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# Adaptive Control with Self-tuning for Non-invasive Beat-by-beat Blood Pressure Measurement

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*Abstract*— **Up to now, we have successfully carried out the non-invasive beat-by-beat measurement of blood pressure (BP) in the root of finger, superficial temporal and radial artery based on the volume-compensation technique with reasonable accuracy. The present study concerns with improvement of control method for this beat-by-beat BP measurement. The measurement system mainly consists of a partial pressurization cuff with a pair of LED and photo-diode for the detection of arterial blood volume, and a digital self-tuning control method. Using healthy subjects, the performance and accuracy of this system were evaluated through comparison experiments with the system using a conventional empirically tuned PID controller. The significant differences of BP measured in finger artery were not showed in systolic (SBP), p=0.52, and diastolic BP (DBP), p=0.35. With the advantage of the adaptive control with self-tuning method, which can tune the control parameters without disturbing the control system, the application area of the non-invasive beat-by-beat measurement method will be broadened.**

## I. Introduction

Due to considerable increase in cardiovascular diseases in an aging society, there has been an increasing need to measure arterial blood pressure (BP) non-invasively, conveniently and reliably for clinical diagnosis and therapy as well as healthcare. For example, elevated BP is a consistent and independent risk factor for cardiovascular and renal diseases. On the other hand, lowered BP can cause depression due to dizziness and faintness in daily living. Cuff-oscillometric and/or auscultation method have been widely used for clinics as well as at home. However, these methods can only provide intermittent information of BP and only allow a low measurement rate such as about once per minute caused by the measurement principles [1]. Moreover, repeated measurements by these methods attached with a whole circumference cuff can cause ischemia and discomfort [2]. Therefore, continuous BP measurement on a beat-by-beat basis has still been most desirable. Although several methods are available for non-invasive beat-by-beat BP measurement, each method also has shortcomings. For instance, the tonometric method in radial artery requires initial as well as frequent calibrations using the cuff-oscillometric method during the BP monitoring [3]. The Penaz method in digital artery, so-called "the volume clamping method" [4], has also been required frequent calibrations with alternating two fingers and confronted with venous congestion in the distal portion of the occlusive cuff during long-term monitoring [5]. In contrast, we have also proposed a non-invasive instantaneous BP measurement called the volume-compensation method based definitely on the arterial tube law [6-8]. In this technique, the volume-oscillometric method also proposed by us [7, 8] is applied in order to determine a servo-reference value which corresponds to the arterial volume in an unloaded state of the arterial wall. Up to the present time, we have developed several non-invasive BP measurement systems based on these methods using various measuring sites such as digital, radial, superficial and perforating artery and carried out comparison experiments with direct BP measurements [9-13]. In some of these, a partial pressurization cuff was adopted so as to avoid venous congestion to achieve a long-term measurement [9-13]. The present study concerns with improvement of the servo control method for this beat-by-beat BP measurement. The performances of this improvement are described.

## II. Material and Methods

### A. Nov-invasive BP Measurement System

The non-invasive BP measurement system for the present study was developed based on the volume-compensation method. The volume-compensation method consists of three procedures as the following: (1) the cuff pressure (Pc) is increased gradually and photoelectric plethysmogram signal (PG) is obtained simultaneously. Then, the PGdc level corresponding with an unloaded vascular volume (Vo) is

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found from the mean level of the DC component of the PG signal (PGdc) where the pulsatile component of the PG signal (PGac: AC component of superimposed on the PG signal) has maximum amplitude. This is the principle of the volume-oscillation method that can measure BP level intermittently [7, 8]. The level of PGdc corresponds to the Vo is adopted as the servo-reference value (PGdc) in the following procedure. (2) The Pc is controlled under a servo control mechanism to clamp the PGdc level at the PGdc. (3) Intra-arterial pressure waveform (BP waveform) is obtained continuously from the measurement of the instantaneous Pc changes. Details of the principle of the volume-compensation method have been previously described [6].

The schematic drawing of the non-invasive instantaneous BP measurement system based on volume-compensation method is shown in Fig 1. The system consists of four parts as follows (a) a arterial sensor part that including a cuff-fixation holder with PG sensor unit (consisted of a photodiode and two LEDs) and a partial pressurization cuff, (b) a sensor control and signal conditioning unit that includes an electro-pneumatic converter for instantaneous pressure control, an air pump, a pressure sensor for cuff pressure measurement, an LED driver and PG amplifiers, (c) a system control unit that carries out the volume-oscillometric and the volume-compensation method and (d) an ordinal PC having a human interface of the total system and recording obtained all signals.

