System for Simultaneous Measurement of Breathing Rate and Heart Rate using Photoplethysmogram

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ABSTRACT

Wearable vital sensors for monitoring parameters such as breathing rate and heart rate are important for the daily care of patients and solitary people in home healthcare applications. At present, there are many types of heart rate measurement sensors, including those that are attached to the fingertips, chest, and wrist. However, these types of sensors are unsuitable for home healthcare use because they are too bothersome for daily use. These sensors use a photoplethysmogram to measure the heart rate. Although a breathing signal is also superimposed on the heart rate, the problem is that this signal is very weak and unstable. In the work described in this paper, we developed a reliable breathing rate and heart rate measurement sensor. The sensor is attached on the wrist, like a wristwatch. Such wrist-worn sensors already exist, but they are unreliable due to their generally low sensitivity. In contrast, our newly developed sensor employs an array of multiple photo-interrupters and selects the most reliable photo-interrupter by employing a unique algorithm. In addition, the sensor data is sent to a data logger wirelessly in order to achieve stress-free daily health care monitoring.

Categories and Subject Descriptors

J.3 [**LIFE AND MEDICAL SCIENCES**]: Health, Medical information systems

General Terms

Algorithms, Measurement, Experimentation

Keywords

wearable sensor, wrist-watch type pulse sensor, healthcare, photoplethysmogram

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1. INTRODUCTION

Recently, the proportion of the population made up of elderly people has increased. Maintaining the health of these people has become a very important issue [1][2][3][4][5]. Monitoring vital signs, such as the heart rate and breathing rate, 24 hours a day is very useful for this purpose [6][7][8][9]. Some heart rate sensors have been developed for home healthcare use, including those that attach to the fingertip [10][11] and the chest. However, these types of sensors are unsuited for daily use because they are troublesome to use and often cause the users much stress.

A photoplethysmogram (PPG) is a kind of pulse wave obtained by measuring the amount of infrared reflection from a capillary vessel. Although a PPG includes respiratory fluctuations [12][13], breathing measurement devices that exploit such signals have not been developed.

In the work described in this paper, we developed a wrist-worn PPG sensor for measuring heart rate and breathing rate simultaneously. A wrist-worn PPG sensor measures the PPG at the wrist. Measuring a PPG at the wrist is less reliable than a fingertip measurement because there are fewer capillary vessels at the wrist than at the fingertip [14][15][16]. Thus, we devised a photo-interrupter array sensor for performing PPG measurement with high reliability [17][18]. In a demonstration experiment, we were able to use this device to measure the heart rate and breathing rate simultaneously by analyzing respiratory fluctuations superimposed on the PPG.

The remainder of this paper is organized as follows. Section 2 introduces the principles of a PPG. Sections 3, 4, and 5 give details of the photo-interrupter array sensor, the experimental setup, and the method of distinguishing breathing rate and heart rate, respectively. Section 6 presents the experimental results. Finally, Section 7 concludes the paper.

2. PRINCIPLE OF PHOTOPLETHYSMOGRAM

A PPG is a waveform showing the variation in blood flow volume. Fig. 1 shows the principle of a PPG. In the human body, 97% of blood erythrocytes are hemoglobin, which absorbs infrared rays. Since the amount of infrared rays absorbed changes with blood flow volume, this change can be observed optically and converted into an electrical signal.

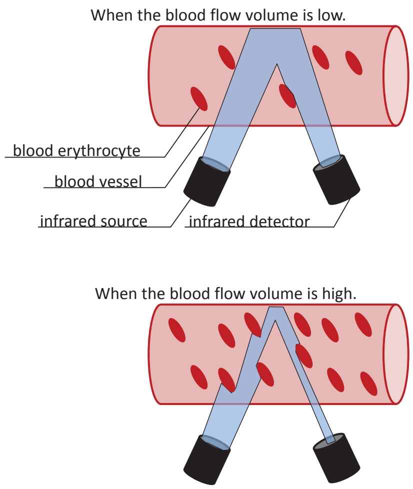


Fig. 1 Principle of photoplethysmogram using infrared absorption.

