Blood Pressure Simulation using an Arterial Pressure-volume Model

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(Received November 15 2007, Accepted February 18 2008)

Using an arterial pressure-volume (APV) model, we performed an analysis of the conventional blood pressure estimation method using an oscillometric sphygmomanometer with computer simulation. Traditionally, the maximum amplitude algorithm (MAA) has been applied to 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 by the shape of the blood pressure waveforms and the cutoff frequency of high-pass filter (HPF) circuitry. Experimental errors result from these effects when estimating blood pressure. To determine an algorithm independent of the influence of waveform shapes and parameters of HPF, the volume oscillation of the APV model and the phase shift of the oscillation with fast Fourier transform (FFT) were tested while increasing the cuff pressure from 1 mmHg to 200 mmHg (1 mmHg/s). The phase shift between ranges of volume oscillation was then only observed between the systolic and the diastolic blood pressures. The same results were obtained from simulations performed on two different arterial blood pressure waveforms and one hyperthermia waveform.

Keywords : Arterial model, NIBP

1. INTRODUCTION

In clinical fields, blood pressure is an important criterion used to determine the health of patients[1]. It is usually measured three to four times in hospital patients; measurements are made when any symptoms occur and before and after important tests. It is measured over a constant time interval in patients in emergency and operation rooms[2]. It is continuously checked in those in intensive care units and during major operations, and patients with hypertension should have it checked daily at a regular time. The blood pressure of normal persons is routinely examined in medical checkups.

Methods of measuring blood pressure are divided into invasive blood pressure (IBP) and noninvasive blood pressure (NIBP) categories. The invasive method, composed of a catheter manometer system and a catheter tip transducer, measures blood pressure after inserting a catheter into a blood vessel. Even though measurement of blood pressure by the invasive method is used in cases of sudden changes in blood or when measuring the heart rate is required, its use is restricted due to the difficulty of operation and the possibility of pain, bleeding, and infection. Noninvasive methods, which have been used widely to measure blood pressure, are classified into auscultation, the oscillometric method, palpation, the ultrasonic method, pulse wave velocity, vascular unloading, and the tonometric method. A popular noninvasive method for measuring blood pressure is auscultation in which the systolic and diastolic pressures are evaluated using the Korotkoff sound generated from pressure changes in a cuff wrapped around the arm. The oscillometric method discriminates between the systolic and diastolic pressure in measuring components of pulse waves transferred to the wall of the blood vessel. The palpation method measures the systolic and the diastolic blood pressure while contacting the radial artery intermittently flowing into the forearm. The ultrasonic wave method distinguishes the systolic and diastolic blood pressure through blood flow by attaching an ultrasonic sensor in the region of the artery. The pulse wave velocity method uses an electrocardiogram (ECG) signal and a pulse wave signal to discriminate the systolic and diastolic blood pressure through conversion of distance and time in which the blood pumped from the heart arrives at peripheral blood vessels. The tonometric method discriminates the systolic and the diastolic blood pressure by integrating measured signals from the array type of the blood pressure sensor attached to the wrist. In 1876, Marey[3] first proposed the oscillometric method, which uses oscillation waves that appear after transferring the component of pulsation occurring in a region of the artery vessel according to pressure variation in a cuff wrapped around the arm. Although the estimation of average arterial blood pressure is possible using the oscillometric method, no criterion exists to determine the systolic and diastolic blood pressures. The maximum amplitude algorithm (MAA) is mainly used to estimate average arterial blood pressure under the oscillometric method[4-6], which is based on the fact that the wall of the arterial blood vessel attains maximum expansion so that a volume change in the arterial blood vessel becomes maximal with regard to the change in arterial blood pressure[7-9].

In this paper, we propose the oscillometric method using the conventional arterial pressure volume model and a blood pressure estimation algorithm excluding the characteristic ratio. A variety of arterial pressure waveforms are reproduced to accomplish this work. The oscillation waveform influenced by a pressure change in a cuff is converted using FFT, and after observing the phase change in classification due to high frequency components, the systolic and diastolic blood pressures are estimated without considering the characteristic ratio.

