Non-contact Pulse Transit Time Measurement using Imaging Camera, and its Relation to Blood Pressure

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Abstract

This study reports pulse transit time (PTT) measurements of two areas of the human body (wrist and ankle) by a single imaging camera. The pulse peaks at both areas were extracted by finite impulse response (FIR) low-pass filtering and phase delay compensation. The interbeat intervals (IBIs) obtained by the camera and a photoplethysmogram sensor were almost identical, confirming the temporal accuracy of the camera-obtained peaks, and suggesting the utility of the camera in noncontact PTT measurements. Next, the PTTs were calculated from the time differences between the pulse peaks of the wrist and ankle images, and correlated with vital parameters such as blood pressure and age in ten subjects. A high correlation coefficient of (−0.88) was obtained between PTT and blood pressure, indicating a direct relationship between these two measures.

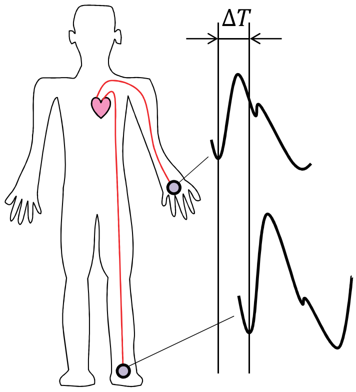

Figure 1. Method of measuring the pulse transit time at two areas of the body.

1 INTRODUCTION

As the global population ages, daily measurements of vital signs such as pulse, heart rate, and blood pressure have become increasingly important for diagnosis and health management. For this purpose, researchers have developed a variety of wearable vital sensors. Vital signs such as pulse rate have also been derived from non-contact sources such as skin surface images[1].

Like the pulse rate, the pulse transit time (PTT) is an important variable in daily health management. The PTT is the time difference between the pulse peaks taken at two distant body regions(Figure 1). In previous study, the PTT was identified as an indicator of blood pressure and arteriosclerosis[2].

However, the PTT can be measured only in a hospital setting by skilled staff using expensive equipment such as blood pressure cuffs. To overcome this limitation, several researchers have proposed PTT measurements using simple contact-based devices[3][4][5]. For example, the PTT can be measured by electrocardiography (ECG) and a photoplethysmogram (PPG)[3][4]. The use of pulse oximeters affixed to the finger and toe has also been suggested[5]. However, the heart rate and pulses detected from cardiac and PPG sensors must be physically contacted with the body. Therefore, continuous monitoring of vital signs in living environments is not easily achieved.

In contrast, if the pulse rate, blood pressure, and other vital signs could be determined from camera images, they could be monitored while subjects are watching television, resting at home, or undertaking other daily activities, enabling continuous monitoring of their health. While non-contact biological measurements based on image signals are simple and noninvasive, the extracted signals are inherently noisy. For calculating the PTT peaks, the temporal accuracy of the signal must be several dozens of milliseconds.

To resolve this problem, we adopted a finite impulse response (FIR) filter with linear phase characteristics, and achieved zero phase by implementing a (number of taps)/2 correction. This techniques extracted the pulse peaks to high temporal accuracy, enabling calculation of the PTT from the time difference between the peaks of the wrist and ankle images. Moreover, the relations between the obtained PTT and physical information such as blood pressure, age, and height, were investigated. The PTT was found to be highly correlated with blood pressure, and less highly correlated with age. Comparing the average PTTs of healthy individuals and individuals with high blood pressure, a significant difference between the two groups was confirmed. The experimental methodology and results are detailed below.

