Preliminary Study of an Objective Evaluation Method for Pulse Diagnosis using Radial Artery Pulse Measurement Device

Akihiro Yamada,*, Yusuke Inoue,*, Yasuyuki Shiraishi,* Takashi Seki,*** Tomoyuki Yambe*

Abstract In traditional Chinese pulse diagnosis, the pulses of bilateral radial arteries are palpated by three fingers. In this study, a device that can objectively perform pulse diagnosis using multiple pressure sensors with a cuff was developed. The device has three pressure sensors in series and a cuff to apply external pressure load. Pulse waves were measured using the non-invasive pulse diagnostic device. The relationship of the data obtained from the proposed system with the diagnosis by the traditional method was examined. The study was conducted with the approval of the Ethics Committee in Tohoku University. Twelve adult male subjects were studied. Data of pulse waveforms recorded from the pulse diagnosis device, electrocardiogram, and continuous blood pressure measured at the fingertip were stored and analyzed. The pulse waves of the subjects were categorized as middle pulse, floating pulse, or sunken pulse according to pulse diagnosis in traditional Chinese medicine. Pulse–waveform data were obtained to measure the pulse–pressure changes, which showed different patterns of the rise time at the three measurement sites. Envelope analysis of the pulse waveform from the middle sensor revealed that the peak value of the pulse pressure increased during calculation stress compared to the resting state. It was possible to measure the pulse waves even when a higher external pressure was applied. Objective pulse-wave measurement using a method similar to that in traditional pulse diagnosis was realized, and pulse waveforms were measured using the proposed pulse diagnosis system.

Keywords: traditional Chinese medicine, pulse diagnosis, biological information analysis.

Adv Biomed Eng. 10: pp. 113–122, 2021.

1. Introduction

In the traditional Chinese diagnostic procedure called pulse diagnosis, the examiner places three fingers in contact with the radial artery on the left and right wrists [1, 2]. Traditional Chinese medicine has been attracting attention in recent years as an inexpensive alternative and complement to modern medicine from the viewpoint of rising medical costs. Even for Japanese people, acupuncture and moxibustion have traditionally been regarded as important. Pulse diagnosis is one of the most basic diagnostic techniques in traditional Chinese medicine, and it discriminates various pathological conditions. However, pulse diagnosis is often criticized in traditional medicine because of its subjective and qualitative nature. In addition, it is difficult to introduce expensive medical devices in clinical practice involving alternative medicine, such as Chinese medicine and acupuncture and moxibustion. Figure 1 depicts traditional pulse diagnosis performed by a traditional Chinese doctor. Figure 2 shows the positional relationship between the palpation sites called cun (distal), guan (middle), chi (proximal), which are standard measurement sites in the radial artery for pulse diagnosis. Pulse diagnosis is considered the most important of the four examinations (inspection, listening, inquiry, and palpation) that determine the treatment policy of oriental medicine. It is routinely used for diagnosis in traditional Chinese medicine, acupuncture, and traditional Indian medicine. In this method, various diseases are diagnosed by palpating while changing the pressure...
of the fingers. The factors determining the pulse condition are the depth, width, length, frequency, rhythm, and strength [1, 3, 4]. By palpating the pulse, traditional Chinese medical doctors read the physical properties of blood vessels, heart rate variability, blood pressure reflex, and pulse wave velocity. Various diseases and health conditions are diagnosed using these factors as cues. These parameters of pulse diagnosis reflect autonomic nerve activity. However, pulse diagnosis depends on tradition, inheritance, and experience. Furthermore, the examination techniques and diagnoses vary depending on the subjectivity and proficiency level of the doctors, and may be influenced by the physical conditions of the operator and the patient. Thus, this diagnosis method is medically inaccurate. Moreover, there are no reports that clarify the relationship between autonomic nerve activity and pulse diagnosis.