Detailed information of the instantaneous BP measurement system is as follows. The partially compression cuff was employed to minimize venous congestion due to continuous inflation based on the previous experimental results [9-11]. A silicon sheet (thickness: 0.3 (mm)) bonded flat cuff was used as the partially compression cuff with the size of 15x20 (mm). As for the PG sensor, a near infrared LED (EL321; Kodenshi Corp, Kyoto, Japan) of center emission wavelength 910 nm, and a near infrared photodiode (PD) (TPS704; Toshiba Corp, Tokyo, Japan) of peak sensitivity wavelength 1000 nm were mounted on the cuff with the center-to-center LED-PD separation distance 3 (mm). For the cuff pressure sensing and control unit, commercially available electro-pneumatic convertors (EPC) (SV-302W; Kohritsu Co. Ltd, Saitama, Japan) and an air pump (AC0102; NITTO KOHKI CO., LTD, Tokyo, Japan) were applied. For the system control unit, a digital signal controller with A/D and D/A converters (MicroAutoBox MABX 1501_815; dSPACE GmbH, Germany) was used. And the controller was programmed with graphical programming technique using MATLAB/SIMULINK (Matlab 2007b; Mathworks. Inc, Massachusetts, USA) and ControlDesk (ControlDesk 3.5; dSPACE GmbH, Germany) software installed in an ordinary PC (Satellite PXW/59LW, Toshiba, Tokyo, Japan) with the Microsoft Windows XP OS. An operator was able to operate the total system of BP measurement from the PC. The EPC was controlled by the signal from digital signal controller in the rate of 2 (kHz). The data of cuff pressure (Pc), PG signal including DC component (PGdc) and pulsatile component of the PG signal (PGac) were digitized with 12 (bit) precision at a sampling frequency of 2 (kHz) by the digital signal controller and stored in the HDD on the PC.

### *B. Adaptive Control with Self-tuning Method*

The servo controller of cuff pressure (Pc) control in the previous studies had been conventional digital or analog PID (proportional–integral–derivative) controllers [6-13]. Using such conventional control techniques, control parameters such as proportional gain, integral gain and derivative gain should be determined. And for taking proper control, the parameters should be tuned empirically for each subject and each measurement part and tuning process could disturb the control procedure. However, one of the modern control techniques, the self-tuning adaptive controller is allowed to determine the control parameters without disturbing the control [14].

A self-tuning controller type adaptive controller was introduced to the BP measurement system. The lower panel of the Fig. 1 shows a block diagram of the implicit self-tuning controller. This type of control system has a controller of which control parameters can be updated dynamically in real time. For updating the controller properly, the system identification function estimates the controlled process dynamically and the parameters on the controller are determined obeying the characteristics of the identified system consistently.

In this study, the system identification was done by the recursive least squares method. And the transfer function of the process, including optical and mechanical properties around dorsalis pedis artery, was identified as a second order autoregressive exogenous (ARX) model in every 10 (msec). Subsequently, the controller was designed by the pole assignment method also in every 10 (msec) in order to determine the transfer function G(s) from input (cuff pressure Pc) to output (PG signal PGdc) properly. All procedures were able to be performed without disturbing the control. The form of the G(s) was determined as equation (1), because the transfer function of the process was estimated as a second order system.