3. PHOTO-INTERRUPTER ARRAY SENSOR

A photo-interrupter, which is formed of an infrared LED and a phototransistor, can be used to detect a PPG. Fig. 2 shows a PPG measured at a fingertip. The breathing rate and heart rate can be clearly measured from this PPG. Fig. 3 shows a PPG measured at the wrist, which exhibits a strong detection level. In Fig. 2 and Fig. 3, the wave with a period of 3 to 4 seconds is the respiratory fluctuation, and the wave with a period of slightly less than 1 second is the heart rate. In Fig. 2, the heart rate amplitude is approximately 0.8 V, and the breathing rate amplitude is approximately 0.2 V. In Fig. 3, the heart rate amplitude is approximately 0.2 V, and the breathing rate amplitude is approximately 0.9 V. Therefore, the heart rate can be clearly detected from a PPG measured at the fingertip, whereas the breathing rate can be clearly detected from a PPG measured at the writs. Fig. 4 shows a PPG measured at a wrist, which shows a weak detection level. It is not possible to detect the breathing rate nor heart rate from this PPG.

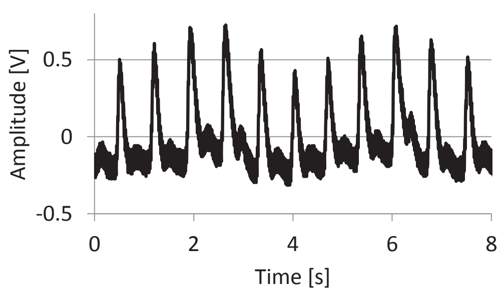


Fig. 2 Photoplethysmogram waveform at the fingertip.

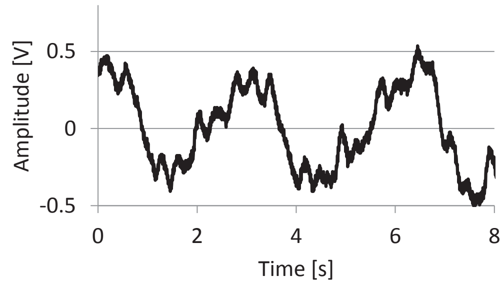


Fig. 3 Photoplethysmogram waveform at the wrist (strong).

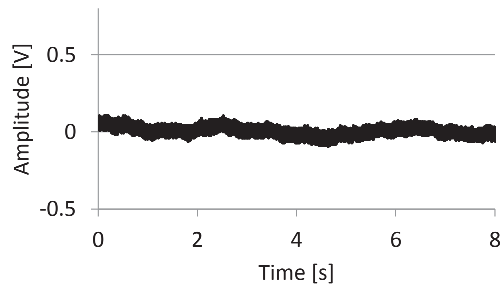


Fig. 4 Photoplethysmogram waveform at the wrist (weak).

A PPG is obtained not only from capillary vessels but from arteries. However, a single photo-interrupter cannot detect a PPG from the arteries because arteries in the wrist are distributed over a wide area, as shown in Fig. 5.

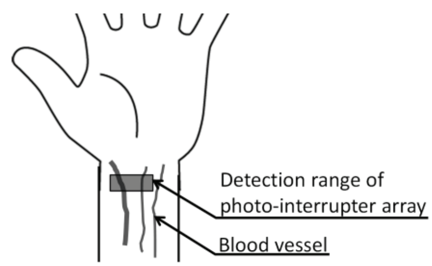


Fig. 5 Detection range of photo-interrupter array.

