ABSTRACT
We proposed two unconstrained methods for blood pressure monitoring in a ubiquitous home healthcare. Instead of a conventional oscillometric method, unconstrained pulse arrival time was used. Pulse arrival time is the time delay between Electrocardiogram (ECG) and Photoplethysmogram (PPG). In first method, ECG and PPG could be unconstrainedly obtained in a computer desk environment. In second method, ECG and PPG could be measured in a toilet seat unconstrainedly. The relationship between systolic blood pressure and pulse arrival time was investigated with several experiments. Additionally, the potential of pulse arrival time for blood pressure monitoring was validated in a practical application in a daily life. It showed that these methods were useful for the long term monitoring in a telemedicine.

KEY WORDS
Telemedicine, pulse arrival time, blood pressure, unconstrainedly, ubiquitous home healthcare.

1. Introduction
Blood Pressure (BP) is a vital sign of the physiological status and reflects autonomous activities as well as cardiovascular abnormalities [1]. There are some conventional blood pressure monitoring devices such as oscillometric method and auscultation method. However, theses methods used a cuff, and it could cause tissue necrosis in an application site [2]. Additionally, blood pressure has a circadian rhythm, so it varies distinctly with the time of day, day of week, and season. This variability in blood pressure makes the long-term monitoring of BP necessary. There are a few long-term monitoring devices. However, the cost of the devices is quite expensive, and the devices should only be used under close clinical observation.
There have been some studies to estimate blood pressure from the relationship between pulse arrival time (PAT) and BP without using a mechanical cuff [3][4]. In these studies, blood pressure was altered by various stimulation experiments, and the correlation between PAT and BP was evaluated. In particular, PAT has been shown to be a cardiovascular parameter related to SBP more than diastolic blood pressure and mean blood pressure. However, the PAT in these studies was obtained in a constrained manner with a catheter or a PPG clipped to a finger or toe. Those methods are not consistent with the concept of ubiquitous healthcare and telemedicine because patients should not be burden in their daily life.
In this study, we proposed two methods for estimating SBP by PAT, and to measure PAT unconstrainedly. PAT was calculated from ECG and PPG. Those could be measured unconstrainedly in two methods. In first method, ECG and PPG could be obtained in a computer desk environment, and toilet seat was used in second method. A linear regression method was used to derive a subject-specific BP estimation equation for each person. The methods were verified through a series of experiments. Finally, the two methods were practiced to the application in a daily life.

2. Methods
2.1 Measurement method I: M-PAT (computer mouse)
In this study, the first method was defined as a M-PAT. It means that PAT could be obtained in an office. Previously, we reported a non-intrusive capacitive-coupled ECG measurement system (CC-ECG) on a chair [5]. This system is presented in Figure 1. The chair has two active electrodes and a capacitive ground within the seat cushion. It could measure ECG without a conductive contact, such as a Ag-AgCl electrode, so the patient did not need to take off the clothes for the measurement. A reflective-type PPG sensor (NONIN finger clip 800R, USA) was also mounted on a computer mouse as shown in Figure 1. PPG was obtained from a patient’s thumb as the patient held the computer mouse. ECG and PPG were acquired by a BIOPACK data acquisition system. The
signals were digitized at a sampling rate of 2 kHz with 12-bit resolution.

Fig. 1. Measurement system for ECG and PPG. ECG was measured with two capacitive coupled active electrodes and a capacitive ground. PPG was measured at the patient’s thumb on a PC mouse.

2.2 Measurement method II : T-PAT (toilet seat)

In this study, the second method was defined as a T-PAT. It means that PAT could be obtained in a toilet seat. ECG could be measured by three copper tapes that were placed on a toilet seat as shown in Figure 2. A reflective-type PPG sensor was also set up beneath the toilet seat as shown in Figure 2. The contacting force might affect the PPG signal [6]. However, in this system, the PPG sensor was beneath the toilet seat with a dark gap so that the sensor was not contacting the subject’s skin directly. ECG and PPG were also acquired by BIOPACK system with same sampling frequency above.

Fig. 2. Schematic diagram of the equipment location on the toilet seat. ECG is measured through contact between three copper coated electrodes and the subject’s thigh skin. PPG is measured with a reflective type PPG sensor. PAT is calculated from the time intervals of ECG and PPG.

2.3 Data Processing

Figure 3 shows the measured ECG and PPG signals in this study. PAT was defined as the time delay between the ECG R-peak and the characteristic point of the PPG signal. The characteristic point was defined as a maximum derivative point in this study [7]. So PAT was calculated using the time delay between the ECG R-peak and the maximum derivative point of the PPG signal in each method.

