A Novel Pulse Wave Analyzer for Personal Health Monitoring

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***Abstract*— We have newly developed a next-generation portable pulse wave analysis platform that can measure both radial augmentation index (rAI) and aortic PWV (aoPWV) with a smartphone/tablet to prevent future disease.**

Keywords—augmentation index, radial wave, aorta, pulse wave velocity, aortic PWV.

I. Introduction

Arterial pulse wave research in the medical field has been energetically conducted for a long time and many types of methods have been introduced in the past 20-30 years [1].
The main driving force could be attributed to combination of new sensor developments and IT technology [2]. *Aortic pulse wave velocity (PWV) and augmentation index (AI) are independent predictors of adverse cardiovascular events, including mortality* [3].
This newly developed pulse wave analyzer named SPA (Smart Pulse Analyzer) can easily measure both rAI and aoPWV on daily life to detect arterial conditions which are fluctuated by body conditions like blood pressure. In addition, the measurement of autonomic balance/lyapunov index (LLE) is also available. SDPTG vascular age estimation approach [4] and arrhythmia detection can be added. The aim of this study is to show potential useful capabilities as a personal pulse wave analysis system for monitoring daily health.

II. System

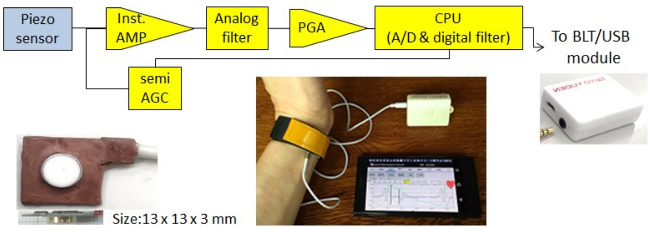

Fig. 1. Block diagram of sensor module and a measurement setup. The sensor is pressed onto the radial artery with a band and wound with appropriate pressure, checking amplitude and SNR of raw waveforms.

The novel high-sensitive piezo sensor consists of two parts: an intelligent sensor unit integrated with a series of electronic circuits including an A / D converter, a CPU, and a subsequent Bluetooth / USB module. The BLT / USB module is equipped with a rechargeable lithium-ion battery that can be charged via USB and can also perform wired measurements with a USB cable. Data can be automatically uploaded to a secure server by FTP for sharing with healthcare professionals. The cut-off frequency of low pass filter is set to 40 Hz. The power consumption of the PZT sensor is extremely small (μW) compared to conventional optical based sensors (mW), and even if it is measured several times a day, continuous measurement of about one week will be possible with one charge.

III. Basic Performance

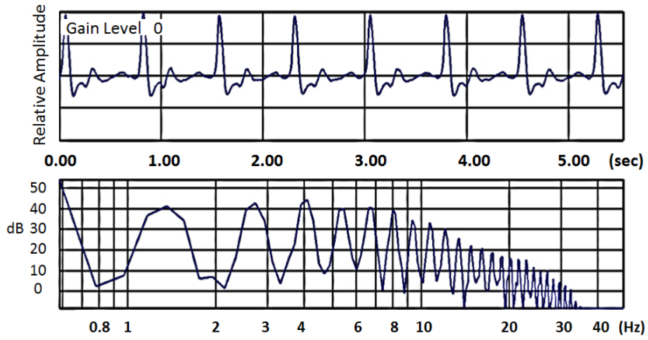

Fig. 2. A raw signal waveform (top) and its FFT spectrum (bottom).

The sampling frequency is 400 Hz, the number of quantization bits is 12 bits, and the number of data is 2048 in Fig. 2. The raw sensor signal generates a first derivative signal of the arterial pressure pulse. Savitzky–Golay filter is employed (10-25 points, polynomial degree 2,3) to smooth raw waveform. As can be seen in this figure, it is possible to confirm up to the 24 the harmonic of the 1.39 Hz fundamental frequency at the pulse rate of 83.4 bpm. This is twice higher resolution than the frequency band conventionally used in Generalized Transfer Function research [5] and the like. The differentiation characteristic by the device itself removes the signal offset, thus providing the advantage of SNR and reducing the resolution requirement for digital acquisition of the signal. By taking advantage of the high amplitude resolution and SNR, an original calculation algorithm have been established that can estimate the arrival timing of a reflected wave extracted from a single waveform, as will be discussed later.