2. RELATED THEORY

2.1 The artery pressure-volume model

The characteristics of arteries include several primary factors such as elasticity and compliance, and viscoelasticity affecting the blood flow. However, blood flow dynamics of arterial blood vessels reveal diversified characteristics as a result of blood pressure change.

In this study, we applied the arterial model considered characteristic of compliance, without elasticity and viscoelasticity. This is known as the arterial pressure-volume (APV) model, which describes the characteristics of volume change with the pressure change in the arterial blood vessel.

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

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

where a and b are index coefficients of the model, V_0 is the volume of the blood vessel when the blood pressure is reduced in the artery, and V_{max} indicates volume of the blood vessel when the arterial blood vessel is fully expanded. Values of a, b, V_0, and V_{max} were determined from animal experiments. Values used in this study were a = 0.09 $mmHg^{-1}$, b = -0.03 $mmHg^{-1}$, V_0 = 1 ml, and V_{max} = 4 ml. V indicates the volume change of the arterial blood vessel attributed to the change in P_t as an output result of the model. Variable P_t represents the difference in pressure between the artery and the cuff, indicating the internal pressure of the blood vessel. It can be expressed as follows:

$$P_t = P_a - P_c \tag{2}$$

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

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

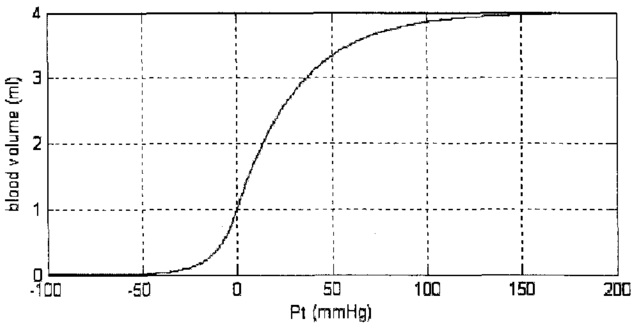


Fig. 1. Correlation curve of P_t and arterial volume in the arterial pressure–volume model.

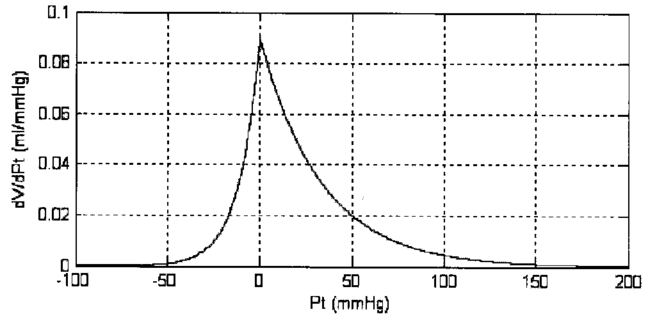


Fig. 2. The first-order differential curve of the arterial pressure-volume model.

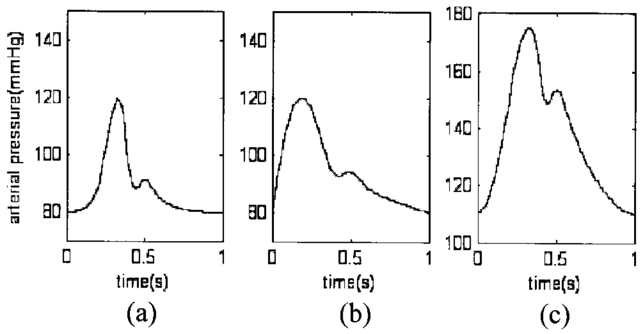
Figure 2 shows the first-order differential curve of equation (1), indicating compliance of the model. The volume change becomes the maximal when P_t is zero. This implies that the blood pressure in the arterial blood vessel equals the cuff pressure.