In theory, pulse diagnosis is expected to realize objective and scientifically reproducible quantitative diagnosis by applying three precise pressure sensors. Recently, various studies have investigated the quantitative evaluation of pulse diagnosis [2–8]. According to these studies, there is a possibility that the anatomical position of blood vessels and the pulse waveform can be measured accurately. However, existing pulse measurement devices have some unsolved problems and deficiencies. Traditional knowledge cannot be effectively used to differentiate measurement principles such as ultrasonic waves. Mechanical pressurizers are large, heavy, require complex mechanics, and ultrasound or optical methods cannot assess the physical properties of blood vessels. Moreover, such mechanisms are not cost-effective. Thus, we considered that an easy-to-operate and low-cost device conforming to traditional techniques that can effectively utilize the vast knowledge in traditional medicine was necessary.

In this study, we propose an easy-to-operate and effective pulse diagnosis system for conventional pulse diagnosis. We examined the relationship between the diagnostic results of traditional pulse diagnosis, changes in autonomic nerve activity, and pulse wave data obtained from the proposed device. In addition, we collected basic data to provide objective data for pulse diagnosis. By using the proposed pulse wave measurement device, scientific and quantitative data for traditional Chinese medicine that relies on experience and tradition can be realized.

2. Methods

2.1 Pulse diagnosis measurement system

We developed a non-invasive pulse diagnosis measurement system that contacts the radial artery from above the skin surface using accurate pressure sensors based on pulse diagnosis methodology. The device contains three precision pressure sensors (Electret condenser microphone type pressure sensor, EPG-01, Sony Corporation) in series and a data recorder. External pressure is applied in the vertical direction, while the pressure is changed quantitatively using a cuff type manchette (Tycos type cuff set, Matsuyoshi & Co., Ltd.). The cuff consists of a cuff band (W 140 mm × L 500 mm) and a rubber pressurization bag (W 120 mm by L 230 mm). In this device, pulse waveform can be directly measured by the three high-precision pressure sensors arranged in series on the radial artery, and a matrixed pulse pressure waveform is obtained. In accordance with the traditional pulse diagnosis methodology, the middle (Guan) sensor of the device is placed on the skin on the styloid process of the radius, the chi sensor is placed on the proximal side, and the cun sensor is placed on the distal side. The manchette is wrapped around the wrist on the sensor and pressurized. Figure 3 shows the device and the mounting method of the pulsator. Figure 4 shows the pressure sensor arrangement of the pulse diagnosis device. Based on the structure of the sensors, h1 and h2 were designed to have almost the same height of approximately 7.5 mm. In ad...
dition, the proximal sensor tends to separate from the radial artery when the wrist is extended during pulse diagnosis; therefore the height of h3 was increased by 0.5 mm to improve contact [8]. This device allows easy measurements by placing the sensors on the wrist and wrapping the cuff. In the pressure sensor unit of the pulse diagnosis device, a differential circuit/filter is embedded to obtain an acceleration pulse wave, and to remove baseline fluctuation.

2.2 Examination procedure

This study was approved by the Ethics Committee of the Tohoku University Graduate School of Medicine (approval number: 2016-1-270). Healthy persons aged over 20 years were recruited by posting the requirements for this research on the bulletin board in Tohoku University. The examination was performed after explaining the purpose of this study and obtaining informed consent for participation. Before the measurement, each subject filled out a detailed questionnaire including height, weight, health condition, sleeping time, eating habit, and medical history. In addition, traditional pulse diagnosis was performed by a Chinese medicine doctor before examination was performed using the pulse diagnosis measurement device, and the diagnosis results were recorded. The pulse diagnosis parameters were the pulse depth, pulse smoothness, strength, length, thickness, and hardness. The experimental records (electronic data and paper media) obtained in this study were strictly locked and stored after de-identification.

