International Journal of Innovative Computing, Information and Control
Volume **14**, Number **4**, August **2018**

ICIC International ©2018 ISSN 1349-4198

pp. 1301–1310

DEVELOPMENT OF NON-INVASIVE STEERING-TYPE BLOOD PRESSURE SENSOR FOR DRIVER STATE DETECTION

Toshiya Arakawa[1], Noriaki Sakakibara[2] and Shinji Kondo[2]

[1]Department of Mechanical Systems Engineering
Aichi University of Technology
50-2, Manori, Nishihasama-cho, Gamagori, Aichi 443-0047, Japan
arakawa-toshiya@aut.ac.jp

[2]KANDS Inc.
93-3, Nakamaeda, Igaya-cho, Kariya, Aichi 448-0001, Japan
{ kands; bara_n }@katch.ne.jp

Received December 2017; revised April 2018

Abstract. *There are many professional drivers whose symptoms, such as high blood pressure or arteriosclerosis, worsen owing to an irregular work rotation or overly short break periods, and there have been many cases in which drivers have been incapacitated or even died from overwork. We are therefore attempting to develop a system through which professional drivers can measure their blood pressure, thereby contributing to their overall health. Our system can estimate a driver's blood pressure using an infrared light emitted from a sensor unit attached to the steering wheel ring aiming at the skin of the driver's finger. In addition, our system can measure the blood pressure continuously, and the driver's body motions while driving are also considered in the system design. Thus, our system can monitor the driver's health continuously while driving. Based on the results of an evaluation, it was found that the blood pressure determined by our system tends to be affected by differences in the individual, and it is necessary to make further refinements to the algorithm used to estimate the blood pressure.*

Keywords: Blood pressure, Photoplethysmography, Cuffless, Driver's state

1. Introduction.

There is a growing awareness regarding the importance of lifestyle in achieving a healthy life [1]. As such awareness increases, the basic lifestyles of all people are changing. This is related to a national strategy, and thus, the possibility of new business developments related to healthcare has attracted significant attention. In particular, high blood pressure causes major diseases and ailments such as strokes, and heart and kidney diseases [2,3]. Considering the rapid progression of the aging population and a Westernized diet, it is becoming more and more important to prevent the occurrence of hypertension.

There are many professional drivers whose previous symptoms, including high blood pressure or arteriosclerosis, worsen owing to an irregular working rotation or overly short break time, and there have been many cases of incapacitation and/or death from overwork [4]. It is therefore necessary for professional drivers to manage their own health condition each day, and to become aware that they should not drive without rest; in addition, it is desirable to develop a system that manages the driver's health and prevents them from undesirable conditions or sudden death, thereby decreasing the number of traffic accidents.

DOI: 10.24507/ijicic.14.04.1301

In general, however, non-invasive blood pressure measurements need a cuff, and such measurement techniques can hardly monitor blood pressure continuously. On the other hand, recently, it has gotten easier to measure biological signals daily because sensor technologies have well-developed, and because of availability of many kinds miniaturized measurement instruments consuming less power [5]. Thus, it is suggested the non-invasive cuff-less blood pressure measurement devices has a probability to be realized and mass-produced.

Actually, the standardization of a cuff-less blood pressure measurement system that can measure the blood pressure based on the pulse wave propagation time without a cuff has been considered, and the IEEE published a "Standard for Wearable Cuffless Blood Pressure Measuring Devices", which was certified as IEEE1708 on August 26, 2014. According to this standard, the development of wearable devices based on blood pressure is expected in the future.

We are trying to develop a system by which professional drivers can measure their blood pressure, thus contributing to their overall health. As a feasibility study, we have shown that a driver's state of surprise can be detected based on their blood pressure, and other driver states can be detected using in-vehicle devices [6,7]. In this paper, we report the development of a system that can be attached to a steering wheel, allowing drivers to measure their blood pressure while holding the steering wheel while driving. In addition, we also report the accuracy of this newly developed system compared to a commercial electronic sphygmomanometer, which can measure the blood pressure based on a conventional method. Generically, we report the adequacy and perspective of applying this system to in-vehicle driver's state estimation device.