3. COMPUTER SIMULATIONS AND RESULTS

3.1 The arterail pressure waveform and output

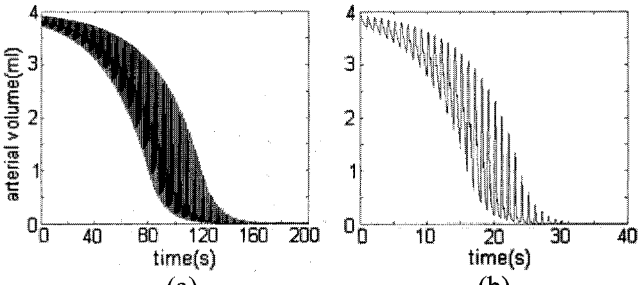
The blood pressure waveform generated in the arterial blood vessel produced various forms as shown in Fig. 3.

Figures 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, values of the X-axis representing maximum pressure, 120 mmHg for both waveforms, were not the same. Furthermore, the average arterial pressure represents different values as shown in Fig. 3(a) (88.15 mmHg) and Fig. 3(b) (94.83 mmHg). As one of the arterial blood pressure waveforms representing second-phase hypertension patients, the systolic and the diastolic blood pressures were reproduced as 175 mmHg and 110 mmHg, respectively.



(a) (b) (c)

Fig. 3. Various blood pressure waveforms reproduced: (a) and (b) are in the normal range and (c) represents the second phase of hypertension.



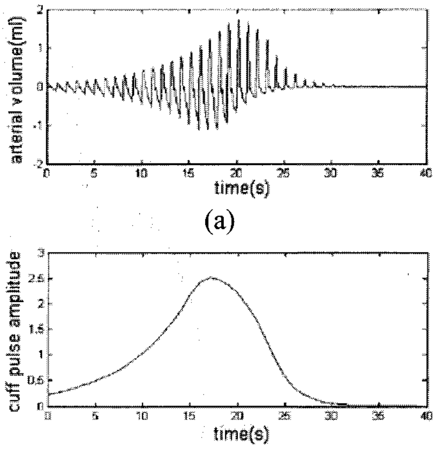
(a) (b)

Fig. 4. The output oscillation waveform of the model: (a) measurement time was 1 s; (b) measurement time was 5 s.

The oscillation waveform for simulations was acquired by applying the proposed arterial pressure wave to the arterial pressure–volume model expressed in equation (1). Figure 4(a) indicates the output oscillation waveform of the model when the arterial pressure waveform reproduced in Fig. 3(b) was used as the input for P_a and the cuff pressure Pc increased at a rate of 1 mmHg/s for 200 s. Figure 4(b) indicates the output oscillation waveform of the model when the arterial pressure waveform reproduced in Fig. 3(b) was used as the input for P_a and the cuff pressure increased at a rate of 5 mmHg/s.

Figure 5 presents the process of acquisitioning the oscillometric waveform from the oscillation waveform.

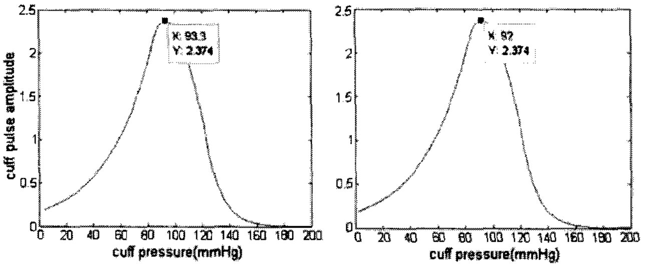
Figure 5(a) shows the waveform in which the component of direct current was removed from the oscillation waveform as shown in Fig. 4(b). Figure 4(b) shows the oscillometric waveform, which obtained the magnitude of the waveform shown in Fig. 5(a).



(a)

(b)

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



(a) (b)

Fig. 6. Output oscillometric waveform of the arterial pressure–volume model: (a) model input signal in Fig. 3(a); (b) model input signal in Fig. 3(b).

3.2 Oscillometric waveform

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

3.3 Oscillometric waveform through a high-pass filter

In the oscillometric method, a high-pass filter is used in commercial electronic sphygmomanometers to remove the components of direct current from the oscillation waveform. The distortion in the oscillation waveform is produced when the component of direct current from the oscillation waveform is removed. To observe the effect on average arterial blood pressure and characteristic ratio according to the high-pass filter, the oscillometric waveform was obtained by applying Butterworth filter to the oscillation waveform of the model. Table 1 shows mean arterial pressure(MAP) through a high-pass filter. These phenomena indicate that the conventional oscillometric method, because of the filter, can exhibit the different blood pressure to patients with the same arterial blood pressure.

