A Simulation for Estimation of the Blood Pressure using Arterial Pressure-Volume Model

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***Abstract*—**A analysis on the conventional the blood pressure estimation method using an oscillometric sphygmomanometer was performed through a computer simulation using an arterial pressure-volume (APV) model. Traditionally, the maximum amplitude algorithm (MAP) was applied on the oscillation waveforms of the APV model to obtain the mean arterial pressure and the characteristic ratio. The estimation of mean arterial pressure and characteristic ratio was significantly affected with the shape of the blood pressure waveforms and the cutoff frequency of high-pass filter (HPL) circuitry. Experimental errors are due to these effects when estimating blood pressure. To find out an algorithm independent from the influence of waveform shapes and parameters of HPL, the volume oscillation of the APV model and the phase shift of the oscillation with fast fourier transform (FFT) were testified while increasing the cuff pressure from 1 mmHg to 200 mmHg (1 mmHg per second). The phase shift between the ranges of volume oscillation was then only observed between the systolic and the diastolic blood pressures. The same results were also obtained from the simulations performed on two different the arterial blood pressure waveforms and one hyperthermia waveform.

***Keywords*—** arterial blood pressure, oscillometric method

I. INTRODUCTION

THE blood pressure is a important criterion to discriminate the health condition of patients in clinical field [1]. Measuring a blood pressure usually takes place 3~4 times for patients in hospital and the blood pressure was measured when there is any symptoms and before and after important test. The blood pressure is measured in a constant time interval for patients in an emergency and operation room [2]. It is continuously checked-up for a person in intensive care unit and major operation. Patients with hypertension should check it at constant time daily. The blood pressure of normal person has also been routinely examined at medical check-up.

Method of measuring the blood pressure is divided into invasive blood pressure (IBP) and non-invasive blood pressure (NIBP). Invasive method, composing of catheter manometer system and catheter tip transducer, measures the blood pressure after inserting catheter into the blood vessel. Even though measurement of the blood pressure by invasive method is operated in case of sudden dynamic change of blood or requirement of measuring the period of heart rate, it is restrictively used due to difficulty of operation and the possibility of pain and bleeding, and infection. Non-invasive methods, which have being used widely measuring the blood pressure, are classified into auscultation, oscillometric method, palpation, ultrasonic, pulse wave velocity, vascular unloading method, and tonometric method. One of popular non-invasive method measuring the blood pressure is auscultation in which the systolic and diastolic pressure are evaluated using the Korotkoff sound generated from pressure change of a cuff wrapping arm. The oscillometric method is to discriminate between the systolic and the diastolic pressure for measuring the components of pulse wave transferred the wall of the blood vessel. The palpation method is to measure the systolic and the diastolic blood pressure while contacting radial artery intermittently flowing into the forearm. The ultrasonic wave method is to distinguish the systolic and the diastolic blood pressure through the blood flow by attaching ultrasonic sensor at region of the artery. The pulse wave velocity method using an electrocardiogram (ECG) signal and the pulse wave signal is to discriminate the systolic and the diastolic blood pressure through conversion of distance and time which the blood

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pumped from a heart to arrives at the peripheral blood vessel. The tonometric method is to discriminate the systolic and the diastolic blood pressure by integrating measured signals from array type of the blood pressure sensor attached in the wrist. In 1876 Marey[3] proposed firstly the oscillometric method using oscillation wave appearing after transferring the component of pulsation occurring at region of the artery vessel according to pressure variation of cuff wrapping to arm. Although the estimation of the average arterial blood pressure is possible using the oscillometric method, there is no criterion to determine the systolic and the diastolic blood pressure. Maximum amplitude algorithm (MAA) is mainly used to estimate the average arterial blood pressure in the oscillometric method [4]-[6]. This comes from the fact that the wall of the arterial blood vessel reaches the maximum expansion so that volume change of the arterial blood vessel becomes maximum value with regard to the change of the arterial blood pressure [7]-[9].

The problem of the oscillometric method using conventional the arterial pressure-volume model was analyzed and, the blood pressure estimation algorithm excluding characteristic ratio was proposed in this paper. A variety of the arterial pressure waveform were reproduced to do these works. The oscillation waveform due to pressure change of a cuff was converted using FFT and, after observing the phase change of classify by high frequency component, the systolic and the diastolic blood pressure were estimated except considering characteristic ratio.