Pulse waves of the radial artery were recorded using the proposed pulse diagnosis device. Electrocardiogram was measured from chest leads by a Holter electrocardiogram (EV-50, Fukuda Co., Ltd.), and a non-invasive continuous sphygmomanometer (BP-608 Evolution II, Fukuda Colin Co., Ltd.) was wrapped around the wrist opposite to the side with pulse diagnosis sensors. These data were stored in a data recorder (ES-8, TEAC Corporation) at a sampling frequency of 1 kHz, and 16-bit quantization. Figure 5 shows the schematic illustration of the pulse diagnostic measurement system. As in the case of normal blood pressure measurement, the manchette was appropriately pressurized (up to 200 mm Hg) until the pulse wave disappeared, and pulse wave measurement was performed while gradually reducing the pressure of the manchette. In order to examine the influences of heart rate fluctuation and blood pressure fluctuation on pulse diagnosis due to hemodynamic changes from psychological load, each subject was given a mental calculation task. The calculation task involved subtracting one-digit random numbers sequentially from 1000. The measurement time was divided into three sections (pre-rest, test, post-rest). The manchette was pressurized in each section, with a one-minute rest between the sections. Each measurement time was 11 minutes, broken down into 3 minutes +1 minute in the pre-rest section, 3 minutes +1 minute in the test section (the calculation task), and 3 minutes in post-rest section. In addition, to examine the effect caused by changes in device attachment, a series of procedures from device attachment, measurement, and removal was performed four times in a single subject, and device reproducibility tests were conducted.
2.3 Data analysis methods
The pulse wave data (peak value and pulse wave velocity parameters) were analyzed for each pulse waveform, and compared with pulse results obtained by the traditional method. In addition, we examined the cardiovascular data obtained from a Holter electrocardiogram and a non-invasive continuous sphygmomanometer, as well as the pulse wave data obtained using the pulse diagnosis device, both at rest and during the calculation task.

Among the frequency components in heart rate variability, the autonomic nervous activity can be determined by analyzing the high- and low-frequency components [16, 17]. The low frequency (LF) component is 0.05–0.15 Hz (Mayer wave) and contains both sympathetic and parasympathetic components. The high frequency (HF) component is 0.15–0.4 Hz, which reflects respiratory sinus arrhythmia and contains the component of parasympathetic nervous system activity. By calculating the ratio of the LF and HF components, changes in sympathetic nerve activity can be investigated [16]. Power spectrum analysis was performed on the HR fluctuation data at rest and during calculation task, and the LF and HF components were extracted. The LF/HF ratio was calculated from the extracted LF and HF components.

The pulse wave velocity was calculated from each peak time. The calculation formula of the pulse wave velocity \( v \) [m/s] is shown in Equation 1, where \( dL \) is the sensor interval [m], \( t_1 \) is the pulse wave peak time of the proximal sensor, and \( t_2 \) is the pulse wave peak time of the distal sensor. First, for each subject, we extracted the pulse waveform at the point where external pressure was 100 mmHg. Next, the pulse wave velocity was calculated from the time difference of the peak value and the distance between the proximal and distal electrodes. Then, the mean value and standard deviation of all subjects were compared. In this study, the pulse wave velocity was calculated uniformly under a cuff pressure of 100 mmHg to limit the variations in the pulse waves among different subjects.

\[ v = \frac{dL}{t_2 - t_1} \]  

(1)

3. Results
Twelve adult male subjects (24 ± 1 years of age) were studied. Subject characteristics are summarized in Table 1. The depth parameter of the pulse wave was classified as medium pulse, floating pulse, and sunken pulse by traditional pulse diagnosis. In all subjects, the pulse rhythm was normal smooth pulse. The middle pulse is an intermediate normal pulse; the floating pulse is a pulse that can be felt under weak pressure, and the sunken pulse is a pulse that can only be felt unless strong pressure is exerted.