Fig. 6 and Fig. 7 show measurement points around the wrist (5 mm spacing) and the variation in the detection level of respiratory fluctuations and heart rate pulses, respectively. The horizontal axis in Fig. 7 corresponds to the point numbers shown in Fig. 6, and the vertical axis indicates the magnitude of the frequency spectrum) (f_s = 50 Hz, n = 2048).

We used a reflection-mode photo-interrupter (TPR-105, λ = 940 nm, GENIXTEK CORP., 3.2 mm × 2.7 mm × 1.4 mm, for low-cost and easily-available). We observed that a point having a high detection level ("A" in Fig. 7(a) and (b)) and a point having a low detection level ("B" in Fig. 7(a) and (b)) were close to each other. Thus, we arranged multiple photo-interrupter sensors in a one-dimensional array, so that at least one photo-interrupter sensors can find and detect point "A".

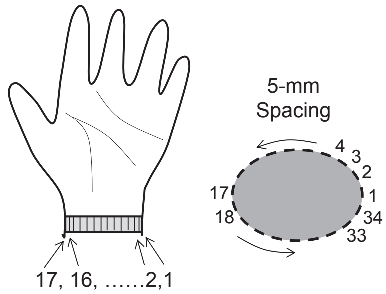
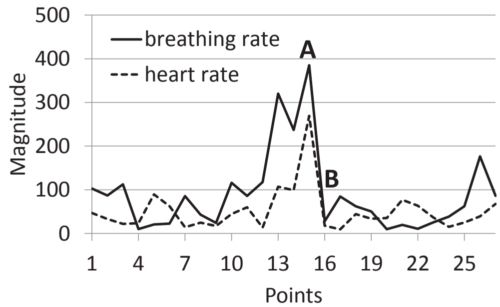
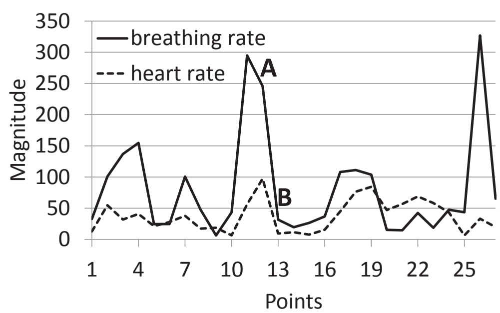


Fig. 6 Detecting points around the wrist.



(a) Right wrist



(b) Left wrist

Fig. 7 Signal strength variation around the wrists.

Fig. 8 shows details of the signal strength distribution around the wrist. The horizontal axis corresponds to the number of points in Fig. 6, and the vertical axis indicates the magnitude of the frequency spectrum, similar to Fig. 7. It was difficult to detect the breathing rate or heart rate spectrum due to the low signal-to-noise ratio when the magnitude was less than 20. Therefore, we regard a point with a magnitude of 20 or more as a detectable point, and a point with a magnitude of less than 20 as an undetectable point.

The maximum distance between detectable points was 16 mm, and the minimum width of each detectable point was 6.4 mm. Therefore, if the total length of the sensors is less than 16 mm, the sensors may miss detectable points, and likewise, if the center-to-center sensor spacing is 6.4 mm or more, the sensors may miss detectable points. Thus, we used four photo-interrupter sensors since the total length of the sensors should be 16 mm or more, and the sensor spacing should be less than 6.4 mm.

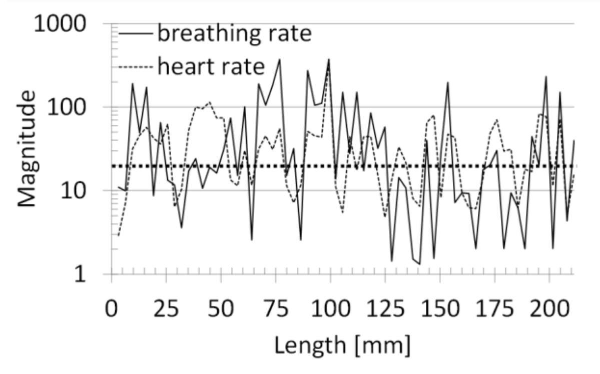
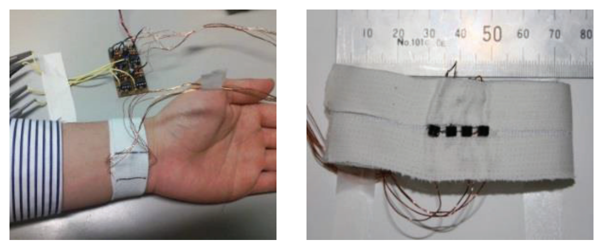