In previous studies, a cuff-less sphygmomanometer that can measure the blood pressure by touching a finger has been developed [8], as has a system that measures the driver's pulse wave by sensors attached to a steering wheel, which can estimate the changes in the driver's physical condition [9] when driving. These systems are example applications of non-contact sensing technology. The former has a merit in that the system can measure the blood pressure without a cuff; however, it can only detect a fingertip pulse wave. Thus, the attachment position of the sensor is restricted to the positions that the driver's finger can reach, such as behind the steering spoke. The latter is a system in which the pulse wave is detected when the driver holds the steering wheel, and the blood pressure is estimated based on the propagation time of the pulse wave and various databases. However, this system is based on a combination of various databases, and thus the system becomes large in scale, and there is concern that it will be expensive.

Comparing these systems, our system can measure the blood pressure continuously and easily, and as mentioned above, the driver's body motions when driving are considered in the system design. Thus, our system can take control of the driver's health continuously while driving.

2. Development Details.

Here, we introduce the outline of the developed system.

2.1. System outline.

We consider this development a feasibility study, and the system was created for a desktop driving simulator, not for a real vehicle. Thus, we developed the system to measure the blood pressure while playing a racing game on a PlayStation 4®. A steering controller for a PlayStation 4® (Hori Co., Ltd.) is used as the steering wheel. This steering-type sphygmomanometer is connected to a tablet PC through Bluetooth. The blood pressure data measured by the sphygmomanometer are transmitted to the tablet PC, which displays the driver's blood pressure in real time.

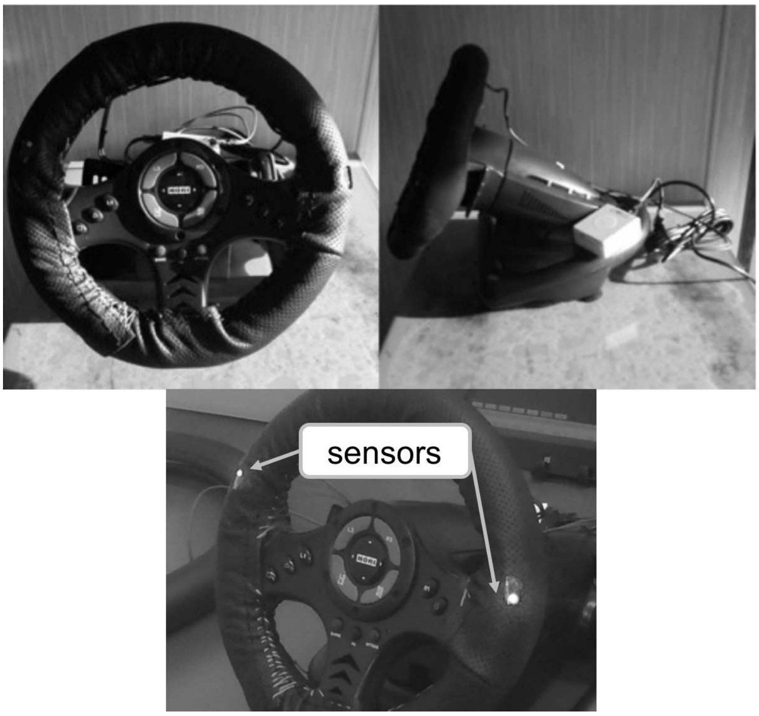


Figure 1. Appearance of the developed system. Sensors that can detect and measure the driver's blood pressure are attached at positions of 10 and 2 o'clock on the wheel.