Table 1 Characteristics of subjects participating in pulse diagnostic measurement. BMI: body mass index, HR: heart rate, Sys.BP: systemic blood pressure, Dia.BP: diastolic blood pressure.

|                | Medium (N = 7) | Floating (N = 2) | Sunken (N = 3) |
|----------------|---------------|-----------------|--------------|
| Age[years]     | 24 ± 1        | 24              | 24           |
| BMI[kg/m²]     | 22.4 ± 2.4    | 20.5 ± 1.5      | 22.7 ± 0.8   |
| HR[bpm]        | 76 ± 10       | 68 ± 7          | 73 ± 7       |
| Sys. BP[mmHg]  | 123 ± 10      | 123 ± 10        | 121 ± 13     |
| Dia. BP[mmHg]  | 68 ± 9        | 61 ± 2          | 61 ± 4       |

Figure 6 shows comparison of heart rate, mean blood pressure and LF/HF among the pre-rest, rest, and post-rest sections.

Figure 7 shows an example of the time-series data of the pulse waveforms obtained using the pulse diagnosis device and the cuff pressure (external pressure) at rest. In addition, the envelope of the peak values of the pulse waveforms at the middle sensor with the clearest pressure waveforms was compared between the resting and calculation task sections. The pulse waveform allows measurement of the change in pulse pressure, showing variations in rise time at the three sensors. As a result of the envelope analysis of the pulse waveform from the middle sensor, the peak value of the pulse pressure was increased during the calculation stress compared to the resting state. Figure 8 shows a comparison of the middle sensor pulse waveforms diagnosed as floating and sunken pulse. In the floating pulse, strong pulse waves were recorded at low external pressure. On the other hand, in the sunken pulse, weak pulse waves with low peak values were recorded at low external pressure.

Figure 9 shows the relationship between cuff pressure and the envelope of pulse wave from the middle sen-
sor at rest and during the calculation task (cuff pressure on the horizontal axis, and pulse wave envelope on the vertical axis). Comparing the pulse wave envelope at rest and during calculation task, the peak of pulse pressure shifted to higher cuff pressure, from 100 mmHg at rest to 120 mmHg during calculation task, although there was variation among individuals. The results in Figures 8 and 9 suggest that the pulse waveform changed due to the difference in pulse diagnosis or autonomic nerve activity.

Figure 10 shows an example of a single waveform of the pulse wave obtained from each sensor of the pulse diagnosis device at a cuff pressure around 100 mmHg.
The pulse wave velocity was calculated at each peak time (Equation 1).

The pulse wave velocity was calculated from the first peak of the pulse wave recorded at each sensor according to Equation (1). Figure 11 shows a comparison of the pulse wave velocities between pre-test, during test, and post-test conditions of the calculation task, obtained from the pulse diagnosis device. Although there was no significant difference, we were able to observe an increase in the pulse wave velocity under psychological load in Figure 11.

Figure 12 shows the results of device reproducibility test in a single subject measured four times. The waveforms recorded from the middle sensor and the envelopes are shown in Fig. 12(a), (b), (c) and (d). However, at #03 measurement, data at low cuff pressure (below 60 mmHg) was partially missing. We also compared the relationship between cuff pressure and pulse wave height. In this analysis, #2, 3 and 4 showed a similar tendency with peaks at around 80–100 mmHg. On the other hand, #1 showed a higher tendency with a peak at 120 mmHg.

4. Discussion

In this study, the three pressure sensors placed on the wrist were able to measure three different pulse waves with only a single cuff-type manchette. The same results as those obtained in this study have been reported in previous studies using different systems [3–8]. However, in those studies, large and complicated mechanical systems were required, and ultrasonic diagnostic imaging equipment was used in measurements. In addition, expensive medical devices were needed. By comparison, the device developed in this research can be configured only with a pressure sensor, a cuff for applying external pressure, and a data measuring device; measurements can be performed at extremely low costs. Therefore, our device is inexpensive and capable of quantitative analysis in the field of oriental medicine, which is expected to be an alternative to modern medicine. Using the device developed in this research, it is possible to reduce medical expenses, and this device is expected to be utilized in developing countries. In addition, pulse wave information can be measured easily even at home, which is expected to contribute to the advancement of home medical care by linking with other medical devices and wearable terminals [22].