IV. Arterial Pulse Transmission Model

Figure 3 shows schematic of a pulse wave which is constructed by superposition of forward wave and its reflected wave, and the definition of the radial augmentation index [6]. I It also shows the definition of the pulse transit time, PTT, and the effective aorta length required for the aoPWV calculation.
The ejected forward wave propagates from the heart to peripheral arteries. The forward wave transmitted from the aortic arch through the inferior aorta generates a reflected wave at the reflection site of the common iliac artery bifurcation [7]. We assumed the reflection site is at the common iliac artery bifurcation, although there are reports that the first reflection site is the renal artery [8] or the site

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of pulse wave reflection varies with age [9]. This point will be focused at Results and Disscusion. The reflected wave then returns to the heart and also reaches the radial artery through brachial artery. Pulse wave is observed as superposition of forward wave and reflected wave. Since the pulse wave velocity increases as arterial stiffness increases, the pulse transit time PTT, which is the time difference between forward wave and reflected wave, becomes shorter.

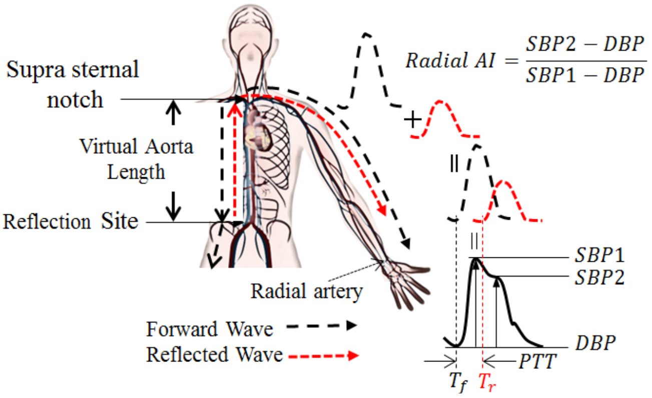

Fig. 3. Definition of Virtual Arota Length, Pulse Transit Time (PTT), and Radial Augmentaion Index.

V. Estimation of Aortic PWV

As a shape of pressure pulse waveform is determined by the incident wave itself and both the return time (PTT) of the reflected wave and its amount of amplitude (reflection coefficient), therefore, the PTT calculation algorithm needs to separate these contributions quantitatively. Figure 4 shows both of (a) young to middle age and (b) older age (right) examples of pressure pulse (green) and its high order of derivatives from 1st (raw signal) to 3rd orders. The calculated arrival timing of the reflected wave is indicated (red star).

The rise time T_f of the forward wave was determined by using the first + to - zero cross position of the fourth derivative against the integrated waveform [10] .We use the first +peak position of 3rd derivative, instead of using the zero cross position at + to - of 4th derivative as they are mathematically equivalent. The T_r time which is beginning of upstroke of the reflected wave was basically determined by using two specific points: a second +peak of the 3rd derivative (shoulder point) and a second + peak of the 2nd derivative (inflection point) [11]. This key hypothesis in this study that " T_r will be between these two points" was devised with reference to [3] and [11].

PW50 was defined as a sharpness parameter of the rise of the forward wave. As shown in Fig. 4, the PW50 is pulse width in time domain at 50 % amplitude of 1st derivative. It relates to the strength of ejection of heart (and also extensibility of artery) should be considered to the PTT calculation.