Fig. 8 Signal strength distribution around the wrist.

(Measurement resolution: 3.2 mm)

Fig. 9 shows how the photo-interrupter sensor array was mounted and details of the photo-interrupters. Fig. 10 shows a circuit diagram. In this setup, the signal from the photo-interrupter is amplified and filtered. A high pass filter) (f_c = 0.034 Hz) was used to cut high-frequency noise. An amplifier amplified the signal by 60 dB.



(a) Mounting (b) Photo-interrupters

Fig. 9 Photo-interrupter array.

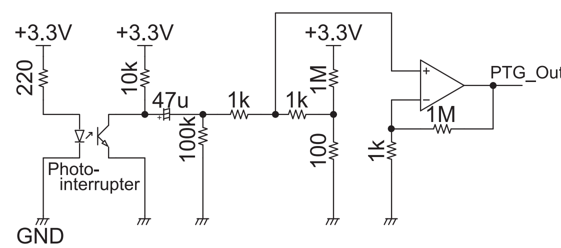


Fig. 10 Circuit diagram of photo-interrupter and amplifier.

4. EXPERIMENTAL SETUP

Fig. 11 and Fig. 12 show the experimental setup. Four photo-interrupter sensors were arranged in a one-dimensional array on each subject's wrist (five subjects participated: two males in their 20s, two females in their 20s, and one male in his 60s), and each output voltage was transmitted to a signal processing PC using a programmable system-on-a-chip microprocessor (PSoC, CY8C29466, Cypress) and a ZigBee RF communications module (XBee, XB24-ACI-001, Digi). The analog-to-digital converter (ADC) had a sampling frequency of f_s = 50 Hz and a resolution of 13 bits.

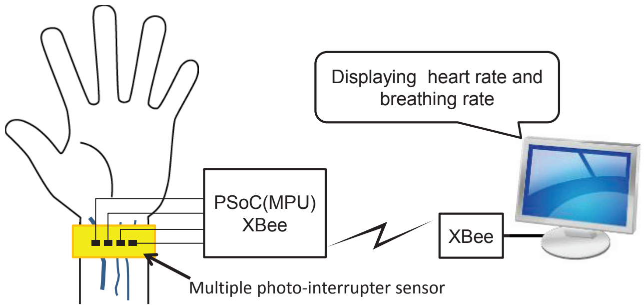
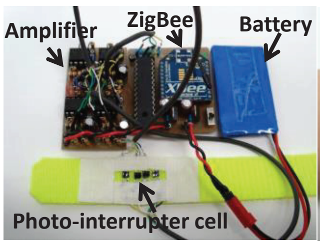
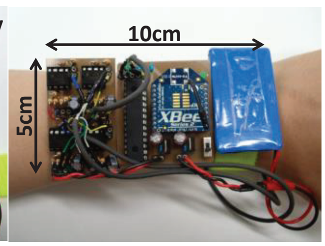


Fig. 11 Configuration of wireless sensor system.



(a) Components



(b) Mounting

Fig. 12 Wireless sensor.

Table I Specifications of wireless sensor.