For pulse diagnosis in oriental medicine, there are three different sensing sites; namely, the site located in the radial artery closest to the styloid (Guan) and its proximal (Chi) and distal (Cun) sites. It is necessary to measure the pressure continuously and pressure changes. The device used in this study has three different precision pressure sensors, and it is possible to measure three different pulse waves by arranging the sensors at appropriate positions and applying external pressure. The floating pulse was observed as high pulse wave at low external pressure, and the Sunken pulse appeared only at high external pressure [18]. Although, there were few subjects with floating and sunken pulses in this study, these pulse waves were characteristic and comparable to pulse waveforms in previous studies [5, 6, 18, 19]. However, the number of subjects was insufficient to obtain reproducible data for determining floating pulse or sunken pulse. In our device under development, reproducibility of the pulse diagnosis is an important factor. However, the waveform may fluctuate depending on the sensor position, misalignment of attachment, and the positional relationship of the wrist. Although, some similarities of
the pulse waveforms were observed in repeated testing of a single subject (Fig. 12), it is necessary to confirm the reproducibility of the data in a large number of subjects and improve the pulse diagnostic device in the future.

In actual pulse diagnosis, both wrists are palpated to examine the general pulse condition. In oriental medicine, the organs and body parts that reflect the pulse diagnosis results obtained from palpat ing the right and left hands are considered different. In this study, to investigate the usefulness of the device, the sensors were attached to only one hand and a continuous sphygmomanometer was attached to the wrist on the opposite side for blood pressure measurement. Theoretically, using two devices, it is possible to perform measurements by synchronizing the pressurization or shifting the phase, and to perform measurements by the same procedure as that in clinical pulse diagnosis. In the future, more detailed analysis will be possible by performing machine learning through associating pulse wave measurement data with medical examination results.

Traditional Chinese medical doctors diagnose the physical properties of blood vessels, heart rate variability, blood pressure reflex, and pulse wave velocity by experience. The floating pulse is a pulse that is measured using a weak pressure of palpation, and the sunken pulse is a pulse that cannot be measured unless a strong pressure is applied. The subjects in this study were divided into three groups. The pulse waveform data of the subjects diagnosed with a weak pulse (sunken pulse) tended to have pulse pressure lower than that of other subjects, according to the diagnosis of a Chinese medicine doctor who conducted pulse examination. Previous studies have proposed a classification algorithm for floating and sunken pulses [18, 19]. Attempts have been made to discriminate these pulses from the hold-down pressure and pulse strength curves. The curve of the pulse strength as a function of the hold-down pressure was developed. In addition, the relationship of anatomical position between the blood vessels and blood flow velocity was analyzed as deep / shallow, thick / thin by ultrasound [8]. Although it is not possible to analyze the depth and diameter of blood vessels with our device alone, the pulse versus pressure relationship was obtained as in a previous study [20] (Fig. 9). In Fig. 6, the heart rate, blood pressure, and LF/HF increased during mental arithmetic task compared to at rest, suggesting that autonomic nerve activity tended to increase in this study. In Fig. 9, comparing the pressure waveforms at rest and during mental arithmetic task, the peak of pulse pressure was shifted to higher pressure, from 100 mmHg at rest to 120 mmHg during stress, suggesting a tendency of the sunken pulse in pulse diagnosis [18]. Until now, the relationship between autonomic nervous activity and pulse diagnosis has not been clarified. The results of this study suggest that autonomic nervous activity may affect the pulse diagnosis waveform. The pulse diagnosis may reflect the autonomic nervous activity. In the future, if data from more subjects can be gathered and the tendency of the pulse waveform can be clarified in detail, the relationship between the autonomic nervous activity and pulse diagnosis may be elucidated in detail. If biological information can be accumulated by introducing conventional comprehensive analyses by electrocardiogram, blood pressure measurement, and autonomic nerve activity, it is possible to analyze different pulse waveforms due to various pathological conditions in detail. Providing scientifically accurate knowledge for traditional medicine that depends on the experience or intuition of the practitioner is a potential application of our results. Although the number of subjects was insufficient to analyze statistical significance, it is considered that medical engineering-based quantitative analysis of pulse diagnosis can be performed by calculating various parameters such as pulse waveform, rise time, pulse propagation time, and peak value in detail.