By using these parameters, the PTT is calculated as follows;

$$\mathrm{PTT} = T_{r1} - (T_{r2} - T_{r1}) \cdot \left\{ \frac{r_2}{r_1} - \left(1 - \frac{PW_{50}}{\alpha_2}\right) \right\} \cdot \alpha_1 \quad (1)$$

where PW_{50} , α_1 , and α_2 are parameters experimentally determined, respectively. No discontinuity of the PTT calculation between (a) and (b).

The aortic length is defined as Virtual Aorta Length using an empirical formula in which the umbilical-clavicular distance of the subject is calibrated by height. The time difference between T_f and T_r can be assumed as the round trip time of reflected pulse for the Virtual Aorta Length.

Finally, the SPA-aoPWV is calculated as follows;

$$\mathrm{aoPWV} = 2 \cdot \text{Virtual Arota Length} \,/\, \mathrm{PTT} \quad (2)$$

VI. Simulation for Pulse Transit Time

A pulse wave simulation has been conducted to show a validity of the PTT calculation method above.

Logarithmic normal function was used to calculate forward wave as it is known to fit pressure pulse waveform which is asymmetry expressed by following equation [12];

$$y = y_0 + \frac{A}{\sqrt{2 \cdot \pi} \cdot w \cdot x} \cdot Exp\left[-\frac{(ln(x/x_c))^2}{2 \cdot w^2} \right] \quad (3)$$

The lognormal wave in Fig. 5 seems to describe well the measured radial forward waveform obtained from a 25 years old healthy male (no figure). Optimization of parameters utilized the function of OriginPro2017, where

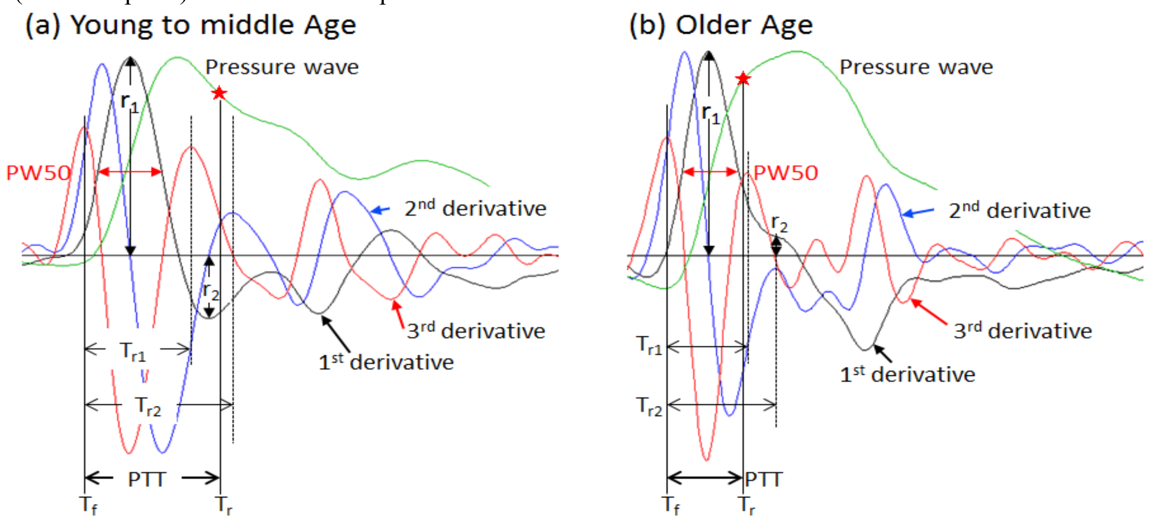

Fig. 4. Definition of each parameters obtained from waveforms of both time and amplitude domain to calculate Pulse Transit Time (PTT).