II. RELATED THEORY

The artery pressure-volume Model

The characteristic of artery has several primary factors such as elasticity and compliance, and viscosity-elasticity affecting the blood flow. However, blood flow dynamic property of the arterial blood vessels reveals the diversified types of characteristic due to the blood pressure change [10]-[12].

The arterial model considered characteristic of compliance, without elasticity and viscosity-elasticity, was used in this work. This is called as the arterial pressure-volume (APV)model, describing the characteristic of volume change due to pressure change of the arterial blood vessel.

The mathematical relationship of APV model can be expressed as the following:

$$V = \begin{cases} V_0 e^{aP_t}, & \text{for } P_t \le 0 \\ V_{\max} + (V_0 - V_{\max}) e^{bP_t}, & \text{for } P_t > 0 \end{cases} \qquad (1)$$

where a and b are index coefficient of model, V_0 is the volume of the blood vessel when the blood pressed is reduced in the artery and V_{max} indicates the volume of blood vessel when the arterial blood vessel is fully expanded. These values such as a, b, V_0, and V_{max} are determined from animal experiment and a=0.09 mmHg^{-1}, b=-0.03 mmHg^{-1}, V_0= 1 ml and V_{max}= 4 ml are used in this work [12]. V indicates the volume change of the arterial blood vessel due to the change of P_t value as an output result of model. Variable P_t means the difference pressure between the arterial and the cuff, indicating the internal pressure inside the blood vessel. It can be expressed as the following:

$$P_t = P_a - P_c \qquad (2)$$

where P_a indicates the pressure of an arterial blood vessel and the P_c indicates the pressure of a cuff.

Fig. 1 represents the correlation curve of blood pressure when increasing P_t value in equation (1) from -100 mmHg to 200 mmHg.

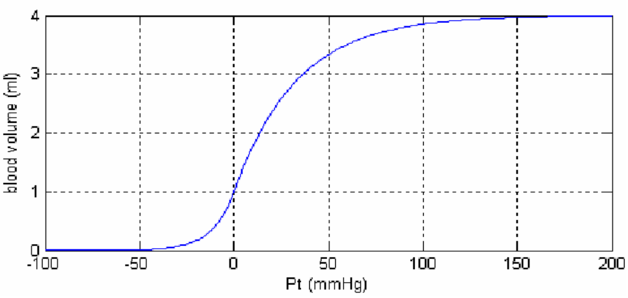


Fig. 1 A correlation curve of the P_t and the arterial volume in the arterial pressure-volume model.

Fig. 2 shows the 1’st differential curve of equation (1), indicating the compliance of model. The volume change becomes the maximum when P_t value is 0. This implies that the arterial blood pressure in the arterial blood vessel is same as the cuff pressure.

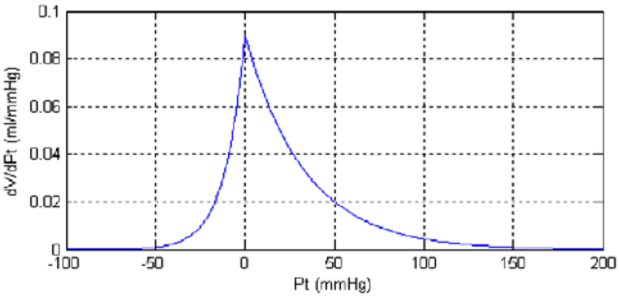
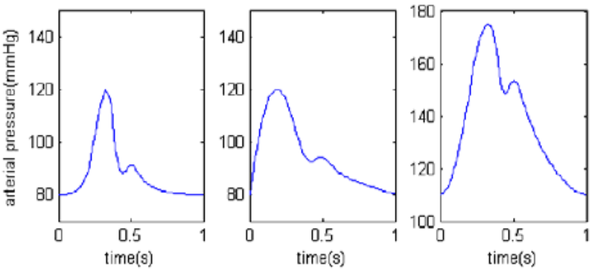


Fig. 2 The first-order differential curve of the arterial pressure-volume model.