In modern medicine, pulse wave velocity is regarded as an important parameter representing arterial stiffness for quantitatively diagnosing the extent of arteriosclerosis [9–15]. In traditional pulse diagnosis, the degree of transmission of smooth pulse waves and rough pulse waves are determined [1, 2]. In the proposed pulse diagnosis system, the three high-precision pressure sensors arranged in series on the radial artery allow physical measurement of pulse waves directly, and a matrixed acceleration pulse waveform can be obtained. The pulse wave velocity of healthy people is approximately 7–10 m/s [21]. The pulse waveform sampling frequency used in this study was 1 kHz, and the pressure sensor distance (distal-proximal) was 26 mm. However, only very coarse data was attained for the pulse wave velocity in the 7–10 m/s region at a sampling frequency of 1 kHz. In addition, the data resolution was insufficient in Fig. 11, because velocity changed by approximately 0.5 m/s when sampling data changed by 1 ms in the region near 3.5 m/s. In the future, we have to improve the device by measuring at a higher sampling frequency. The measurement conditions used for determining pulse wave velocity in this study were fixed uniformly at a cuff pressure of 100 mmHg to limit variations in pulse waves among subjects. Calculations under cuff pressure caused a difference in blood flow distribution owing to the compression of the blood vessels, yielding different results from those reported in the literature. By calculating the cuff pressure condition from the diastolic blood pressure, it may be possible to discuss the pulse wave velocity without compressing blood vessels.
For pulse measurement, pulse wave changes associated with physical changes in blood vessels can be measured by externally applying mechanical energy with an air cuff. This index can be one of the parameters for explaining the parameters that are dependent on the pulse wave velocity in traditional pulse diagnosis. Many of the subjects in this study were young, and there was no difference in the results of pulse diagnosis. In the future, it is necessary to collect pulse diagnosis data also from elderly people.

The limitations of this study included the sensor array and the pressurization method. In traditional pulse diagnosis, information such as the depth and length of the arteries are obtained by scanning the fingertip repeatedly. However, our device could not obtain such information, because the three pressure sensors were fixed in position and only one pressure cuff was used. Therefore, the results obtained from the pulse diagnosis system cannot be quantitatively compared to the results from the traditional method. To obtain detailed information about blood vessels, it is necessary to improve the device by considering new measurement methods such as further dividing the sensor unit into structures capable of accurately measuring the pressure distribution. In the traditional pulse diagnosis procedure, the radial artery is palpated, but since the ulnar artery is not occluded, blood flow is not interrupted. However, as our device uses a cuff-type manchette, pressure is applied all around the whole compressed area. Therefore, the blood flow distribution differs between when the cuff is pressurized and when the pulse is palpated. Therefore, as a future task, we intend to develop a pressurization method that is separate for each sensor instead of a single pressurization method, and a system that can pressurize only the local sensor.

In addition, there is no comprehensive statistical analysis of the pulse diagnosis and pulse waveform, because there was negligible difference in the diagnostic results for each subject by traditional pulse diagnosis. Further studies recruiting a wide variety of subjects are needed for clarification of pulse diagnosis and pulse waves. Big data analysis and machine learning of pulse diagnosis may further yield improved results.