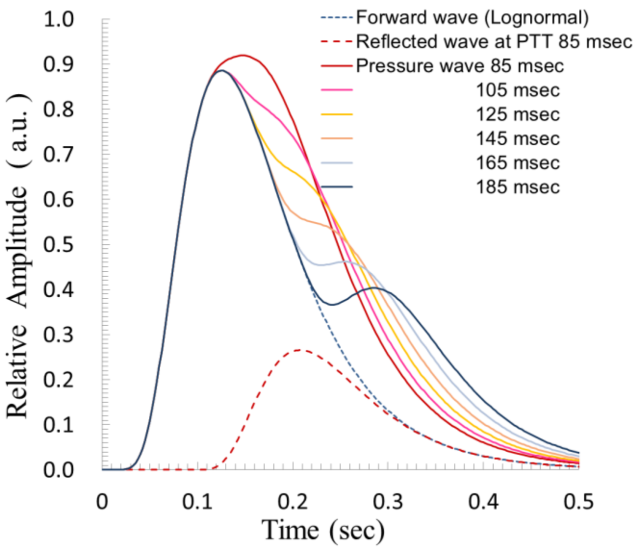

Fig. 5. 6 of systole pressure pulse waveforms in which each of 20 msec relative PTT difference at reflection coefficient 0.4

y_0=0.031, x_c=0.152, w=0.44, A=0.1344, respectively.

A reflected waveform was simply obtained as reflection coefficient x forward wave、 and these two waves were superimposed by PTT time difference to make a pressure wave. Although there is a diastolic waveform after dicrotic notch in the actual pulse wave, this pulse wave analysis assumes that the reflected wave arrives at systole before dicrotic notch, so we assume that it is possible to simulate the validity of the estimation algorithm using the two waves. The reflection coefficients defined as amplitude ratio were set to 0.3, 0.4, and 0.5, and the PTTs were set at intervals of 20 msec from 85 msec to 185 msec. The simulated 6 waveforms at reflection coefficient 0.4 are shown in Fig. 5.

As shown in Figure 6, it is demonstrated that the newly developed estimation formula (1) can calculate the arrival timing of reflected pulse wave almost independently of the reflection coefficient with an accuracy within 5% except two points at 85 msec.

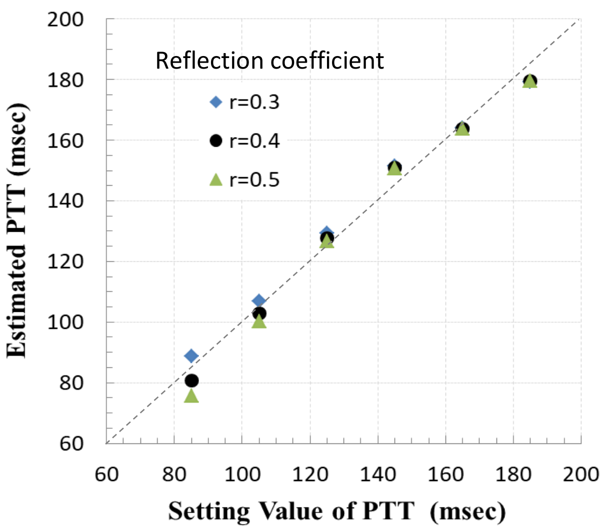

Fig. 6. Accuracy of the estimated PTTs at each setting value by using both equation (1) and (3).

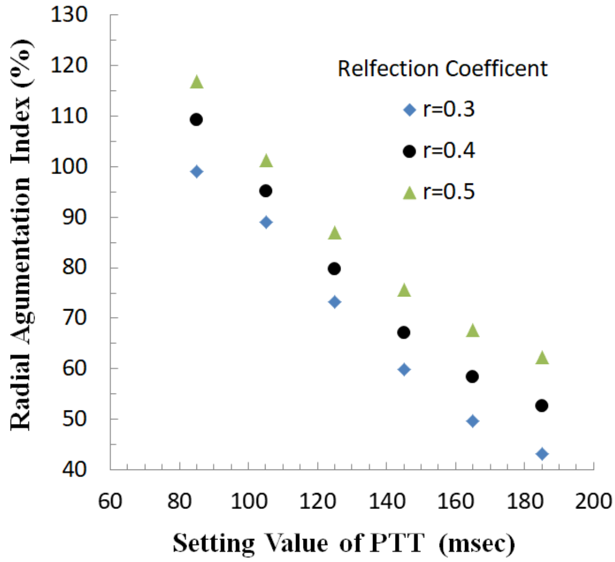

Fig. 7. Calculated Radial Agumentation Index at each of PTT setted.