III. COMPUTER SIMULATION AND RESULT

A. *The arterial pressure waveform and output*

The blood pressure waveform generated in the arterial blood vessel was produced as a various form as shown in Fig. 3. Fig. 3(a) and (b) represent the pressure waveforms in the artery. While the systolic and the diastolic blood pressure are identical to 120 mmHg and 80 mmHg respectively, the values of x-axis representing maximum pressure, that is, 120 mmHg of both waveform were not same. Furthermore, the average arterial pressure represent difference value as Fig. 3(a) shows 88.15 mmHg and Fig. 3 (b) shows 94.83 mmHg. As one of the arterial blood pressure waveform representing the 2nd phase hypertension patients, the systolic and the diastolic blood pressure were reproduced as 175 mmHg and 110 mmHg.

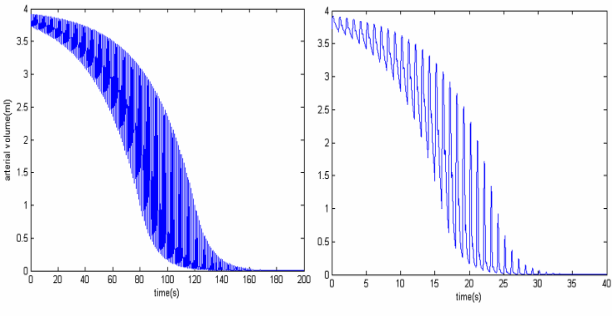


(a) (b) (c)

Fig. 3 Reproduced various blood pressure waveforms: (a) and (b) is normal range, and (c) second phase of hypertension.

The oscillation waveform for simulation was acquired by applying the proposed arterial pressure wave to the arterial pressure-volume model expressed in equation (1).

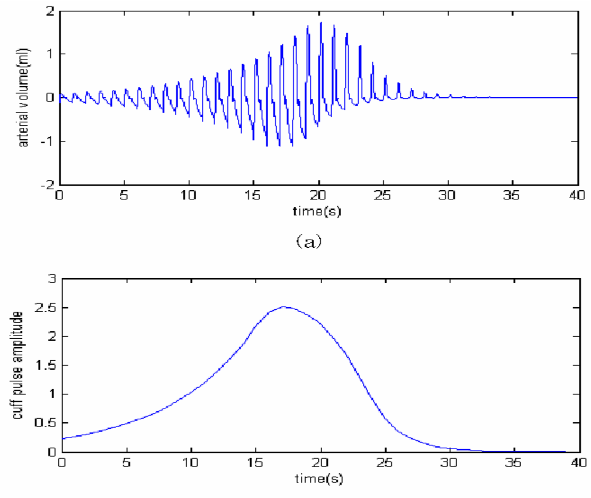
Fig. 4(a) indicates the output oscillation waveform of model when the arterial pressure waveform reproduced in Fig. 3 (b) was used as the input of P_a and the cuff pressure P_c increase at a rate of 1 mmHg per sec. for 200sec. Fig. 4(b) indicates the output oscillation waveform of model when the arterial pressure waveform reproduced in Fig. 3 (b) was used as the input of P_a and cuff pressure increases at a rate of 5 mmHg per sec.



(a) (b)

Fig. 4 The output oscillation waveform of the model: (a) measuring time is 1 second and (b) measuring time is 5 second.

Fig. 5 indicates the process acquisitioning of the oscillometric waveform from oscillation waveform. Fig. 5(a) represent the waveform in which the component of direct current was removed from oscillation waveform as shown in Fig. 4 (b). Fig. 4(b) is call as oscillometric waveform, it obtained the magnitude of waveform as shown in Fig, 5(a).



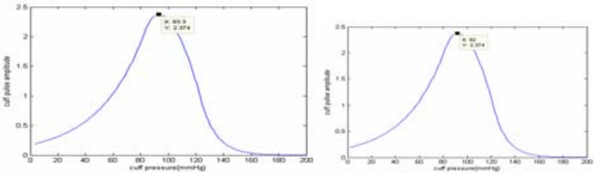
(a)

(b)

Fig. 5 The procedure acquisitioning of the oscillometric waveform: (a) oscillation waveform removed DC component in Fig. 4 and (b) oscillometric waveform.