MPU	PSoC CY8C29466 (Cypress)
Wireless communication module	XBee XB24-ACI-001(Digi)
Battery	Lithium-ion 3.7 V 1050 mAh
Power consumption	~165 mW
Frequency	2.405 GHz
Transmit power	1 mW
Bit Rate	250 kbps
Width	~10 cm
Depth	~5 cm
Height	~1.5 cm
Transmission distance	~5 m
Battery life	Greater than 20 hours

5. METHOD OF DISTINGUISHING BREATHING RATE AND HEART RATE

Fig. 13 shows an example of the PPG frequency spectrum in which a respiratory fluctuation is superimposed. The respiratory fluctuation frequency was about 0.32 Hz, and the heart rate frequency was about 1.31 Hz. The resting heart rate of a human ranges from about 140 beats per minute (bpm) for newborn infants to about 50 bpm for elderly people, which corresponds to a frequency from about 2.33 Hz to 0.83 Hz [19][20]. Thus, a spectral peak falling within these limits is determined to be the heart rate, and a spectral peak of less than 0.83 Hz is determined to be the breathing rate.

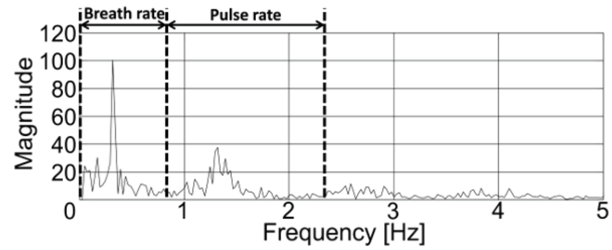
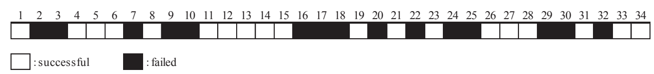


Fig. 13 Frequency spectrum based on data from wireless sensor.

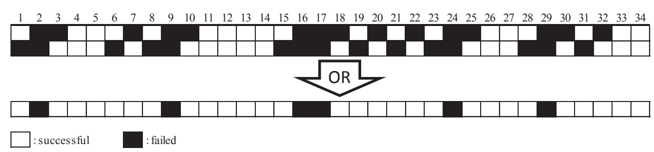
6. EXPERIMENT

6.1 Output of sensor array

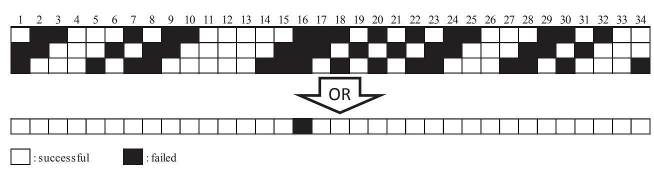
Fig. 14 shows the success rate of correctly discriminating between the breathing rate or heart rate with different numbers of photo-interrupters. White points indicate success, and black points indicate failure. For example, in Fig. 15(a), point 1 shows that detection was successful, and points 2 and 4 show that detection was unsuccessful. If the number of photo-interrupter sensors is increased, the success rate will also increase. Fig. 16 shows the result of five subjects.



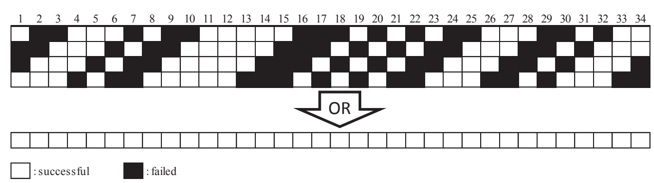
(a) One photo-interrupter



(b) Two photo-interrupters



(c) Three photo-interrupters



(d) Four photo-interrupters

Fig. 14 Success rate of correctly discriminating between heart rate and breathing rate with different numbers of photo-interrupters.