The rAI values were also calculated for these sets of simulation wave using with our algorism.

Figure 7 shows that the rAI is determined by the combination of the pulse transit time PTT and the reflection coefficient. That is, pulse wave velocity cannot be estimated from only its rAI value. (This may suggest a reason why both rAI and aoPWV are independent predictor for cardiovascular disease.)

From the above, it is concluded that there is sufficient estimation accuracy in the formula (1) to determine the time when the reflected wave has arrived by using a single pulse wave.

VII. MEASUREMENT

Figure 8 shows an example of raw waves for 1 minute measured with the SPA, and its analytical results which includes pressure pulse waveform and higher order differential waveforms of radial pulse. The average pulse rate of 76 bpm, rAI corrected with 75 bpm [13] is 68.2 (%), analysis results of PTT is 141.4 (msec), and its estimated aortic PWV is 5.44 (m / s) are displayed, respectively.

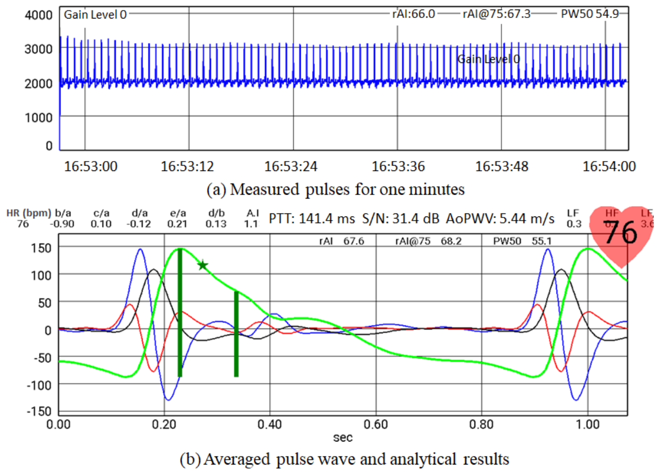

Fig. 8. An example of raw pulse waves (a) and its ensemble averaged waveforms and analytical results (b). Green: pressure pulse wave, black: raw wave (1st derivative), blue: 2nd derivative, red: 3rd derivative. Star mark: Arrival point of reflected wave determined.

Regarding the validity of rAI calculation, we compared with Omron HEM-9000AI. The Pearson's correlation coefficients between rAI with HEM-9000AI (x) for 30 seconds and rAI recalculated with our rAI algorithm (y) were almost the same as $y = 0.96x + 4.33$, $R^2 = 0.99$.

VIII. Results and Discussions

To examine whether measured rAI and aoPWV show values with similar age-related change multiple reported previously, a small clinical trial was conducted with the 35 healthy volunteers shown in Table I. It was approved by the Clinical Ethics Review Committee of Yokohama University of Pharmacy (No.C18009).

Table-I Basic parameters of subjects

Items	Male	Female
Number of subjects	18	17
Age (years)	47.1 (23-73)	55.4 (20-73)
Height (cm)	170.5 (161-177)	156.5 (146-171)
Virtual aorta length (cm)	38.4 (35.7-40.3)	34.4 (31.4-38.7)

A: Radial Augmentation index (rAI)

Figure 9 summarizes the relationship between radial AI @75 and age, obtained by the SPA. A significant positive correlation between age and rAI for both male and female was observed, where the female rAIs showed relatively larger value than those of male. This tendency is the same as reported in the previous paper [6], although these age-related line slope of the SPA were larger than that of Omron HEM-9010AI. This primal reason should be attributed to the limited amount of measured samples for this experiment.