B. *oscillometric waveform*

It is attempted to confirm in oscillometric method applied to the maximum amplitude algorithm that the average arterial pressure appear differently according to the type of arterial pressure waveform, even the arterial pressure waveform with identical the systolic and the diastolic blood pressure. Two arterial pressure waves with same the systolic and diastolic blood pressure, 120 mmHg and 80 mmHg but different waveform were used as an input waveform. By increasing the pressure of cuff at the rate of 1 mmHg per sec., the average arterial pressure was respectively obtained by seeking the maximum point of wave form after obtaining oscillometric waveform, the output of model. Fig. 6(a) and Fig. 6 (b) show the acquired oscillometric waveforms by applying the reproduced arterial pressure wave as Fig. 3(a) and Fig 3(b) to model. The average arterial pressures were 93.3 mmHg and 92mmHg respectively for the case of maximum amplitude algorithm. Even though the systolic and the diastolic blood pressure are identical, measured errors are generated in case of same characteristic ratios are applied to the oscillometric waveform which are different from the average arterial pressure.



(a) (b)

Fig. 6 Output oscillometric waveform of the arterial pressure-volume model: (a) model input signal is Fig. 3 (a) and (b) model input signal is Fig. 3 (b).

C. *Oscillometric waveform through high pass filter*

High-pass filter is used in commercial electronic sphygmomanometer applied to the oscillometric method, to remove the components of direct current from oscillation waveform. The distortion in the oscillation waveform is produced when the component of direct current from oscillation waveform is removed, to acquisition of the oscillation waveform.

In order to observe the effect on average arterial blood pressure and characteristic ratio according to high-pass filter, the oscillometric waveform was obtained by applying butterworth filter to oscillation waveform of model.

Fig. 7 represents the average arterial blood pressure revealing maximum amplitude, and oscillation amplitude of the systolic and the diastolic blood pressure. These phenomena indicate that conventional oscillometric method can exhibit the different blood pressure to patients with same the arterial blood pressure due to filter.

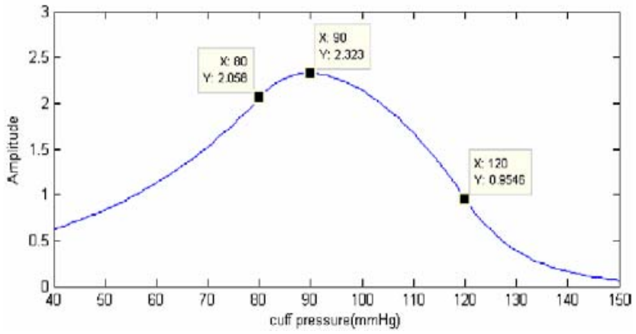
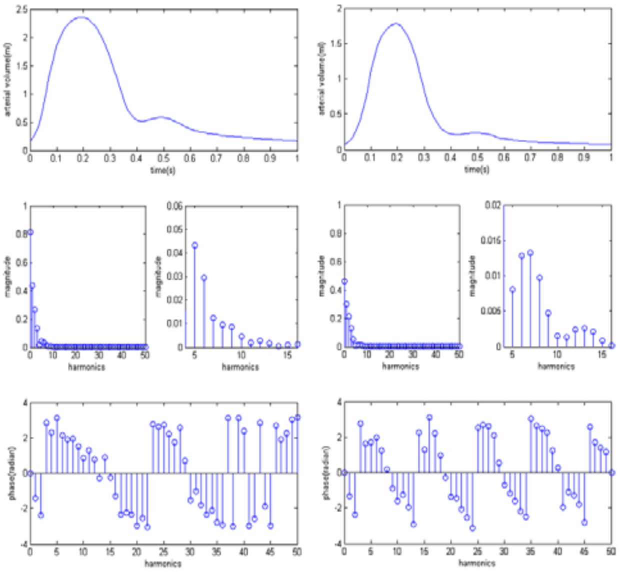


Fig. 7 The oscillometric waveform.through high pass filter.

D. *Frequency Analysis of the Oscillation waveform*

The frequency of oscillation waveform was analyzed to propose the algorithm estimating exactly the systolic and the diastolic blood pressure, compared to conventional MAA. The magnitude, classified by harmonics component and phase spectrum of the oscillation waveform due to the pressure change of cuff was investigated to accomplish this work. The arterial pressure wave with a normal range of 80 ~ 120 mmHg was used for input signal of the arterial pressure-volume model. And classified by harmonics and phase were obtained by Fourier transform as to the output oscillation waveform of model after fixing cuff pressure at 1 mmHg. Thereafter magnitude of classified by harmonics component and phase were also obtained using the same method while increasing the cuff pressure at 1 mmHg. While increasing the cuff pressure up to 200mmHg at a rate of 1 mmHg, magnitude of classified by harmonics component and phase was acquired by Fourier transform after acquiring the output oscillation waveforms as total 200 according to cuff pressure.