5. Conclusion

Pulse wave measurement was performed in healthy subjects using the proposed pulse diagnosis measurement system. Pulse wave measurement with similar methodology as traditional pulse diagnosis techniques was realized, and pulse waveforms measured by the pulse diagnosis system were analyzed. Our results indicate the possibility of quantitative pulse diagnosis.

Conflict of interest statement

The authors have no conflicts of interest directly relevant to the content of this article.

Acknowledgement

This research was supported by AMED under Grant Number JP16lk0310022h0001.

References

1. Li P, Du YK, Chen XN, Jiang SM, Liu JS, Yang C, Zhang XP: Anatomy of the Cun position at wrist and its application in pulse diagnosis. Evid Based Complement Alternat Med. 2019;1796576, 2019 [Published online]
2. Wu HK, Ko YS, Lin YS, Wu HT, Tsai TH, Chang HH: The correlation between pulse diagnosis and constitution identification in traditional Chinese medicine. Complement Ther Med. 30, 107–112, 2017.
3. Wang H, Cheng Y: A quantitative system for pulse diagnosis in Traditional Chinese Medicine. Conf Proc IEEE Eng Med Biol Soc. 2005: 5676–5679, 2005.
4. Kabigting JET, Chen AD, Chang EJ, Lee W, Roberts RC: MEMS pressure sensor array wearable for Traditional Chinese Medicine pulse-taking, 2017 IEEE 14th International Conference on Wearable and Implantable Body Sensor Networks (BSN), 59–62, 2017.
5. Kan-heng Z, Peng Q, Chun-ming X, Yi-qin W: Research on a novel three-channel self-pressurized wrist pulse acquisition system. In: Fred A, Gambou H, Elias D. (eds) Biomedical Engineering Systems and Technologies. BIOSTECH 2015, pp. 49–59, 2015.
6. Jaeuk UK, Jeon YJ, Kim YM, Lee HJ, Kim JY: Novel Diagnostic model for the deficient and excess pulse qualities. Evid Based Complement Alternat Med. 2012, 1–11, 2012.
7. Shin KY, Jin SO, Youn SH, Joo SB, Jo YO, Kwon OK, Huh Y: A pulse wave simulator for palpation in the oriental medicine. Conf Proc IEEE Eng Med Biol Soc. 2011, 4163–4166, 2011.
8. Lee YJ, Lee J, Kim JY: A Study on characteristics of radial arteries through ultrasonic waves. 30th Annual International IEEE EMBS Conference, 2008. 2453–2456, 2008.
9. Smulyan H, Csermely TJ, Mookherjee S, Warner RA: Effect of age on arterial distensibility in Asymptomatic humans. Arteriosclerosis, 3(3), 199–205, 1983.
10. Wahlgvist ML, Relf IR, Myers KA, Lo CS: Diabetes and macrovascular disease: risk factors for atherogenesis and non-invasive investigation of arterial disease. Hum Nutr Clin Nutr. 38(3), 175–184, 1984.
11. Ishihara F, Hiramatsu K, Shigematsu S, Aizawa T, Niwa A, Takanasu N, Yamada T, Matsuo K: Role of adrenal androgens in the development of arteriosclerosis as judged by pulse wave velocity and calcification of the aorta. Cardiology. 80(5–6), 332–338, 1992.
12. Yambe T, Yoshizawa M, Sajo Y, Yamaguchi T, Shibata M, Konno S, Nitta S, Kuwayama T: Brachio-ankle pulse wave velocity and cardio-ankle vascular index (CAVI). Biomed Pharmacother. 58(1), S95–98, 2004.
13. Yambe T, Meng X, Hou X, Wang Q, Sekine K, Shiraiishi Y, Watanabe M, Yamaguchi T, Shibata M, Kuwayama T, Maruyama M.
Konno S, Nitta S: Cardio-ankle vascular index (CAVI) for the monitoring of the atherosclerosis after heart transplantation. Biomed Pharmacother. 59(1), S177–179, 2005.