Table 1. The MAP through a high-pass filter.

Cutoff Frequency(Hz)	0.1	0.2	0.3	0.4	0.5	0.6	0.7
MAP(mmHg)	90	90	92	93	93	94	95

3.4 Frequency analysis of the oscillation waveform

The frequency of the oscillation waveform was analyzed to propose the algorithm that could exactly estimate the systolic and the diastolic blood pressure as compared to conventional MAA. The magnitude classified by the harmonics components and phase spectrum of the oscillation waveform that resulted from the pressure change in the cuff were investigated to accomplish this work. An arterial pressure wave with a normal range of 80-120 mmHg was used for the input signal of the arterial pressure-volume model. In addition, classifications by harmonics and phase were obtained by fast Fourier transform (FFT) as to the output oscillation waveform of the model after fixing the cuff pressure at 1 mmHg. Thereafter, the magnitude of the harmonics component and phase were also obtained using the same method while increasing the cuff pressure at 1 mmHg/s. While increasing the cuff pressure up to 200 mmHg at a rate of 1 mmHg/s, the magnitude of the harmonics component and phase was acquired by FFT after acquiring the output oscillation waveforms as 200 total according to the cuff pressure. Figurer 7 shows the model output for a constant Pc value. Figurer 7(a) indicates the model output and result on the FFT of the oscillometric waveform when Pc is 100 mmHg. Figurer 7(b) also indicates the model output and result on the FFT of the oscillometric waveform when Pc is 100 mmHg.

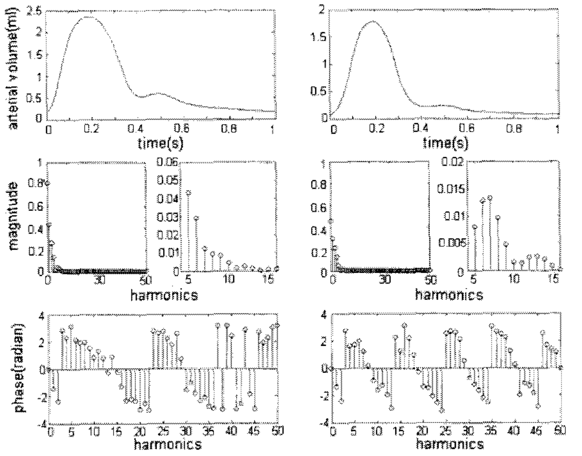


Fig. 7. Model output and results from FFT of the oscillometric waveform: (a) when Pc is 100 mmHg; (b) when Pc is 110 mmHg.

Table 2. The phase variation between the systolic and the diastolic.

Pc(mmHg)	phase value as homonics					
	2homonic	3homonic	4homonic	5homonic	6homonic	7homonic
1~80	-1.680	-2.193	-3.007	-2.107	-2.817	-3.031
81	-1.679	-2.192	-3.008	-2.104	-2.819	-3.032
82	-1.678	-2.190	-3.010	-2.098	-2.822	-3.051
83	-1.674	-2.187	-3.020	-2.100	-2.838	-3.085
⋮	⋮	⋮	⋮	⋮	⋮	⋮
118	-1.292	-2.376	2.763	1.599	0.606	-0.408
119	-1.291	-2.375	2.763	1.598	0.596	-0.450
120~200	-1.290	-2.374	2.762	1.598	0.593	-0.461

The upper figures represent the model output waveform according to the Pc value. The middle figures represent the measured magnitude spectra after applying FFT. The lower figures represent the phase spectra. Figurer 8 shows the variation aspect of the magnitude spectrum of the harmonics component according to the pressure change of the cuff.

Figures 8(a-f) represent the magnitude spectrum classified by harmonics components from the 2nd to 7th harmonics. Figurer 9 shows the variation aspect of the phase spectrum of the harmonics components according to the pressure change of the cuff. Figures 9(a-f) represent the phase spectrum of the harmonics components from the 2nd to 7th harmonics.