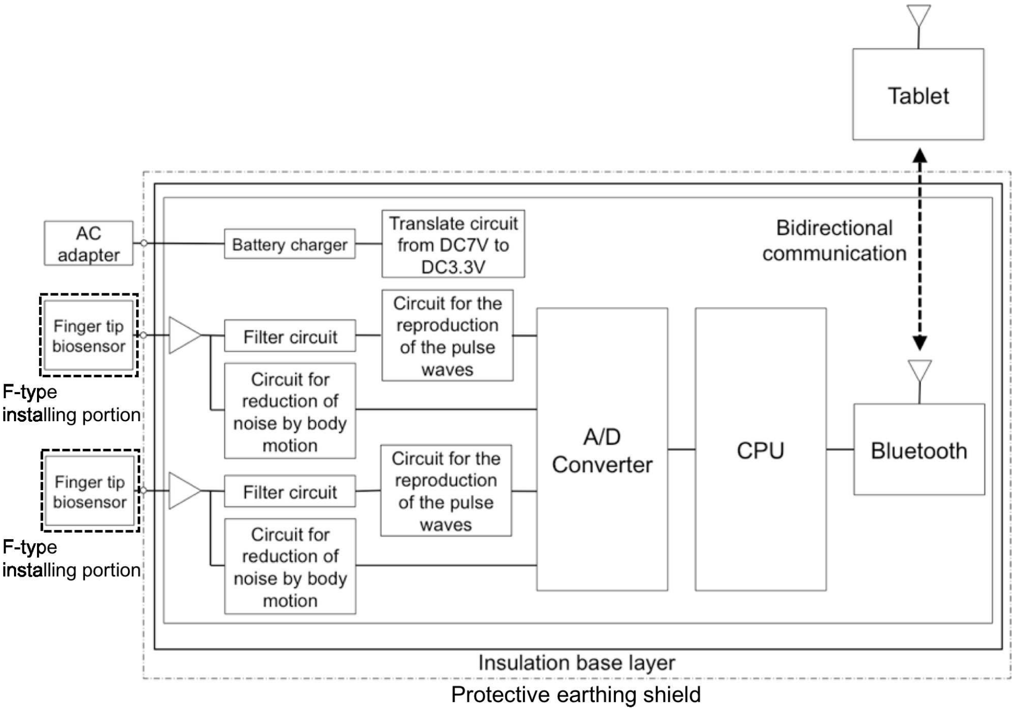


Figure 2. Block chart of the developed system

Figure 1 shows the appearance of the developed system, and Figure 2 illustrates a block chart. Two sensors are attached to the steering wheel spokes because the steering wheel turns from −90 to +90 [deg], and drivers place their hands at almost the same location on the steering wheel when driving. The sensors are therefore attached at positions of 10 and 2 o'clock on the wheel, and can detect the driver's pulse even if driver removes one hand from the wheel.

2.2. **Measurement procedure.**

A conventional sphygmomanometer is a traditional tool for measuring blood pressure. This device is advantageous in that no transducer needs to be placed over the brachial artery, and it is less susceptible to external noise (but not to low-frequency mechanical vibrations), and the cuff can be removed and replaced by the patient during ambulatory monitoring, for example, when taking a shower. The main disadvantage, however, is that such recorders do not work well during physical activity, when considerable movement artifacts may occur. An oscillometric technique has been used successfully in ambulatory blood pressure and home monitors [10]. Thus, it is inadequate to apply a conventional sphygmomanometer for detecting the driver's state, and application of photoplethysmography as a noninvasive sensor technique has been considered [11]. Thus, we developed a noninvasive blood pressure detection system using photoplethysmography.

With this system, infrared light is emitted from a sensor unit attached to the steering wheel ring aiming at the skin of the driver's finger. The transition of the finger plethysmogram, which is the integral value of the photoplethysmogram, is calculated for every pulse beat, and the reference light quantity is used to determine the average blood pressure. In addition, blood flow, the condition of the hemoglobin, and the vascular elasticity rate are calculated. The systolic and diastolic blood pressures can be continuously calculated based on these results.

The algorithm for calculating for the blood pressure is shown in the following [12,13]. Photoplethysmography is applied to a pipe flow in a viscous fluid (Hagen-Poiseuille flow, the algorithm of which follows the equation below).

$$Q = \pi \times R^2 \times V = \frac{\pi \times R^4}{8 \times \mu} \times \frac{P_1 - P_2}{L} \tag{1}$$

where Q is the flow volume, R is the radius of the pipe, V is the flow velocity, μ is the viscosity of the fluid, and $(P_1 - P_2)/L$ is the pressure gradient between two points (L).

In short, the pressure correlates the flow volume in a pipe. The above equation was applied for the photoplethysmography. The premises below were used in the logic of the estimation.

1) The blood pressure correlates positively to blood flow.
2) The mural pressure correlates positively to the pressure against a tissue (e.g., the cuff-pressure or application of the probe pressure).
3) A constant probe pressure is applied to the tissue.
4) The pressure difference is higher for the arteries than for the venous vessels.
5) The photoplethysmographic signals are sensitive only to the hemoglobin dynamics.

Therefore, when adequate pressure and adequate light emission are applied to the tissue, the transmitted light is hypothesized to correlate with the blood pressure, i.e., the systolic pressure was estimated for the peak of the light transmitted, and the diastolic pressure was estimated for the volley transmission of the light.