Fig. 8 shows the model output for constant P_c value. Fig. 8(a) indicates the model output and result on the FFT of oscillometric waveform when P_c is 100 mmHg. Fig. 8(b) also indicates the model output and result on the FFT of oscillometric waveform when P_c is 100 mmHg. Upper figures represent model output waveform according to P_c value. Middle figures represent measured magnitude spectra after applying FFT. Lower figures represent the phase spectra.

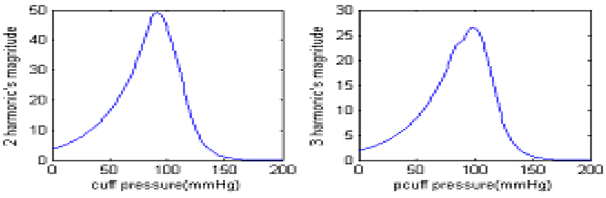


(a) (b)

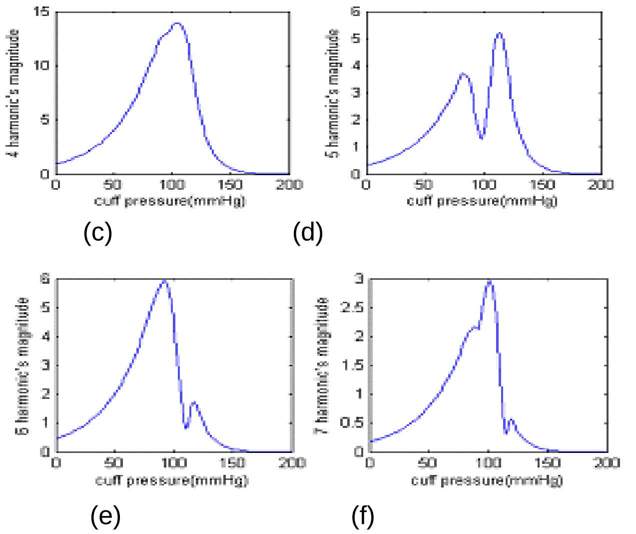
Fig. 8 Model output and result on FFT of oscillometric waveform: (a) When P_c is 100 mmHg and (b) when P_c is 110 mmHg.

Fig. 9 represents the variation aspect of the magnitude spectrum of classified by harmonics component according to the pressure change of cuff. Fig. 9(a) through Fig. 9(f) represent the magnitude spectrum of classified by harmonics component from 2nd harmonics to 7th harmonics. Fig. 10 represents the variation aspect of the phase spectrum of classified by harmonics component according to the pressure change of cuff. Fig. 10(a) through Fig. 10(f) represent the phase spectrum of classified by harmonics component from 2nd harmonics to 7th harmonics.

It was difficult to find out the characteristic point of the systolic and the diastolic blood pressure in the magnitude spectrum of classified by harmonics component according to increasing of the cuff pressure. However, the phase variation phenomenon was observed only at the systolic and the diastolic blood pressure in the phase spectrum of classified by harmonics component according to increasing of the cuff pressure. And other range between the systolic and the diastolic blood pressure were no phase variation with constant value.



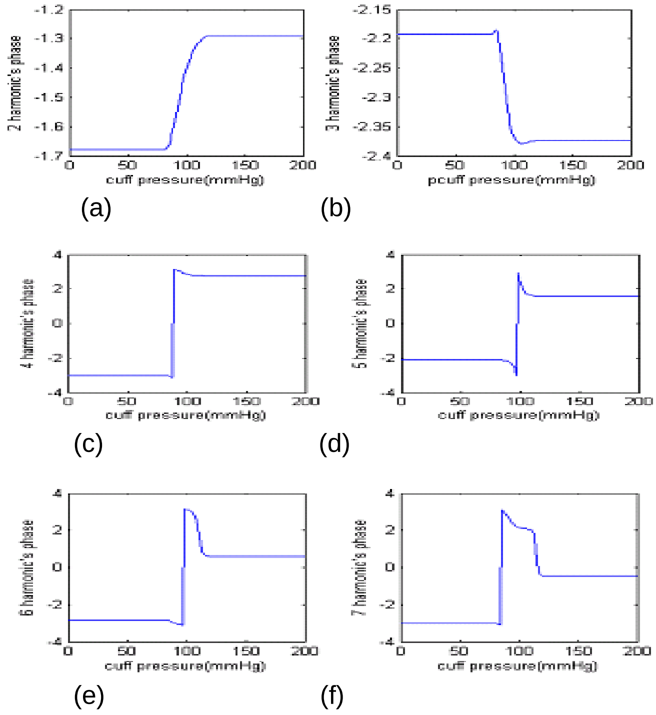
(a) (b)