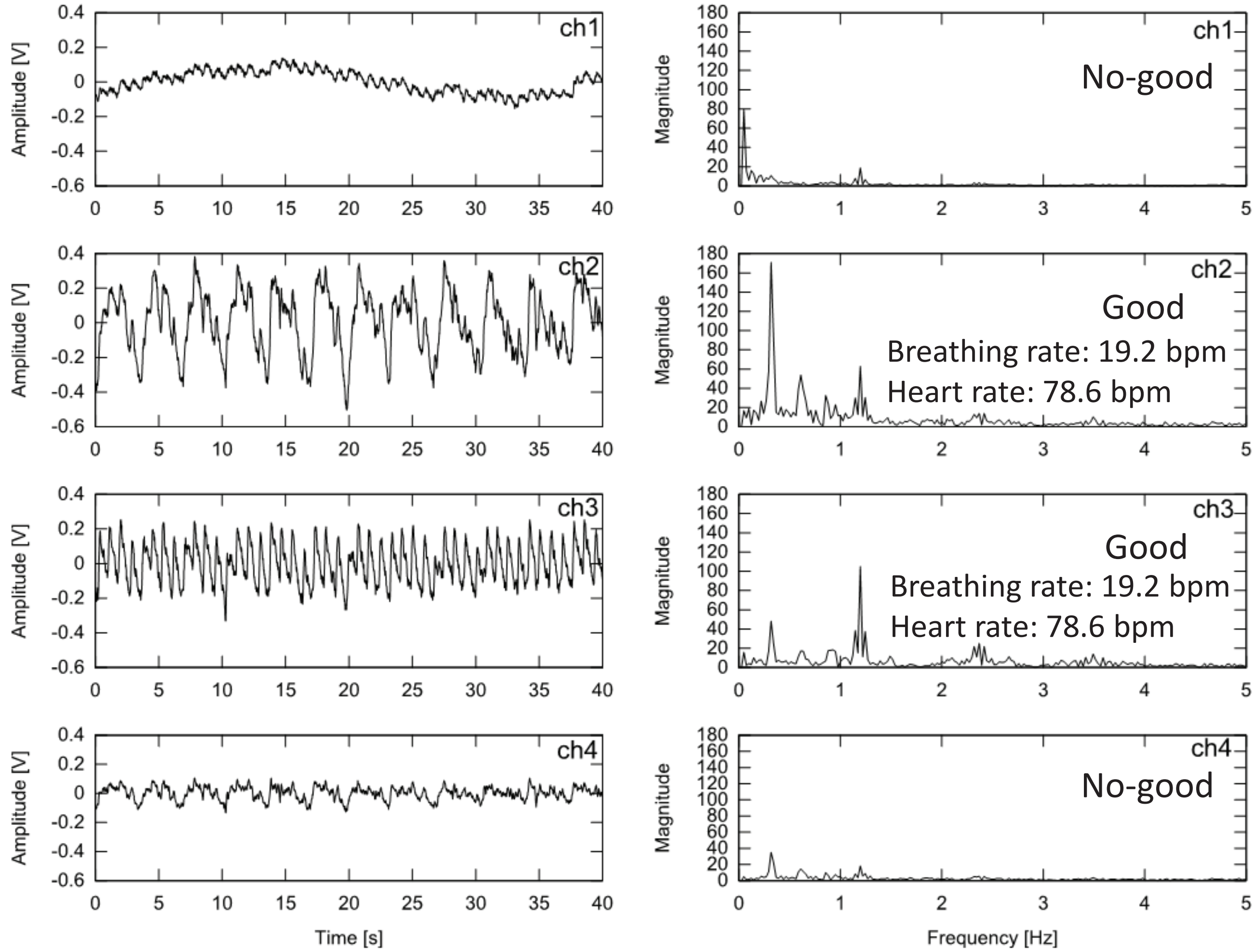


Fig. 15 Detection of the most reliable sensor.