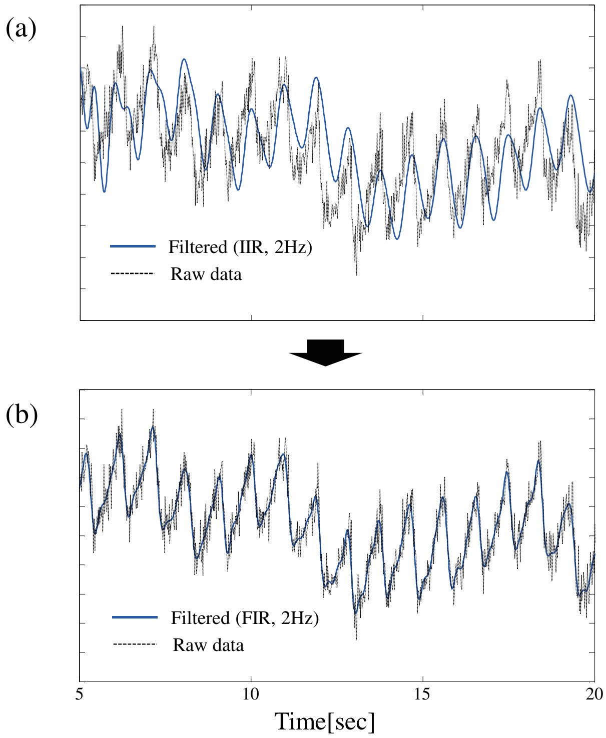

Figure 2. Processing of image data by (a) IIR filter (tap number = 20, cutoff frequency = 2Hz), and (b) FIR filter, (tap number = 100, cutoff frequency = 2Hz). Black dotted lines and blue solid lines show the raw and filtered data, respectively.

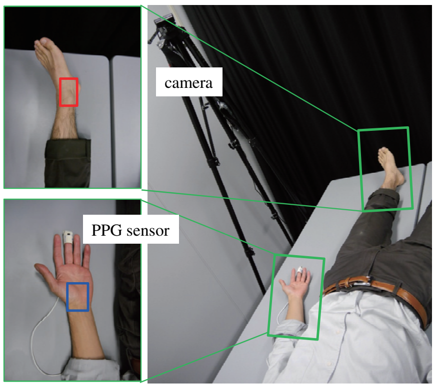

Figure 3. View of the experimental setup. The pulse waves from the wrist and ankle were measured from camera images. The captured pulse waves were validated by PPG measurements collected from a PPG sensor. A camera (60 fps; 640 × 480 resolution) was placed 90 cm from the subject.

2 PULSE PEAK DETECTION METHOD

This section explains how peaks are detected in the pulse signals obtained by the image sensor. In the proposed method, peaks are found by filtering the brightness sequence in the wrist and ankle images obtained by the image sensor. More specifically, the subjects' wrists and ankles were captured by an image sensor, and their raw brightness sequences were smoothed by FIR filtering. The pulse peaks were then detected in the smoothed brightness sequences.

Figure 2 shows the brightness sequence extracted from a subject's wrist image. In this study, the green channel was used because green wavelengths are absorbed by hemoglobin in the blood; therefore, the brightness of the pulse peaks is directly related to the hemoglobin content[6]. The PTT is usually calculated from the arrival point of the pulse (the rising point in a PPG)[7]. As mentioned above, the arrival of a pulse is marked by reduction in the image brightness. Accordingly, the brightness peak (starting point of the decline) indicates the start of the arriving pulse.

The raw brightness data of the green channel contain significant noise (see Figure 2(a)), which largely obscures the peaks. To avoid this difficulty, several researchers have filtered the pulse waves through a low pass filter[8]. However, the phase-delay and distortion of the signal caused by filtering and phase property were not considered.

Since the arrival times of the pulses differ by only several dozen milliseconds, the high accuracy in the peak time is critical. In contrast, the latency caused by the number of taps and the filter process is relatively less important because this study aims to monitor health and blood pressure trends on a daily basis. Therefore, we must consider the accuracy in the peak time and the error introduced by the phase property of the filter.

To achieve the desired accuracy, we applied an FIR (100 taps) low pass filter to the obtained raw data, and implemented a zero phase shift (50 taps) to compensate for the resulting phase distortion. Although the FIR filter generates a processing delay related to the number of taps, it preserves the shapes of the peaks and the waveforms of the vital sign.

In a pilot study, sufficiently accurate peaks with suppressed noise were obtained by imposing a cutoff frequency of 2 Hz. Panels (a) and (b) of Figure 2 show results of filtering through a 20-tap IIR filter, and a 100-tap FIR filter with zero phase shift, respectively. Temporal deviations between the derived and true peaks are clearly visible in Figure 2(a), whereas the peaks in Figure 2(b) neatly overlap the original signal.

This result confirms that the abovementioned processing extracts temporally accurate pulse peaks from images of distant body parts. Furthermore, the accurate PTTs can be measured from the time differences between peaks.