Figure 3 shows a schema of the blood pressure pulsation and time course. The following equations were hypothesized for measuring blood pressure.

$$s_1 = \frac{s_p - d_p}{2} \times t \tag{2}$$

$$s_2 = d_p \times t \tag{3}$$

$$S = s_1 + s_2 \tag{4}$$

$$K = \frac{s_1}{s_2} \tag{5}$$

where s_p means the systolic pressure, d_p means the diastolic pressure and t means the wave period.

Figure 3 shows a schema of the photoplethysmpgraphic pulsation and time course. The equations below were then hypothesized in terms of the photoplethysmographic pulsation.

$$ps_1 = \frac{p_1 - p_2}{2} \times t \tag{6}$$

$$ps_2 = p_2 \times t \tag{7}$$

$$pS = ps_1 + ps_2 \tag{8}$$

$$pK = \frac{ps_1}{ps_2} \tag{9}$$

where p_1 means the maximum photoplethysmographic signal intensity, p_2 means the minimum photoplethysmographic signal intensity.

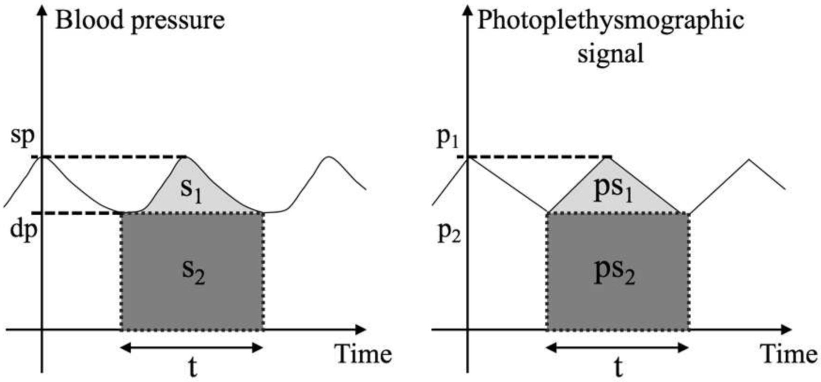


FIGURE 3. A schema of the BP pulsation and time course (left) and a schema of the photoplethysmographic pulsation and time course (right)

The equations below are deduced when K is hypothesized as pK.

$$ps_1 = \frac{K}{1+K} \times pK \tag{10}$$

$$ps_2 = \frac{1}{1+K} \times pK \tag{11}$$

$$p_1 = \frac{(2K+a) \times pK}{(1+K) \times t} \tag{12}$$

$$p_2 = \frac{pK}{(1+K) \times t} \tag{13}$$

Therefore, p_1 and p_2 are estimated as the systolic and diastolic pressures, and a means arbitrary constant.

Figure 4 shows a flow chart of the blood pressure detection using the developed system. Next, we describe the calibration procedure in Figure 4.

1) As a reference to determine the upper and lower limits of their blood pressure, the drivers input their systolic and diastolic blood pressures based on a past diagnostics into the tablet.

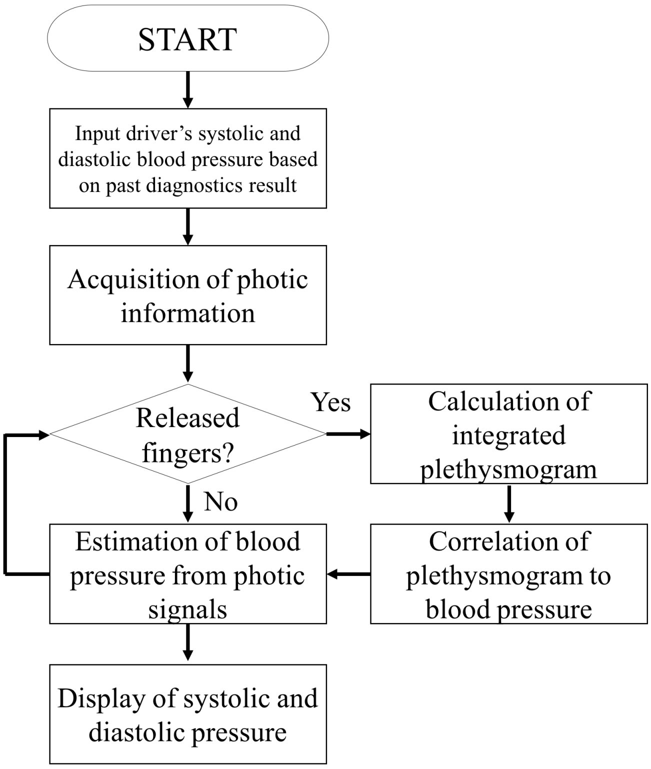


FIGURE 4. Flow chart estimating continuous blood pressure using a photoplethysmogram