14. Okura T, Watanabe S, Kurata M, Manabe S, Koresawa M, Irita J, Enomoto D, Miyoshi K, Fukuoka T, Higaki J: Relationship between cardio-ankle vascular index (CAVI) and carotid atherosclerosis in patients with essential hypertension. Hypertens Res. 30(4), 335–340, 2007.

15. Takaki A, Ogawa H, Wakeyama T, Iwami T, Kimura M, Hadano Y, Matsuda S, Miyazaki Y, Matsuoka T, Hiratsuka A, Matsuzaki M: Cardio-ankle vascular index is a new noninvasive parameter of arterial stiffness. Circ J. 71(11), 1710–1714, 2007.

16. Task Force of the European Society of Cardiology: the North American Society of Pacing Electrophysiology: Heart rate variability: standards of measurement, physiological interpretation and clinical use. Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology. Circulation. 93(5), 1043–1065, 1996.

17. Assoumou HG, Pichot V, Barthelemy JC, Dauphinot V, Celle S, Gosse P, et al: Metabolic syndrome and short-term and long-term heart rate variability in elderly free of clinical cardiovascular disease: The PROOF study. Rejuvenation Res. 13(6), 653–663, 2010.

18. Kim JI, Jeon YJ, Lee YJ, Kim KH, Kim JY: Novel diagnostic algorithm for the floating and sunken pulse qualities and its clinical test. Evid Based Complementary Altern Med. 2011, 1–10, 2011.

19. Kim SH, Kim JU, Lee YJ, Kim KH, Kim JY: New algorithm of determining the floating and sinking pulse with a pulse diagnosis instrument. Korean Journal of Oriental Physiology & Pathology. 3(6), 1221–1225, 2009.

20. Kim JU, Lee YJ, Lee J, Kim JY: Differences in the properties of the radial artery between Cun, Guan, Chi, and nearby segments using ultrasonographic imaging: a pilot study on arterial depth, diameter, and blood flow. Evid Based Complementary Altern Med. 2015, 1–7, 2015.

21. Milan A, Zocaro G, Leone D, Tosello F, Buraioi I, Schiavone D, Veglio F: Current assessment of pulse wave velocity: comprehensive review of validation studies. J Hypertens. 37(8), 1547–1557, 2019.

22. Tamura T: Progress of home healthcare sensor in our experience: development of wearable and unobtrusive monitoring. Adv Biomed Eng. 9, 189–196, 2020.

Akihiro Yamada

Akihiro Yamada received Ph.D. degrees in Biomedical Engineering from Tohoku University in 2015. From 2015 to present, he worked at Institute of Development, Aging and Cancer, Tohoku University as an Assistant Professor. His research interests include artificial organs, ventricular assist device, shape memory alloy actuator, congenital heart disease, and electrical engineering for medical devices, etc. He is a member of the Japanese Society for Medical and Biological Engineering, Japanese Society for Artificial Organs, IEEE, and Japan Society for Simulation Technology.
Tomoyuki Yambe

Tomoyuki Yambe received the M.D. and Ph.D. degrees in Medicine from Tohoku University in 1985 and in 1989, respectively. He was a Research Associate from 1992 at the Division of Medical Engineering and clinical investigation and Department of Medical Engineering and Cardiology, Institute of Development, Aging and Cancer, Tohoku University. He has been a Professor in the same department from 2004. From 2015 to present, he became the director of the PreClinical Research Center, Institute of Developing, Aging and Cancer, Tohoku University. He engages in artificial internal organs, autonomic nervous system analysis and telemedicine. He is a member of Japanese College of Cardiology, the Japanese Society for Medical and Biological Engineering, Japanese Society for Artificial Organs, Japan Society of Circulation Control in Medicine, Japanese Society of Clinical Physiology and Japanese Society of Neurovegetative Research.