3 EXPERIMENT

The experimental setup is presented in Figure 3. Ten male subjects (age: from 25 to 60; six healthy, four with high blood pressure (systolic blood pressure (SBP) > 135 mmHg)) participated in this experiment. The subjects with high blood pressure were free of any other illness.

As already reported, the PTT depends on the posture of the subject, and can be measured relatively stably in the recumbent position[9]. Therefore, the subjects were requested to lie on their backs and remain still during the measurements, as shown in Figure 3. The

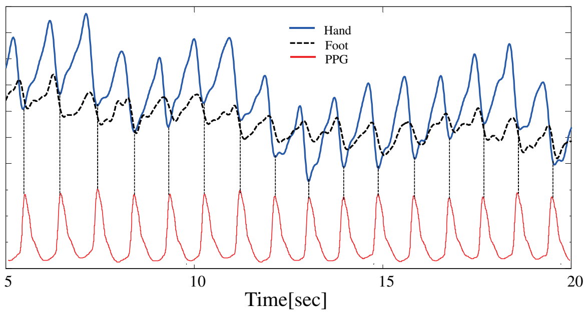

Figure 4. Pulse waves extracted from video images of the wrist (blue solid line) and ankle (black dotted line) and PPG signals taken at the fingertip (red solid line). The peak times of the wrist pulses and PPG signals coincide.

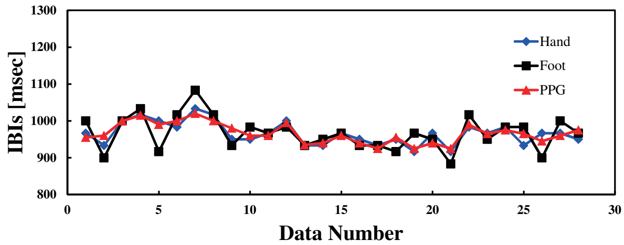

Figure 5. The interbeat intervals (IBIs) between hand pulses (blue), foot pulses (black) and digital pulse volumes (red)

hands and feet were illuminated by an ordinary adjustable fluorescent lamp. Images were by a commercially available camera (Sony, CEJH-15007; frame rate 60 fps) placed 90 cm above the subject (see Figure 3). In this configuration, the wrist and ankle could be simultaneously photographed.

Furthermore, to confirm the temporal accuracy of the pulses obtained from the images, a reference PPG sensor was attached to the fingertip of each subject. The brightness sequences on the wrist and ankle were then acquired. The measurement period was 30 sec, and measurements were duplicated on each subject. To examine the correlation between the PTT and blood pressure, the blood pressure of each subject was measured after each experiment by a cuff-type blood pressure gage (Panasonic, EW-BU35).

4 RESULTS AND DISCUSSION

4.1 Pulse waves extracted from captured images

Figure 4 plots the results of one of the ten subjects. Plotted are the wrist and ankle pulses derived from the camera images the PPG signals. Note that the pulses from the images are inverted from those of the PPG sensor. Inversion occurs because the arrival of a pulse causes a decreases in image brightness, as described previously. In Figure 4, the peaks of the wrist pulse extracted from the images nearly coincide with the PPG peaks.

Table 1. Anthropometric data of all subjects ($n = 10$)

Subject No.	PTT [msec]	SBP [mmHg]	Height [cm]	Age [year]
1	129.9	112	177	42
2	138.2	114	170	30
3	123.4	116	165	37
4	127.2	104	157.5	28
5	120.3	123	164	27
6	129.7	125	178	25
7	110.3	142	170	48
8	85.6	157	174	49
9	92.4	179	146	37
10	100.3	165	168	60

Table 2. Correlations between PTT and vital parameters(SBP, Height and Age)

	SBP [mmHg]	Height [cm]	Age [year]
PTT	-0.879	-0.270	-0.646

In this study, the image sensors and the PPG sensor were manually started, introducing a slight time lag at the beginning of the measurements. Therefore, the temporal accuracy of the image-derived pulse peaks was measured by comparing the interbeat intervals (IBIs) between the wrist pulses and the PPG signals. The results are plotted in Figure 5. In this figure, the horizontal and vertical axes represent the number of data aligned in a temporal sequence and the IBI value in milliseconds, respectively. The average IBI in the PPG data during the 30-s measurement period was 966 ms (62 bpm), which is consistent with the expected number of pulses (50 - 100 bpm) under normal conditions. Although the IBIs vary from 925 to 1020 ms, the IBIs of the wrist pulses and the PPG signals almost coincide. The two IBIs were well-correlated (correlation coefficient = 0.871) and differed throughout 30-s measurement period by 12 ± 9 ms (mean $\pm$ SD).

