Estimation of Vascular Impedance Using a Log-linearized Viscoelastic Model

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***Abstract*- This paper proposes a new nonlinear model, called a log-linearized viscoelastic model, to estimate the dynamic characteristics of human arterial walls by employing mechanical impedance factors including stiffness and viscosity in beat-to-beat measured from biological signals such as arterial blood pressure and photoplethysmograms. The validity of the proposed method is discussed by showing how arterial wall impedance properties change during arm position testing in the vertical direction. The estimated stiffness indices are compared with those of the conventional linear model. Estimated impedance parameters with the contribution ratio exceeding 0.97 were used for comparison. The results indicated that stiffness and viscosity decrease when the arm is raised and increase when it is lowered, showing the same tendency as mean blood pressure. However, the changes of the proposed nonlinear viscoelastic parameter are smaller (*P* < 0.05) than those of the linear model. This result suggests that our proposed nonlinear arterial viscoelastic model is less affected by changes of mean intravascular pressure during arm position changes.**

***Keywords*—Mechanical impedance, Arterial wall, intravascular pressure, nonlinear viscoelastic parameter, Photoplethysmogram.**

I. Introduction

Blood vessels perform an essential role in human life by supporting the transport of oxygen and nutrients to the whole body, and play an important part in state changes such as vasoconstriction/vasodilatation blood volume adjustment [1]. Vascular changes of state can usually be divided into the two general categories of organic and functional change. In organic change (arteriosclerosis), the quality of collagen in the arterial wall changes due to aging, causing stiffness and resulting in poor wall condition stemming from reduced amounts of elastic fiber [2]. Arterial walls demonstrated functional changes such as contraction and relaxation in response to various kinds of stimuli and stresses. If a blood vessel becomes stiff at the peripheral part due to organic changes, active vascular reaction to external stimuli is deadened, which activates autonomic nerves and in turn reduces blood circulation. Accordingly, if the dynamic characteristics of arteries can be measured quantitatively without unnatural stimulation, it will be possible to estimate the internal condition of the body not only during surgical procedures but also in activities of daily healthcare such as physical training and arteriosclerosis treatment.

Therefore, modeling is useful for cardiovascular dynamics interpretation, and values obtained from cardiovascular signals demonstrate a precise correlation with physiological parameters. As the properties of blood vessels are linked to endothelial and smooth muscle cell function, some researchers have tried to describe the detailed characteristics of vascular smooth muscles, whose vascular elasticity can be used as an index of the arterial wall [3 – 5]. However, it is quite difficult to use such an invasive approach on healthy individuals because of the ethical problems involved. Some researchers have attempted to describe vascular dynamic characteristics using non-invasive approaches such as arterial wall compliance [6], but these dealt only with stiffness and provided insufficient analysis of vascular characteristics. Accordingly, Sakane et al. modeled the dynamic characteristics of the human arterial wall by employing mechanical impedance factors, and investigated a method to estimate changes in the beat-to-beat conditions of blood vessels and ascertain vascular condition from impedance changes in response to a physician's surgical actions [7], [8]. However, the proposed linear model has some limitations in terms of estimated stiffness parameters depending on intravascular blood pressure, as it has been confirmed experimentally that the relationship between vascular internal pressure and vascular diameter exhibits nonlinearity [9], [10]. For example, Hayashi et al. confirmed the nonlinearity of the pressure-radius curve through an *in vitro* experiment, and the proposed stiffness parameter β as an intravascular pressure-independent elastic modulus was identified [10]. However, this index is suitable only for evaluating elasticity, uses only the maximal/minimal values of blood pressure and arterial diameter, making it difficult to estimate the details of arterial dynamics such as viscoelastic properties [11].

In this paper, we propose a novel log-linearized arterial viscoelastic model that considers the nonlinearity between arterial diameter and intravascular pressure [9], making it possible to evaluate advanced arterial dynamics including stiffness and viscosity in beat-to-beat. In this model, intravascular pressure-independent arterial viscoelastic indices are estimated from the arterial displacement waveform and the logarithmic blood pressure waveform, enabling more precise identification of vascular changes with autonomic nerve activity than with the conventional method. The paper explains the proposed method and discusses the results of experiments to validate the vascular viscoelastic index.

II. LOG-LINEARIZED ARTERIAL VISCOELASTIC MODEL

In this method, the dynamic characteristics of arterial walls are expressed in a viscoelastic model (the Voigt model), and internal pressure dependency is reduced using natural logarithm linearization. Furthermore, to quantify beat-to-beat changes in viscoelastic properties, time series of natural logarithmic blood pressure and radial strain are used for evaluation.