2.4 Experimental Setup

Three subjects were participated in the experiment (age: 25-31, weight: 61-75kg). They have no history of cardiovascular disease. To make the variation of BP within a short time, various stimulations were applied like Valsava Maneuver, Cold Pressor, Static Exercise with horse riding posture. Also, for the reference measurement of blood pressure, Tonometer (CBM 7000, Colin) was used.

3. Results

3.1 Measurement method I: M-PAT (computer mouse)

Figure 4 shows the result of one subject. PAT was calculated by the method suggested above. SBP was measured by Tonometer. Linear regression model was applied to find the relationship between PAT and SBP. With three kinds of stimulation that changes blood pressure temporarily, it has the close relation and SBP can be estimated. In table 1, Pearson Correlation Coefficients were shown for each subject. When we consider the data of 3 subject altogether, based on the differences of many physiological parameters of each person like height, weight, age and others, the correlation coefficient decreases so much. It is not feasible to find the one linear regression parameter value which can be applied to all of the subjects. So the parameter should be customized for each person.

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Fig. 3. Waveforms measured and calculated from each system. PAT was defined as the time delay between the ECG R-peak and the maximum first derivative point of the PPG signal.

Fig. 4. PAT and SBP parameters of each subject during blood pressure changes in M-PAT method.
Table 1. Correlation coefficients and Linear Regression Equation between SBP and T-PAT for each subject in M-PAT method

<table>
<thead>
<tr>
<th>Subject</th>
<th>Correlation coefficient</th>
<th>P-value</th>
<th>Linear Regression Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject 1</td>
<td>R = -0.7868</td>
<td>P &lt; 0.001</td>
<td>SBP = -0.48PAT + 243.59</td>
</tr>
<tr>
<td>Subject 2</td>
<td>R = -0.8933</td>
<td>P &lt; 0.005</td>
<td>SBP = -0.97PAT + 379.95</td>
</tr>
<tr>
<td>Subject 3</td>
<td>R = -0.693</td>
<td>P &lt; 0.001</td>
<td>SBP = -0.59PAT + 289.78</td>
</tr>
</tbody>
</table>

3.2 Measurement method II: T-PAT (toilet seat)

As we did in section 3.1, the correlation between PAT and SBP for one subject was shown in Figure 5. Also, Bland-Altman plot was shown. In Table 2, Pearson Correlation Coefficients were shown for each subject. The correlation showed a good agreement in case of customized analysis for individual too. Subject-specific BP equations may be practical because PCs are often user-specific and the personal identification can be done by weight difference for toilet application. Consequently, M-PAT and T-PAT systems could be suitable for BP estimation if the calibration was made for each individual.

Table 2. Correlation coefficients and Linear Regression Equation between SBP and T-PAT for each subject in T-PAT method

<table>
<thead>
<tr>
<th>Subject</th>
<th>Correlation coefficient</th>
<th>P-value</th>
<th>Linear Regression Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject 1</td>
<td>R = -0.9453</td>
<td>P &lt; 0.001</td>
<td>SBP = -0.68PAT + 317.01</td>
</tr>
<tr>
<td>Subject 2</td>
<td>R = -0.9013</td>
<td>P &lt; 0.001</td>
<td>SBP = -0.43PAT + 246.48</td>
</tr>
<tr>
<td>Subject 3</td>
<td>R = -0.7287</td>
<td>P &lt; 0.001</td>
<td>SBP = -0.80PAT + 336.72</td>
</tr>
</tbody>
</table>

3.3 Long term BP monitoring

Long term BP monitoring was executed in a daily life. For each method, the estimation of BP was made from each person’s linear equation mentioned above. Figure 6 indicates that the estimation of SBP correlated well with the measured SBP. It took for 15 days. The subject went to restroom in the morning, and PAT was obtained in the toilet seat. These two systems have the capacity for long-term BP monitoring.

Fig. 6. Measured SBP and M-PAT-estimated SBP for long term BP monitoring. This data was obtained from 9 AM to 5 PM in an office environment.

Fig. 7. Measured SBP and T-PAT-estimated SBP for long term BP monitoring. This data was obtained from subject 1 every morning for 15 days.

4. Conclusion

The pulse arrival time were measured in non-intrusive ways using electrically non-contact ECG and mounting PPG sensor on the computer mouse and toilet seat cover. To estimate systolic blood pressure, linear regression method was used for the data of each subject. With this method, SBP can be estimated in non-intrusive method. These technologies can be used for long term monitoring, non-intrusive monitoring of the blood pressure for ubiquitous healthcare system and home healthcare system in the future.

Acknowledgements

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References