2) The pulse waves recorded when holding the steering wheel are detected to determine the reference finger plethysmogram, and the finger plethysmogram is tuned to the specified gain based on the amount of light and sensitivity.
3) The tuned photoplethysmographic is considered a standard plethysmogram with regard to the average blood pressure. The ratio of diastolic blood pressure to the average blood pressure is added to the plethysmogram of the average blood pressure, which is determined as a plethysmogram of the diastolic blood pressure. A plethysmogram of the systolic blood pressure is calculated similarly based on the ratio of sysyolic blood pressure to the average blood pressure, and is considered a standard plethysmogram.
4) The observed plethysmogram and plethysmogram of the standard blood pressure are compared, and the current average blood pressure is calculated. Next, the systolic and diastolic blood pressures are calculated based on the pulse pressure ratio calculated based on the ratio of height of the plethysmogram.

Photoplethysmographic detection by sensors attached to the steering wheel is branched into a circuit to reduce the noise from body movements and a circuit for filtering. A photoplethysmogram passes through a circuit to reproduce a pulse wave after passing through the circuit for filtering, and the blood pressure is calculated based on a photoplethysmogram by applying digital processing. Finally, we obtain a pulse wave and the value of the blood pressure as the output.

The appearance of the developed system operation is shown in Figure 5. The lower image of Figure 5 shows the GUI of the tablet. The time-series data on the blood pressure is shown at the top of the GUI, and the middle line is the heart rate.

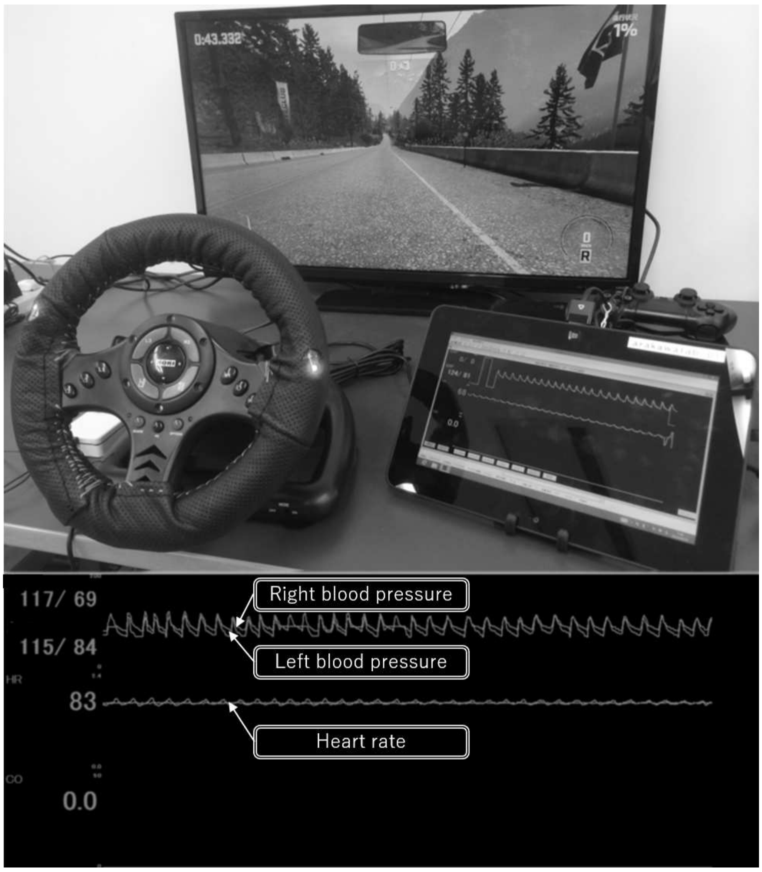
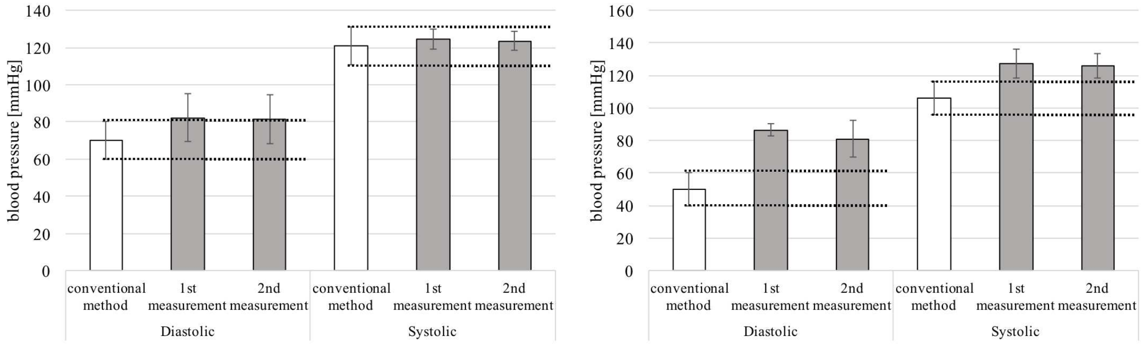