Determining the characteristic point of the systolic and the diastolic blood pressure in the magnitude spectrum classified by harmonics components based on increasing cuff pressure was difficult. However, the phase variation phenomenon was observed only at the systolic and the diastolic blood pressure in the phase spectrum classified by harmonics components according to increasing cuff pressure. The other range between the systolic and the diastolic blood pressure showed no phase variation, with a constant value. Table 2 shows phase variation between the systolic and the diastolic.

3.5 The proposed blood pressure estimation algorithm

On the basis of the variation aspect of the phase spectrum described, an estimation algorithm for blood pressure was proposed using the variation in phase. Figurer 10 shows the flowchart of the algorithm, which is explained as follows. First, the arterial pressure wave in the specific range was used as the input of the arterial pressure–volume model after initially taking a phase value of zero. Second, the model output was obtained by taking cuff pressure (P_c) initially as 1mmHg. Third, the phase spectrum was extracted by FFT on the model

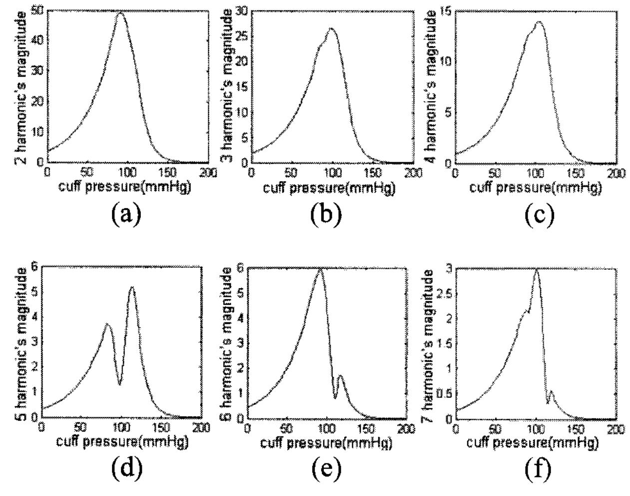


Fig. 8. Variation aspect of the magnitude spectrum classified by harmonics components according to increasing cuff pressure: (a)-(f) represent the magnitude spectrum from 2nd harmonics to 7th harmonics.

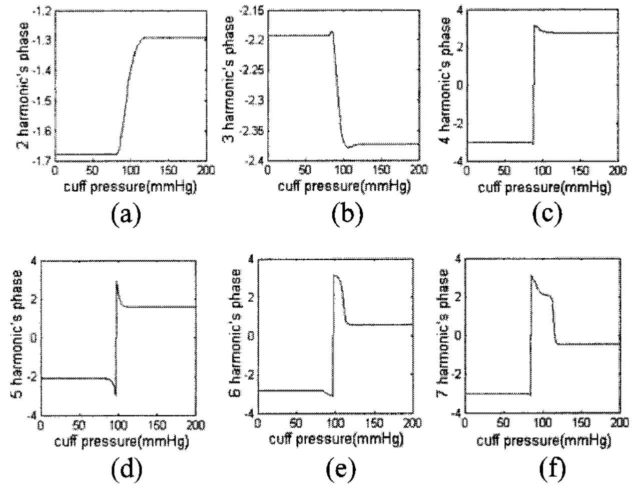


Fig. 9. Variation aspect of the phase spectrum classified by harmonics components according to increasing cuff pressure: (a)-(f) represent the phase spectrum from 2nd harmonics to 7th harmonics.

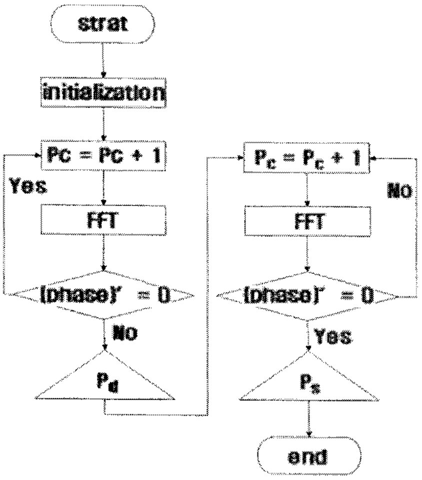


Fig. 10. The proposed flowchart of the blood pressure estimation algorithm.