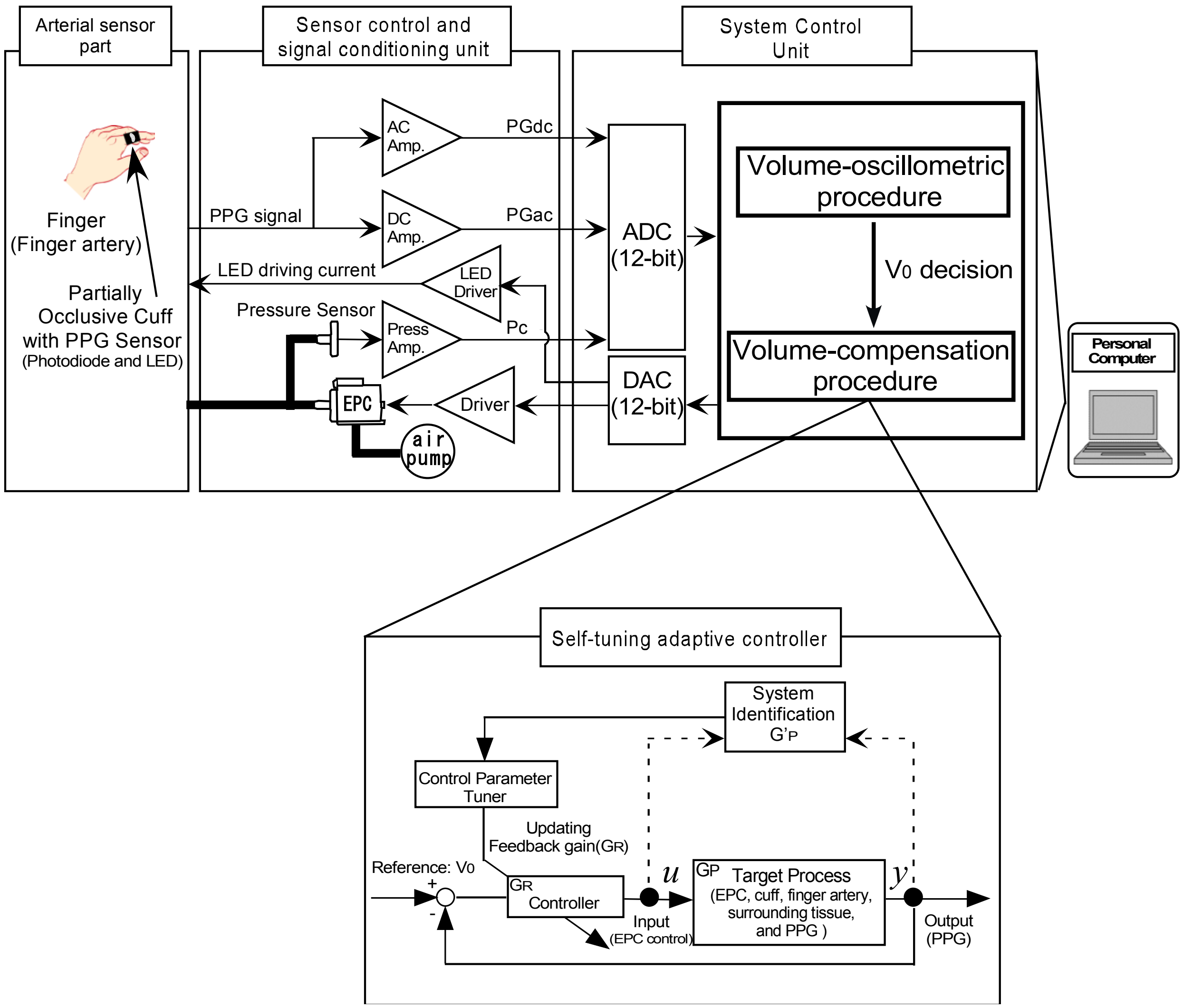


Fig. 1 Schematic drawings of the non-invasive BP measuremnt system with adaptive self-tuning controller

By using the pole assignment method, the transfer function G(s) can be arbitrarily determined. The criterion of the pole assignment was as follows for obtaining stable poles; ξ (the damping factor) of the transfer function was 0.7 and $\omega_n$ (the natural frequency of oscillation) of the transfer function was 40.

$$G(s) = \frac{K_g}{s^2 + 2\xi\omega_n s + \omega_n} \quad (1)$$

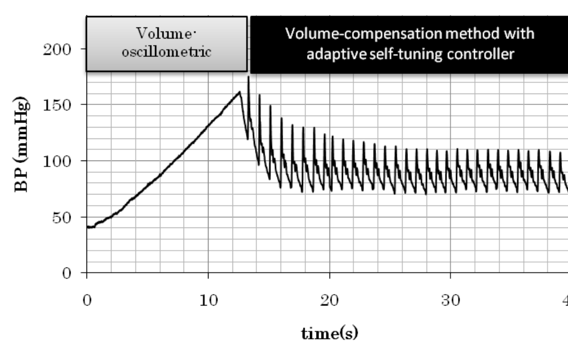


Fig. 2 Typical recording of the non-invasive BP measurement with adaptive self-tuning methd

### C. Experimental Procedure

Using the beat-by-beat BP measurement system described above, beat-by-beat BP measurement from finger artery were attempted and compared in five healthy subjects (20-40 (yrs)) with the adaptive and the conventional PID control method. Prior to the experiments, the local ethics committee of Kanazawa University approved the experimental procedures and informed consent was obtained from each subject.

## III. Results

As shown in Fig 2, beat-by-beat BP in finger artery were successfully obtained through the experiments by using the proposed system. The self-tuning adaptive controller worked well, the controlled process was identified in real time and the parameters for servo control were also updated in real time without any disturbance onto the control and instantaneous BP measurement. The significant differences of BP measured in finger artery were not showed in systolic (SBP), p=0.52, and diastolic BP (DBP), p=0.35 under the Wilcoxson's rank sum test.