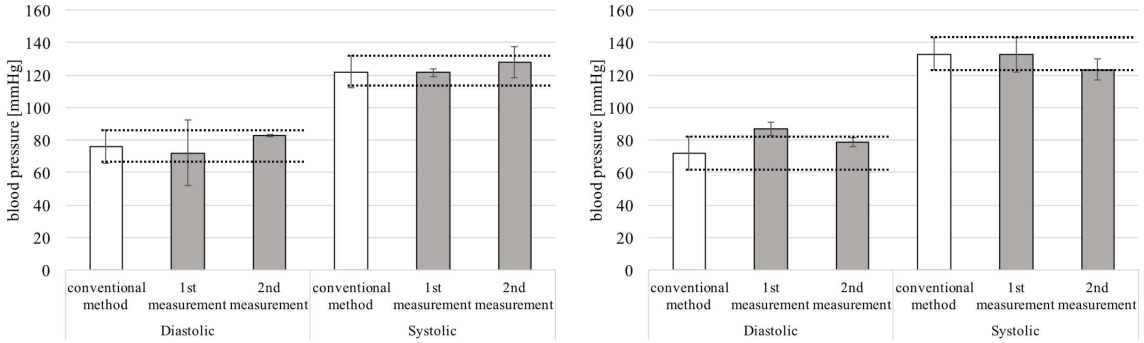
Figure 5. Appearance of the developed system and tablet interface

3. **Evaluation.** Seven people participated in the experiment. Average age of these people is twenty-two years old, and these people were selected randomly from male college student. First, their systolic and diastolic blood pressures were measured using a commercial electronic sphygmomanometer, which can measure the blood pressure based on a conventional method (also known as the Riva Rocci Korotkoff method, or a manual method, for blood pressure measurements) [14]. Their blood pressure was then measured using our system for a 2-min period. The participants then rested for 5 min after their blood pressure was measured, after which their blood pressure was measured for another 2 min. The results of this experiment are shown in Figure 6, along with the measurement results of the systolic and diastolic blood pressures using a commercial electronic sphygmomanometer applying a conventional method for comparison. A box-and-whisker plot comparing a "conventional" method shows the blood pressure as determined using a commercial electronic sphygmomanometer, the range of error of which is ±10 mmHg. The first and second box-and-whisker plots show the average blood pressure of the first and second measurements taken by our system and 2S.D., respectively. It should be noted that outliers from failed measurements were omitted from the data. In addition, as shown in Figure 6, the horizontal dotted line indicates the range of average blood pressure, namely, -10 to $+10$ mmHg, which is within the range of error of the commercial electronic sphygmomanometer. Thus, if the average ±2S.D. of the blood pressure determined by our system is between the dotted lines, it suggests that the blood pressure measured has almost the same accuracy as a commercial electronic sphygmomanometer. Figure 7 shows the idea behind the verification of the validity of our developed system. Based on Figure 7, if the blood pressure range of the developed system, which is between

