the standard device.

|       | r    | RMSE (mmHg) |
|-------|------|-------------|
| SBP   | 0.81 ± 0.08 | 7.47 ± 2.15 |
| DBP   | 0.84 ± 0.07 | 5.17 ± 1.81 |

After the validation process, with linear regression, the measured PWV values were then converted to BP levels. The designed system achieved a low error against the reference with SBP RMSE of 7.47 ± 2.15 mmHg and DBP RMSE of 5.17 ± 1.81 mmHg.

The Bland–Altman plots of all predicted BP versus the reference aggregated for all subjects are shown in Figure 14. The mean is illustrated with a black solid line, and the limits of agreement (±1.96 × SD) are represented by red dashed lines. The mean ± SD of the SBP and DBP difference against the reference device are 0.01 ± 8.1 mmHg and −0.06 ± 5.46 mmHg, respectively. It is obvious that all data points from the proposed design lie within the limit of agreement. Thus, the proposed structure can estimate BP values that agree closely with those of the reference device.

4. Discussion

A vertical BI structure has been applied in many studies [8,9,12] because its electric current field can inject more artery area than the horizontal structure. However, for PWV measurement, the design with electrodes arranged in the horizontal direction has shown more advantages. First, the proposed structure has an advantage in terms of size. It is obvious that the horizontal structure can be designed with two channels for a wearable device [13]. Second, a stable BI waveform can be monitored with a sufficiently robust hardware device as designed in this study. However, the proposed structure may not be applied to all locations. At locations 4 cm or 5 cm away from the wrist, the BI waveform was less stable than at other locations. Those locations provide lower values of impedance variation, SNR, and correlation coefficient of pulse rate. The radial artery is closest to the skin surface at the areas near the wrist, for example, at the 1 cm location. Therefore, the quality of the measured BI waveform at the location is decreased by the distance increasing from the origin of the wrist. For this reason, many studies have applied BI measurement near the wrist to obtain more stable waveforms.

The average DR values were degraded with increasing distance. As the reason mentioned previously, while one BI channel located at the origin of the wrist was stable, another channel yielded
large errors. As a result, the calculated PTTs included more negative values in the long distance, such as 4 cm and 5 cm. The peak-to-peak PTT achieved the highest DR compared with the others for all distances. This result demonstrates that PTT\textsubscript{p-p} is the most useful indicator for estimating PTT and PWV with our proposed structure. Another reason is that detection points at the peak may be more accurate than the middle and the foot points, as can be seen in the ensemble average BI waveforms [1].

The less-stable waveforms at 4 cm and 5 cm resulted in a larger error for PTT detection and higher PWV values. However, after removing the errors, similar PWV values were obtained to those of the other positions. As described in Figure 11f, even at 1 cm, the device achieved high SNR with clear waveforms, although the calculated PWVs were lower than others. That can be explained by the effects of one BI channel on the other at a very short distance. Contact between electrodes and skin may cause a certain pressure on the artery, which is quite close to the skin surface at the 1-cm area. Therefore, the blood can travel lower than normal to the next measured location. Thus, actual PTTs at the area near 1 cm and 0 cm were greater than normal, which result in smaller PWV [4]. This effect is negligible at the other positions. Similar results can be found in other studies [6,14]. Thus, the proposed structure at 2 cm from the wrist between two channels tracks well with both BP levels.

In addition to these contributions, this study has some limitations that should be overcome in further study. First, the dimension of the electrodes was designed to be fixed. The size of the electrode structure may affect the electric current field that passes through the artery. Additionally, the relationship between PTT, the distance of the electrodes, and the electrode-to-skin pressure should be investigated. Second, the study did not examine the proposed structure with the conventional BI structure. Because the measured skin is different with both designed structures, the comparison between the two BI structures is not really correct. In addition, in further study, the proposed BI structure can be compared against the PPG structure to assess the advantages of each method. Third, towards a complete device, the designed device must consider the power consumption, total size, and standards for a wearable device. Finally, the BP validation protocol is not diverse. Different BP perturbations must be applied in a further study on a larger number of human subjects.

5. Conclusions

The study proposed a horizontal structure for BI measurements at the wrist to optimize a BP smartwatch based on the PWV method. The BI hardware was designed to apply in a small body area and tested in different locations on the forearm. After comparing to the commercial pulse sensor, two BI channels then estimated PTT and PWV at various distances between the two channels. The wearable device was designed on the basis of the most optimal distance. The optimal device was proposed on the basis of the analysis results while considering wearability. In sum, the proposed design provided good tracking of BP changes in comparison with the standard device. Future work will focus on refinements to reduce the estimated BP errors as well as on designing a new generation of BP smartwatches. Overall, we conclude that the horizontal BI structure is an adequate design that can be considered as a BP device in the future.

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