## IV. Conclution

The self-tuning adaptive control method was introduced into the measurement system to cramp a Vo level of photo-plethysmographic signal to measure instantaneous BP and demonstrate a good result in healthy voluntary subjects. Practically, the determination of the conventional PID controller parameters has been with difficulties due to not knowing the time-varying characteristics of the control target such as mechanical and optical properties of artery and its surrounding tissue. In contrast, the self-tuning adaptive controller involves a time-varying system identification procedure on its own technique and the time-varying system identification can be performed in real time without disturbing the control system. Though, we have not yet evaluated the performance of the adaptive control method in patients with circulatory disorders and the robustness against heavily motion artifacts, the adaptive control can be considered as a promising technique.

Needless to say, all non-invasive BP measurement should be compared with the direct BP measurement in artery [15]. We will confirm the non-invasive BP measurement with the adaptive self-tuning controller by direct measurement.

## References


[1] T. W. Kurtz, K. A. Griffin, A. K. Bidani, R. L. Davisson, and J. E. Hall, "Recommendations for blood pressure measurement in humans and experimental animals part 2," Hypertension, vol. 45, pp. 299-310, 2005.

[2] R. M. Stern, W. J. Ray and K. S. Quigley, Psychophysiological recording, 2nd ed., Oxford, UK: Oxford University Press, 2001.

[3] G.M. Drzewiecki, J. Melbin and A. Noordergraaf, "Arterial tonometry: Review and analysis," J. Biomech., vol. 16, pp. 141-152, 1983.

[4] J. Penaz, "Photoelectric measurement of blood pressure, volume and flow in finger," in Digest of the 10th International Conference on Medical and Biological Engineering, 1973, p p. 104.

[5] R. D. Boehmer, "Continuous, real-time, noninvasive monitor of blood pressure: Penaz methodology applied to the finger," J. Clin. Monit., vol. 3, pp. 282-287, 1987.

[6] K. Yamakoshi, H. Shimazu, T. Togawa, "Indirect measurement of instantaneous arterial blood pressure in the human finger by the vascular unloading technique," IEEE Trans. Biomed. Eng., vol. 27, pp. 150-155, 1980.

[7] K. Yamakoshi, H. Shimazu, M. Shibata and K. Kamiya, "New oscillometric method for indirect measurement of systolic and mean arterial blood pressure in the human finger. Part 1; Model experiment," Med. Biol. Eng. Comput., vol. 20, pp. 307-313, 1982.

[8] K. Yamakoshi, H. Shimazu, M. Shibata and A. Kamiya, "New oscillometric method for indirect measurement of systolic and mean arterial pressure in the human finger. Part 2; Correlation study," Med. Biol. Eng. Comput., vol. 20, pp. 314-318, 1982.

[9] M. Nakagawara and K. Yamakoshi, "Development of a finger cuff unit for a noninvasive blood-pressure monitoring system based on the volume-compensation method," Japanese journal of medical electronics and biological engineering, vol. 34, pp. 283-290, 2000. [main text in Japanese, abstract in English]

[10] S. Tanaka and K. Yamakoshi, "Ambulatory instrument for monitoring indirect beat-to-beat blood pressure in superficial temporal artery using volume-compensation method," Med. Biol. Eng. Comput., vol. 34, pp. 441-447, 1996.

[11] S. Tanaka, S. Gao, M. Nogawa and K. Yamakoshi, "Noninvasive measurement of instantaneous radial artery blood pressure. An instrument based on the volume-compensation method," IEEE Eng. Med. Biol. Mag., vol. 24, pp. 32-37, 2005.

[12] S. Tanaka, M. Nogawa, T Yamakoshi and K Yamakoshi, "Accuracy assessment of a noninvasive device for monitoring beat-by-beat blood pressure in the radial artery using the volume-compensation method," IEEE Trans. Biomed. Eng., vol. 54, pp. 1892-1895, 2007.

[13] S. Tanaka, K. Motoi, M. Nogawa, T. Yamakoshi and K. Yamakoshi, "Development of a blood pressure monitoring system installed in a toilet seat for use in home healthcare," Japanese journal of medical electronics and biological engineering, vol. 44, pp. 467-474, 2006. [main text in Japanese, abstract in English]

[14] V. Bobál, J. Böhm, J. Fessl and J. Machácek, Digital Self-tuning Controllers. London, UK: Springer-Verlag London, 2005.

[15] K. Yamakoshi, In the spotlight: BioInstrumentation, IEEE Rev. Biomed. Eng., vol. 2, pp. 2-5, 2009.