output. Fourth, the cuff pressure with an increase of 1 mmHg was repeatedly accomplished in the case of no change after obtaining variation in the phase spectrum, while the cuff pressure was then estimated as the diastolic blood pressure (P_d) when change occurred. Fifth, the model output was extracted while increasing the cuff pressure by 1 mmHg after detecting the diastolic blood pressure. Sixth, the phase spectrum was extracted by FFT on the model output. Seventh, when the variation of the phase spectrum was nonzero, the simulation was repeated by adding 1 mmHg to the cuff pressure. The cuff pressure was estimated as the systolic blood pressure (P_s) when the variation of the phase spectrum was zero.

4. CONCLUSION

We analyzed the algorithm for measuring the blood pressure in commercial automatic sphygmomanometers and proposed a new method of accurately estimating blood pressure. The oscillation waveform was acquired by high-pass filtering of the measured pulsation component of blood vessels in a conventional automatic sphygmomanometer. Later, we measured the average arterial blood pressure waveform by applying the maximum amplitude algorithm, and estimated the systolic and the diastolic blood pressures by applying the characteristic ratio on the basis of measured data.

When we applied the distortion phenomena of the oscillometric waveform obtained through high-pass filtering to the characteristic ratio, we excluded characteristics of blood dynamics and experimental error accompanying measurement of the systolic and diastolic blood pressures. Therefore, we proposed an estimation algorithm of blood pressure excluding these error factors.

The proposed algorithm is described as the follows. First, the oscillometric method was analyzed using the arterial pressure-volume model proposed in other studies. The oscillation waveform of the model output was acquired by applying the cuff pressure to the proposed model. An estimation algorithm for blood pressure, with no consideration of the maximum amplitude algorithm and the characteristic ratio used in the oscillometric method, was proposed by observing the variation in the phase spectrum, with the application of FFT. Additional research on the tissues of blood vessels and cuff characteristics are required to reproduce sphygmomanometer readings with the proposed algorithm because characteristics considered in the oscillometric model proposed in this study were static.

ACKNOWLEDGMENT

This work was supported by the Health Medical Technology Research of the Ministry of Health and Welfare(02-PJ3-PG6-EV05-0001).

REFERENCES

[1] A. J. Moss, “Indirect method of blood pressure measurement”, Pediatr. Clin. North Am., Vol. 25(1), p. 136, 1978.
[2] J. K. Cheun, “Cardiopulmonary physiology for the clinicians”, Koon Ja Publishing Inc., p. 57, 1996.
[3] E. J. Marey, “Pression et vitesse du sang, physiologic experimentable”, Masson, Paris, Vol. 2, ch. VII, p. 307, 1876.
[4] J. A. Posey, L. A. Geddes, H. Williams, and A. G. Moore, "The meaning of the point of maximum oscillations in cuff pressure in the indirect measurement of blood pressure: part I", Cardiovasc. Res. Center Bull., Vol. 8, p. 15, 1969.
[5] M. Wang, “Development of K-sound and oscillometric pulse generating system for NIBP monitor tester”, M. Sc. thesis, Department of Mechanical Engineering, Queen's University, Kingston, Ontario, Canada, 1990.
[6] G. Drzewiecki, R. Hood, and H. Apple, "Theory of the oscillometric maximum and the systolic and diastolic detection ratios", Ann. Biomed. Eng., Vol. 22, p. 88, 1994.
[7] L. A. Geddes, M. Voelz, C. Combs, D. Reiner, and C. F. Babbs, “Characterization of the oscillometric method for measuring indirect blood pressure”, Ann. Biomed. Eng., Vol. 10, p. 271, 1982.
[8] S. H. Liu, “A model-based fuzzy logic controller for tracking mean arterial pressure”, IEEE International Fuzzy Systems Conference, p. 1495, 2001.
[9] C. T. Lin, S. H. Liu, J. J. Wang, and Z. C. Wen, "Reduction of interference in oscillometric arterial blood pressure measurement using fuzzy logic", IEEE Trans. Biomed. Eng., Vol. 50(4), p. 432, 2003.