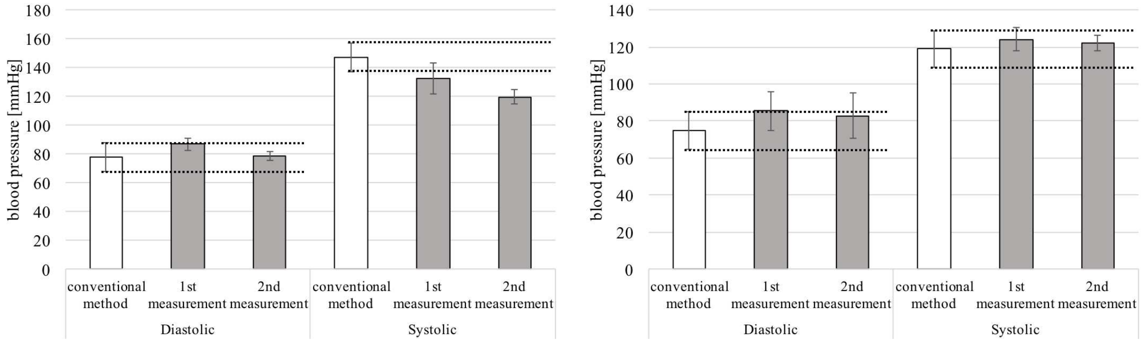
(a) subject A (b) subject B



(c) subject C (d) subject D



(e) subject E (f) subject F



(g) subject G

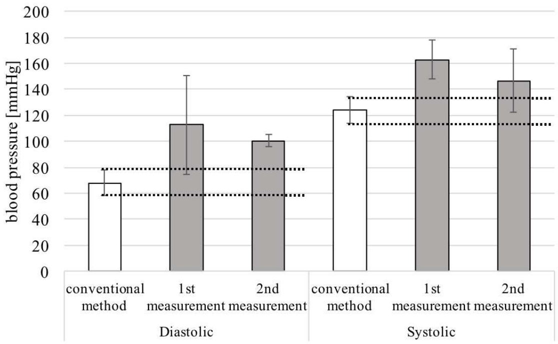


FIGURE 6. Measurement results using a commercial electronic sphygmomanometer through a conventional method and our proposed system

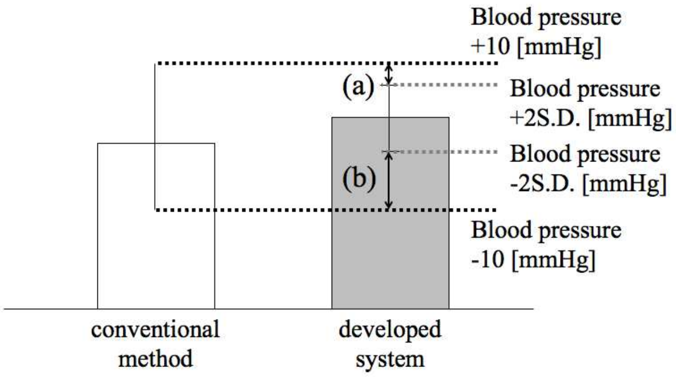


FIGURE 7. Evaluation of the validity of the developed system: (a) difference in blood pressure +10 [mmHg] of the conventional method, and blood pressure +2S.D. [mmHg] of the developed system, and (b) difference in blood pressure −2S.D. [mmHg] of the developed system, and the blood pressure −10 [mmHg] of the conventional method

TABLE 1. Validity evaluation of developed system. If the values in (a) and (b) are both positive, it indicates that the developed system has the same level of validity as the conventional method.

	Diastolic blood pressure				Systolic blood pressure			
	1st		2nd		1st		2nd	
	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)
Subject A	−15.1	9.38	−14.5	8.50	0.940	8.00	2.42	7.46
Subject B	−30.2	42.6	−32.6	30.0	−20.0	22.2	−17.6	22.5
Subject C	−6.20	−14.1	2.59	16.5	7.96	6.90	−5.44	6.64
Subject D	−9.23	20.6	0.240	13.7	0.250	−0.850	12.9	−6.19
Subject E	−3.23	14.6	6.24	7.70	13.8	−15.0	32.6	−22.2
Subject F	−11.0	9.87	−10.2	5.43	−1.67	8.75	2.52	9.22
Subject G	−72.8	16.9	−26.9	38.1	−44.0	33.7	−36.8	8.00

the average ±2S.D., includes the blood pressure range of the conventional system, which is between the average ±10, we can state that our system is valid.

As a reference, Table 1 shows the difference between the diastolic blood pressure, −2S.D. mmHg, of our system, and the diastolic blood pressure, −10 mmHg, using the commercial electronic sphygmomanometer, as well as the difference between the systolic blood pressure, +10 mmHg, by the commercial electronic sphygmomanometer, and the diastolic blood pressure, +2S.D. mmHg, of our system, based on Figure 7. From Table 1, it can be said that our system achieves the same level of performance as a commercial electronic sphygmomanometer based on the range of blood pressure shown when all values are positive.