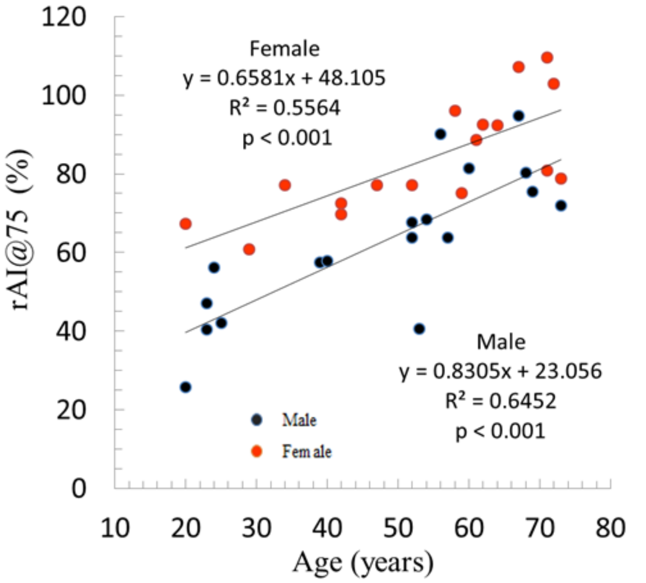

Fig. 9. Correlation between radial augmentation index (rAI) and age.

B: Aortic Pulse Wave Velocity (aoPWV)

The experimentally obtained relationship between estimated aortic pulse wave velocity and age is shown in Fig. 11. A similar age-related positive correlation to previous papers was observed even using with limited 35 samples. The PWV value and its slope were compared to one of the latest cfPWV report [14] in which 2158 healthy adults (1412 female) were examined.

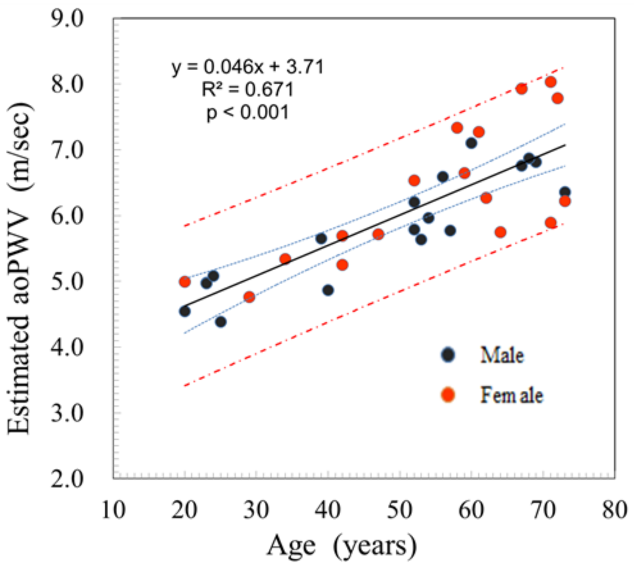

Fig. 10. Age-related change of aoPWV for both healthy subjects. The 95% confidence intervals of the estimation and prediction are plotted in the graph. Estimated (blue), predicted (read)

The average SPA-aoPWV of male / female at age of 50 in Fig. 10 was 6.0 (m/s) vs. the cfPWV 8.7 (m/s), and the increasing slope was SPA-aoPWV 0.046 (m/s/year) vs. the cfPWV 0.055 (m/s/year).

Both of the reported data of the SPA-aoPWV showed smaller values than these of the cfPWV. These differences can be considered that the SPA-aoPWV is a pure PWV targeting the aorta region, while cfPWV is the average PWV between middle of aorta and peripheral femora (relatively hard muscular) artery at the measured site [15].

One of the related paper of the above description is that a report that the local PWV at the femoral region showed about 1.5 times higher than that at the Iliac region (in Figure 4.22) [1], though the data was examined not with a human but with a dog . In addition, measurement data has been reported that the local PWV of the aorta in normal human subjects was suddenly increased up to 6 (m/sec) at the femoral artery region while being less than 4 (m/sec) at aorta region [16].