(c) (d)

(e) (f)

Fig. 9 The variation aspect of magnitude spectrum of classified by harmonics component according to increasing of the cuff pressure: (a) through (f) represent magnitude spectrum from 2nd harmonics to 7th harmonics



(a) (b)

(c) (d)

(e) (f)

Fig. 10 Variation aspect of phase spectrum of classified by harmonics component according to increasing of the cuff pressure: (a) through (f) represent phase spectrum from 2nd harmonics to 7th harmonics.

E. Proposition of the blood pressure estimating algorithm

On the basis of the variation aspect of the phase spectrum described, the estimating algorithm of the blood pressure was proposed using the variation of phase. Fig. 11 shows the flow chart of the estimating algorithm of the blood pressure, which can be explained as the following.

(1) The arterial pressure wave in the specific range was used as the input of the arterial pressure-volume model after initially taking phase value as zero. (2) Model output was obtained by taking cuff pressure as 1mmHg at first. (3) The phase spectrum was extracted by FFT on output result of model. (4) The cuff pressure with increase of 1 mmHg was repeatedly accomplished in the case of no change after obtaining the variation of phase spectrum, while cuff pressure then was estimated as the diastolic blood pressure when there was change. (5) The output result of model was extracted while increasing 1mmHg to cuff pressure after detecting the diastolic blood pressure. (6) The phase spectrum was extracted by FFT on the output result of model. (7) When the variation of phase spectrum is non zero, simulation was repeatedly accomplished by increasing 1mmHg to cuff pressure. The cuff pressure was estimated as the diastolic blood pressure when the variation of phase spectrum is zero.

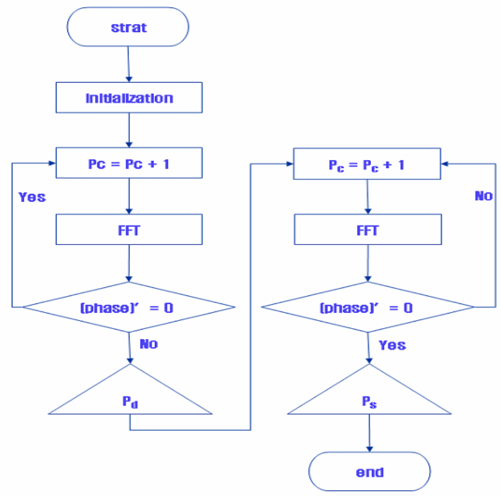


Fig. 11The proposed flowchart of the blood pressure estimation algorithm.

IV. CONCLUSION

The algorithm of measuring the blood pressure was analyzed for commercial automatic sphygmomanometer, and new method estimating accurate blood pressure was proposed. The oscillation waveform was acquired by high pass filtering the measured pulsation component of the blood vessel in conventional automatic sphygmomanometer. Later, the average the arterial blood pressure of blood pressure waveform measured by applying the maximum amplitude algorithm and, the systolic and the diastolic blood pressure was estimated by applying characteristic ratio on the basis of measured data. With the distortion phenomena of the oscillometric waveform occurred through high pass filtering and applied to characteristic ratio no consideration of the characteristic of the blood dynamic, experimental error are accompanied in the measurement of the systolic and the diastolic blood pressure. Therefore, estimating algorithm of the blood pressure excluding these error factors was proposed in this work.

The proposed estimating algorithm of the blood pressure is as the following. First of all, the oscillometric method was analyzed using the arterial pressure-volume model proposed by other researchers. The oscillation waveform of model output was acquired by applying cuff pressure to the proposed model. An estimating algorithm of the blood pressure, with no consideration of maximum amplitude algorithm and characteristic ratio used in the oscillometric method, was proposed by observing the variation of phase spectrum with the application of FFT. An additional research on the tissue of the blood vessel and the cuff characteristic are required to realize sphygmomanometer from the proposed algorithm because the static characteristic are considered in the oscillometric model proposed in this work.

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