6.2 Algorithm for Deciding Optimal Sensor

It is necessary to automatically decide which sensor can acquire the respiratory fluctuation and heart rate wave with the highest detection level among the four photo-interrupters. We considered an algorithm for evaluating the detection level. First, a threshold is set for distinguishing between the respiratory fluctuation and the heart rate wave. A sensor output that is less than this threshold is rejected. Then, the spectral magnitude at frequency f is set to $x(f)$. The maximum magnitude in the respiratory fluctuation range is defined as $S_{max}(t) = \max x(f) \quad \{0 < f < 0.83\}$, and the maximum magnitude in the heart rate range is defined as $S_{max}(t) = \max x(f) \quad \{0.83 \le f \le 2.33\}$. The mean spectral magnitude, $S_{mean}(t)$, is defined by:

$$S_{mean}(t) = \frac{1}{b-a}\sum_{i=a}^{b} x\left(\frac{i}{n\Delta t}\right) \qquad \cdot\ \cdot\ \cdot\ (1)$$

where starting frame (respiratory fluctuation) $a = 0$, the starting frame (heart rate) $a = \lfloor 0.83n\Delta t \rfloor$, ending frame (respiratory fluctuation) $b = \lceil 0.83n\Delta t \rceil$, and ending frame (heart rate) $b = \lceil 2.33n\Delta t \rceil$. The FFT parameters were as follows: observation time, 40.96 s; number of samples, 2048; sampling frequency, 50 Hz; and frequency resolution, 0.024 Hz. Only $S_{max}(t)$ which satisfies the following expression is used:

$$S_{max}(t) \ge cS_{mean}(t) \qquad \cdot\ \cdot\ \cdot\ (2)$$

In this case, $cS_{mean}(t)$ is the threshold of detection, and c is a coefficient. When changing c from 1 to 10, the best effect was acquired at c=3. The optimal sensor output is detected based on a majority of $S_{max}(t)$. When a majority is not realized, the optimal sensor output is detected based on the $\frac{S_{max}(t)}{S_{mean}(t)}$ ratio. Fig. 15 shows examples of the PPGs and frequency spectra decided by this method.

6.3 Displaying breathing rate and heart rate in real-time

Fig. 17 shows the results of breathing rate and heart rate detection. The horizontal axis denotes time, and the vertical axis denotes breathing rate or heart rate. With this method, the breathing rate and heart rate can both be monitored in real-time.