Then we compared our data to a CMR-PWV data which can non-invasively measure pure aorta artery. For the CMR-PWV, it has been read that the male and female mean aoPWV was 4.2 (m/sec), and the increase slope was 0.05 (m/s/year) [17]. Each of the increased slope of PWV are close values , and it can be interpreted that age-related changes are similarly detected, while the SPA-aoPWV value is about 1.4 times larger than the CMR-aoPWV at age 50 years old.

Although we assume that the reflection site is a common iliac bifurcation as previously explained, if it is corrected as a renal bifurcation, the anatomical aortic length becomes as short as about 65-70%, and the aoPWV becomes smaller proportionately. There is a possbility that the reflection site might be a renal bifurcation based on the PWV value. This should be examined more in future works.

It is shown from the above that the SPA-aoPWV can show similar results between cfPWV and CMR-aoPWV values currently reported, even with using a very simple method by just wrapped a new high-fidelity sensor around wrist and measure with an android smartphone.

C: Personal Health Monitoring

Figure 11 plotted all of 577 data of aoPWV of the 1st author (59 years old male) measured for one year from May 22, 2018.

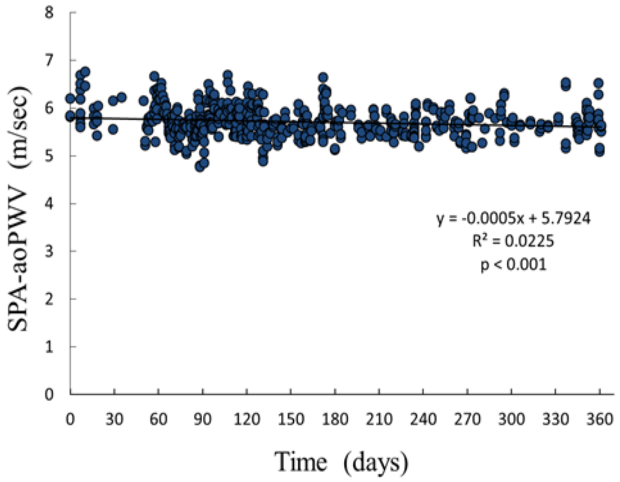

Fig. 11. SPA-aoPWV data measured for one year from May 22, 2018.

The measurement rules were very rough, frankly speaking, and the timing was limited to measurable situation from waking up to bedtime. The pulse rate was fluctuated between 57 and 97 (bpm) immediately after getting up, before and after desk work during the day, and after light exercise. Here, average pulse rate was 70.5 (bpm) and its standard deviation was 5.76 (bpm). The aoPWV may be influenced by all measurement related errors (sensor position error, SNR, etc.) as well as various physical and physiological conditions like blood pressure. Even taking them into account, still the slope of SPA-aoPWV values indicates that no progression of arteriosclerosis related to aging and lifestyle can observed because all of effects are equivalently occurs. In any case, the aging speed can be monitored by capturing the minute change tendency of arterial stiffness of about +0.046 (m / year) = + 1.3E-4 (m / day) on average.To feed back to yourself, you will need to contine the measurement on a daily basis for at least six months to a year. However, if the measurement rules are specified more strictly, it might be possible to grasp the effects in a few months. Anti-aging requires personal efforts of nutrition, additional sulpriment, exercie [18], and the pulse wave measurement.

IX. CONCLUSION AND FUTURE PERSPECTIVE

The relative aortic stiffness changes with aging and progress of arteriosclerosis are measured and checked by rAI and aoPWV, and it was shown that the SPA (Smart Pulse Analyzer) system can be provided new functions that individual can utilize these results for daily health monitoring. In order to realize the era of 100 years of life and beyond, the personal pulse wave analyzers can contribute to individual health maintenance and improvement. If the potential abilities could have been presented through this report, we believe that the first goal of our research has been achieved. Also, well-planned clinical trials will be expected to make the SPA as a novel new medical device beyond the personal health care device.

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CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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