According to these results, a temporally accurate pulse wave peak can be extracted from images by applying a FIR low pass filter and phase delay compensation. In addition, Figure 4 shows that the pulse peaks derived from ankle images are slightly delayed relative to their wrist counterparts. This delay is attributable to the longer length of the blood vessels between the heart and ankle than between the heart and wrist. The PTT is quantified as the difference between the peak times of the wrist and ankle pulses.

4.2 Pulse Transit Time

As described in the previous section, the PTT is calculated from the time difference between the peaks of pulses derived from the wrist and ankle images.

Table 1 lists the PTTs, SBPs, heights, and ages of the ten subjects. The PTT of each subject is the average of PTTs calculated during the 30-s measurements.

Table 2 shows the correlation coefficients between the PTT and the physical information of the ten subjects. The PTT and height are weakly correlated

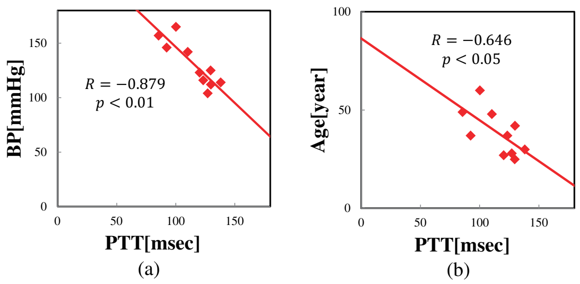

Figure 6. Relations between PTT and (a)Blood Pressure; (b)Age

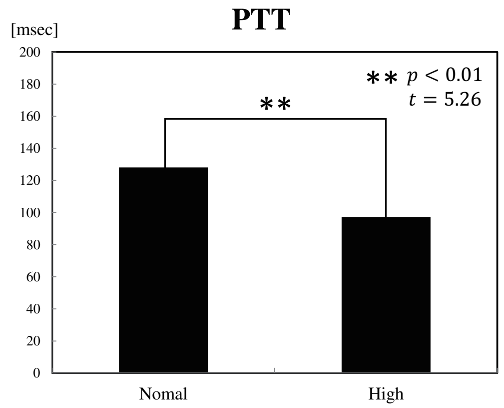

Figure 7. Evaluation of PTT by two-sample t-test. High: hypertensive subjects, Normal: healthy subjects

(-0.2697), indicating that PTT is not an obvious function of height. In contrast, the PTT is significantly correlated with blood pressure and age. The correlation coefficients are -0.879 and -0.646 respectively, indicating that PTT is negatively associated with both variables(see Table 2 and Figure 6). A linearly negative relation between PTT and blood pressure is shown in Figure 6(a). This tendency has also been reported in contact-based measurements[10] and the result indicates the possibility of non-contact PTT and BP measurement.

Next, the relation between PTT and blood pressure was statistically analyzed by t-test. For this purpose, the subjects were divided into two groups; those with SBP of 135 mmHg or higher (the hypertensive group; Subjects 7-10 in Table 1), and the healthy group. A significant difference was observed ($t(8) = 5.26, p < 0.01$, see Figure 7). The mean value of PTT for subjects with high pressure was lower (97.15 ± 10.63 ms) than for healthy subjects (128.12 ± 6.19 ms). The result indicates that PTT may distinguish subjects with high pressure from their healthy counterparts.

5 CONCLUSION

In this study, informative pulses were extracted from human wrists and ankles imaged by camera alone. To obtain the PTT, a FIR low pass filter and phase delay compensation was applied to the captured data, and the peak time differences between the pulses were calculated. The obtained PTT was not strongly correlated with height, but was strongly correlated with blood pressure. The average PTT was significantly lower in hypertensive individuals than in healthy individuals.

In future work, we will improve the accuracy of the PTT measurements by using a camera with a higher frame rate, improving the filter, and refining the peak extraction method with characteristic points. The reliability of the data will be improved by increasing the number of experimental subjects. Finally, the correlations between PTT and blood pressure, and between PTT and other physical information such as arteriosclerosis, require further investigation.

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