From Figure 6 and Table 1, both of the systolic blood pressure does not seem to be within the proper range. However, the diastolic blood pressures of subjects D and E do seem to be within the proper range. In contrast, the systolic blood pressures of subjects A, C and F seem to be within the proper range, whereas the diastolic and systolic blood pressures of subjects B and G seem to be outside the proper range. Based on these results, it was determined that the blood pressure captured by our system tends to be affected by the differences in the individual, and it is necessary to make further refinements to the algorithm used in the blood pressure estimation.

4. **Conclusions.** This study described the development of a system in which a sensor device is attached to a steering wheel allowing drivers to measure their blood pressure while driving with their hands on the wheel. The blood pressure measured by this system shows the effects of differences in the individual, and it was found that further refinements of the algorithm used in estimating the blood pressure are necessary.

In the future, the algorithm for estimating the blood pressure will be improved, and the system will be applied to an actual vehicle. In addition, the driver's blood pressure when driving will be acquired continuously, and such data will help lead to improvements in health when driving.

Acknowledgement. We are grateful to Mr. Kenta Kaminaga (formerly of Aichi University of Technology) for his important contributions to the experiments.

REFERENCES

[1] S. Meguro, Marketing in health care -Strategic insight into new business development-, *Reitaku International Journal of Economic Studies*, vol.19, no.1, pp.56-71, 2001 (in Japanese).

[2] M. Moser, High blood pressure, in *Yale University School of Medicine Heart Book*, William Morrow & Co, New York, 1992.

[3] Stroke Association, *High Blood Pressure and Stroke*, https://www.stroke.org.uk/sites/default/files/high_blood_pressure_and_stroke.pdf, 2017.

[4] M. Kawamura, A problem about work of professional drivers, *Question for Car Society*, vol.44, pp.20-23, 2006 (in Japanese).

[5] S. Suzuki and K. Oguri, Cuffless blood pressure estimation with photoplethysmograph signal by classifying on account of cardiovascular characteristics of old aged patients, *The Transactions of the Institute of Electrical Engineers of Japan. C, A Publication of Electronics, Information and System Society*, vol.130, no.2, pp.261-266, 2010 (in Japanese).

[6] T. Arakawa, M. Tanaka, F. Obayashi, S. Kondo and K. Kozuka, Detection of driver's surprised state based on blood pressure, *ICIC Express Letters, Part B: Applications*, vol.6, no.9, pp.2353-2360, 2015.

[7] T. Arakawa, Validity of detection of driver's surprised state based on systolic blood pressure, *Journal of the Institute of Industrial Applications Engineers*, vol.5, no.3, pp.136-140, 2017.

[8] Nihon Keizai Shinbun, *Nihon University Developed a Blood Pressure Sensor "by Lightly Touching with a Finger" Compatible with Smartphone*, https://www.nikkei.com/article/DGXNASFK1903B_Z11C13A1000000/, 2017 (in Japanese).

[9] Nikkei Digital Health, *Toyota and Denso Developed a System Which can Detect Electrocardiograph and Pulse Wave via Steering and Estimate the Change of Sudden Physical Condition on Driving*, http://techon.nikkeibp.co.jp/article/NEWS/20130326/273292/?ST=ndh, 2017 (in Japanese).

[10] G. Ogedegbe and T. Pickering, Principles and techniques of blood pressure measurement, *Cardiology Clinics*, vol.28, no.4, pp.571-586, 2010.

[11] R. Samria, R. Jain, A. Jha, S. Saini and R. S. Chowdhury, Noninvasive cuffless estimation of blood pressure using photoplethysmography without electrocardiograph measurement, *Region 10 Symposium*, pp.254-257, 2014.

[12] S. Kondo, I. Shimoyama, K. Masuda, R. Inaha, Y. Haruna and N. Sakakibara, Evaluation of blood pressure and cardiac output by non-invasive volume pulse wave continuous blood pressure measurement method and invasive continuous blood pressure measurement method, *Bulletin of Japanese Society for Therapeutics Engineering*, vol.22, no.1, pp.3-9, 2010 (in Japanese).

[13] S. Kondo, I. Shimoyama, A. Yoshida, H. Yoshizaki, F. Hayashi, K. Nagao and S. Oda, Minimal invasive estimation of blood pressure for continuous monitoring, *Chiba Medical Journal*, vol.84, pp.15-25, 2008.

[14] C. Maley, *Intro to Blood Pressure*, https://www.adctoday.com/blog/intro-blood-pressure, 2017.