Considering the relationship [10] of the exponential function in which the intravascular pressure $P_b(t)$ and strain $\varepsilon(t)$ related to vascular diameter change in continuous time, arterial dynamic viscoelasticity can be expressed by the following equation:

$$P_b(t) = C\exp\{\beta\varepsilon(t) + \eta\dot{\varepsilon}(t)\} \qquad (1)$$

where β and η represent stiffness, viscosity of vessel walls, respectively, C is a constant of proportion, and $\dot{\varepsilon}(t)$ is strain velocity. A natural logarithm for both sides of equation (1) gives the following equation:

$$\ln P_b(t) = \beta\varepsilon(t) + \eta\dot{\varepsilon}(t) + \ln C \qquad (2)$$

Also, when time t_0 as the starting time of each heartbeat is introduced, the equation becomes:

$$\ln P_b(t_0) = \beta\varepsilon(t_0) + \eta\dot{\varepsilon}(t_0) + \ln C \qquad (3)$$

Accordingly, the dynamic characteristics of vessel walls can be expressed as shown below based on Equation (3):

$$\ln P_b(t) - \ln P_b(t_0) = \ln\frac{P_b(t)}{P_b(t_0)} = \beta d\varepsilon(t) + \eta d\dot{\varepsilon}(t) \qquad (4)$$

where $d\varepsilon(t) = \varepsilon(t) - \varepsilon(t_0)$ and $d\dot{\varepsilon}(t) = \dot{\varepsilon}(t) - \dot{\varepsilon}(t_0)$.

However, vascular strain is quite difficult to measure directly. For this reason, a plethysmogram is utilized instead of strain as follows [12]:

$$\varepsilon(t) \cong P_l(t) / A_0 \qquad (5)$$

where $P_l(t)$ is the measured plethysmogram and A_0 is the mean value of absorbance $A(t)$ in one period [12]. Equation (4) can therefore be described using a plethysmogram:

$$\ln\frac{P_b(t)}{P_b(t_0)} = \tilde{\beta} dP_l(t) + \tilde{\eta} d\dot{P}_l(t) \qquad (6)$$

where $dP_l(t) = P_l(t) - P_l(t_0)$, $d\dot{P}_l(t) = \dot{P}_l(t) - \dot{P}_l(t_0)$ and $\dot{P}_l(t)$ is plethysmogram velocity.

$$\tilde{\beta} = \beta / A_0\,,\ \tilde{\eta} = \eta / A_0 \qquad (7)$$

$\tilde{\beta}$ and $\tilde{\eta}$ here correspond to the log-linearized viscoelastic properties of the arterial wall.

The log-linearized viscoelastic parameters $\tilde{\beta}$ (stiffness) and $\tilde{\eta}$ (viscosity) can be estimated on a beat-to-beat basis using the least square method from the measured $P_b(t)$ and $P_l(t)$. The following section describes a validation experiment for this log-linearized arterial viscoelastic model.

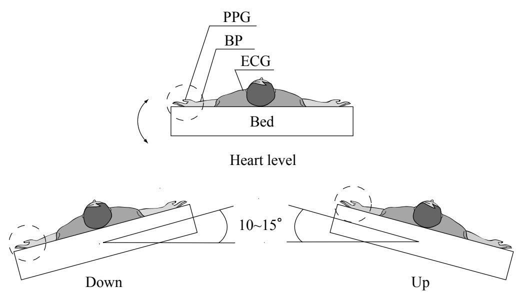

Fig.1 Experimental setup

III. ARTERIAL VISCOELASTIC INDEX ESTIMATION EXPERIMENT

In this study, the proposed method was used to investigate vascular smooth muscle responses [13] induced by changes in intravascular pressure with respect to arm position testing. Intravascular pressure variations were simulated according to an evocation method [14] of transmural pressure/vascular smooth muscle response using the up-and-down motion of the fingertip artery on the basis of the heart position.

The patients lay on an operating table under general anesthesia in a face-up position; the bed was inclined downward and upward on the left side by 10 – 15 degrees, and was tilted twice alternately. At that time, we estimated the arterial viscoelastic index from the arterial blood pressure and a photoplethysmogram, and the intravascular pressure dependence was investigated (Fig. 1). As subjects, we used preoperative patients under general anesthesia in order to prevent the vasomotor center in the hindbrain from functionalizing the neurogenic vascular regulation mechanism. It is considered that the internal-pressure degree of dependence can be reduced if the variation of stiffness values and the difference in resting values become small. Before starting the study, the approval of our institutional Ethical Review Board was obtained, and written informed consent was secured from each patient (Hiroshima University Hospital).