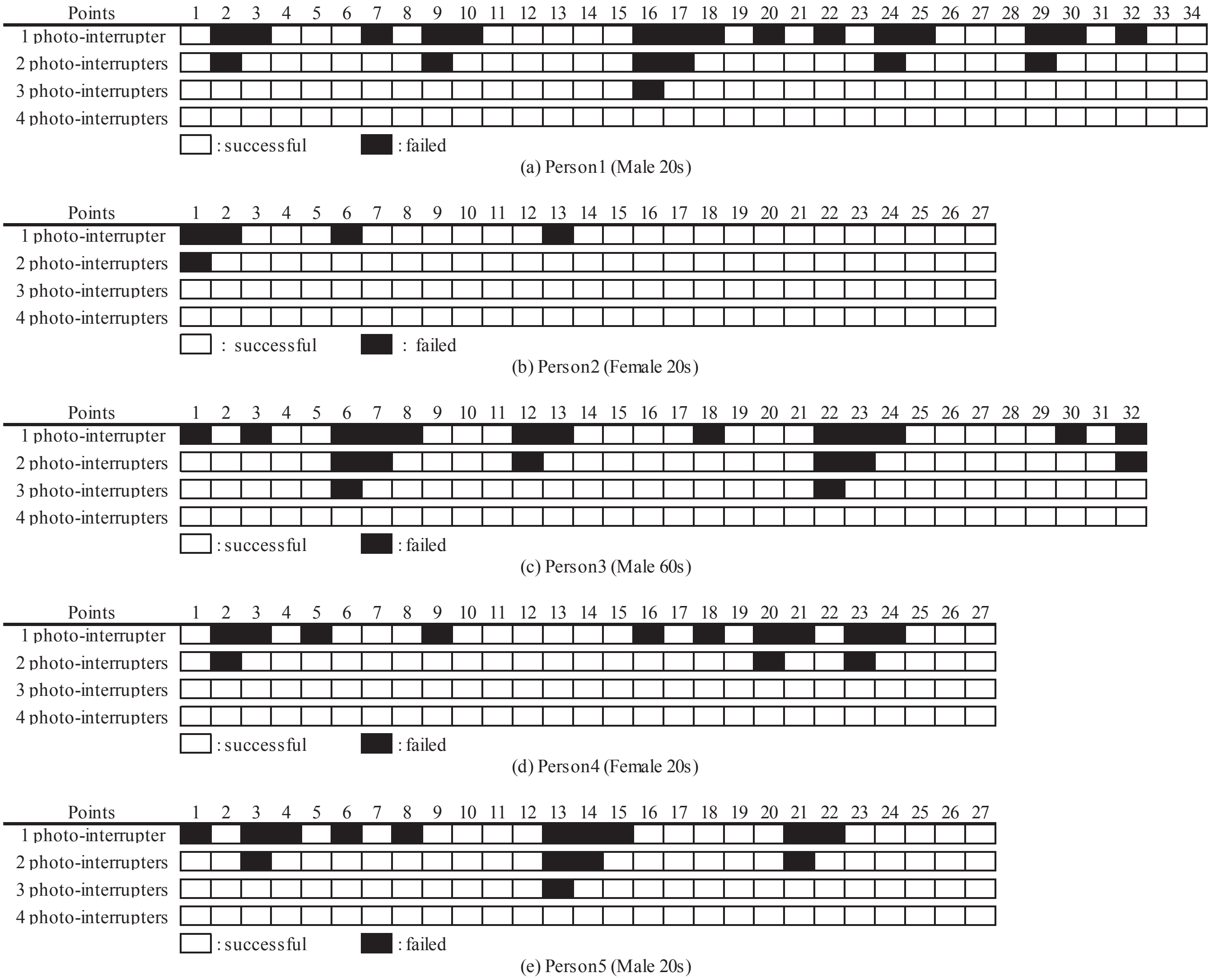


Fig. 16 Pulse wave detection (five subjects).

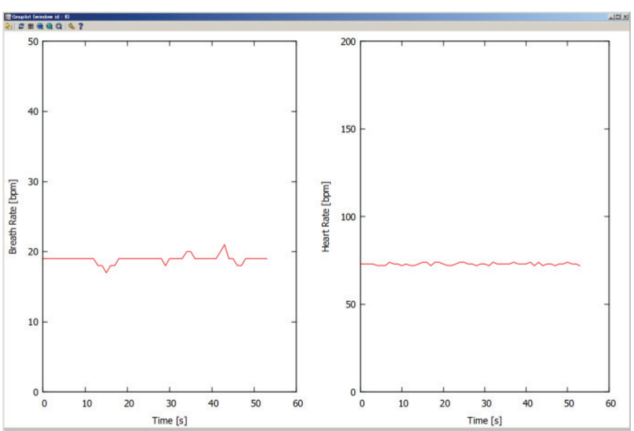


Fig. 17 Breathing rate (left) and heart rate (right) monitored in real-time.

7. CONCLUSION

We developed a novel breathing rate and heart rate sensor using a PPG. Conventional wrist-worn PPG sensors have low reliability because the PPG detection level around the wrist is low. We solved this problem by employing a photo-interrupter array sensor and by developing an algorithm for deciding the optimal sensor in the array. In the demonstration experiment, an array consisting of four photo-interrupter sensors placed at 5 mm intervals enabled reliable PPG measurement. In the future, we will study how to reduce the power consumption of the wireless sensor and noise due to the influence of motion. Moreover, we will consider using advanced signal processing techniques such as blind source separation (BSS) for improvement of detection accuracy.

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