In the experiment, a biomedical signal electrocardiogram (ECG), arterial blood pressure (BP) and a photoplethysmogram (PPG) were simultaneously measured at 125 Hz from a bedside monitor (BSS-9800, Nihon Kohden Corp., Tokyo, Japan) and transferred to a computer using Transmission Control Protocol (TCP). BP was measured through a 22-gauge catheter placed in the left radial artery, and PPG was measured from the ipsilateral thumb. As measured biomedical signals are usually affected by a number of factors such as body movement, digital filters were used to regulate the frequency characteristics. As for the filter properties used in this study, a second-order infinite impulse response (IIR) band-pass filter (14 – 28 Hz) was used for the electrocardiogram, a second-order IIR low-pass filter with a cutoff frequency of 6 Hz and a first-order IIR high-pass filter with a cutoff frequency of 0.3 Hz for the arterial pressure, and an eighth-order finite impulse response (FIR) low-pass filter with a cutoff frequency of 15 Hz and a first-order IIR high-pass filter with a cutoff frequency of 0.3 Hz for the photoplethysmogram. All $P_b(t)$ and $P_l(t)$ values in

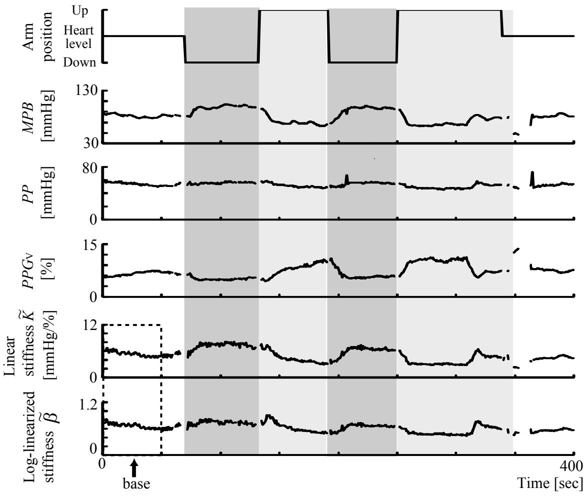

Fig.2 Estimated impedance parameters (Patient A)

the interval between the R wave and the subsequent R wave were used as a data set, and the viscoelastic parameters were estimated by the least square fitting using the data set from Equation (6). Also, in the case of estimation, the coefficient of determination R^2 was established as a contribution ratio for a threshold value. Higher the contribution ratio shows higher the estimation accuracy in the proposed model. In this study, the proposed log-linearized model and the stiffness parameter were compared with the estimation accuracy during the arm positioning. Then, the up/down variations for the proposed log-linearized model and the conventional linear model were compared. Statistical analysis was performed using two-tailed t-test add-in software for Excel 2003, and the level of significance was set at $P < 0.05$.

IV. Results

Figure 2 shows an example of the estimated parameters in the arm position test. The estimated viscoelastic indices are compared with those of the conventional linear model [7]. In order from the top, the figure shows the arm position with the tilting bed (up, heart level, down), the mean blood pressure (*MBP*), the pulse pressure (*PP*), the photoplethysmogram variations (PPG_V), the estimated stiffness parameter $\widetilde{K}$ from the linear model, and the estimated stiffness parameter $\widetilde{\beta}$ from the proposed log-linearized arterial viscoelastic model. The shaded areas correspond to the time when the arm was lowered, and the estimated impedance parameters are shown only for periods when the coefficient of determination R^2 was greater than 0.97. This is to remove the effect whereby estimation accuracy decreases under the influence of the noise that occurs when the bed is moved. The results indicate that the variations of *MBP* and PPG_V show remarkable changes when the arm is tilted. However, it can be seen that the *PP* demonstrates no remarkable changes. Additionally, the stiffness parameter $\widetilde{K}$ shows large changes of increase and decrease when the arm is lowered and raised, and these changes denote the same tendency as *MBP*. On the other hand, it is understood that the variations of $\widetilde{\beta}$ are smaller than those of $\widetilde{K}$.

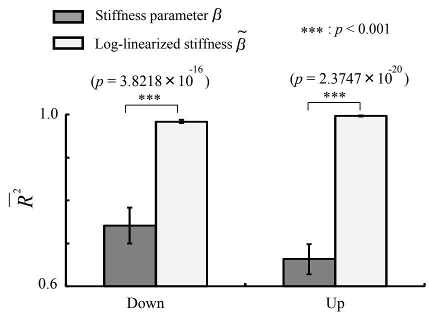

Fig. 3 Coefficients of determination (Patient A)

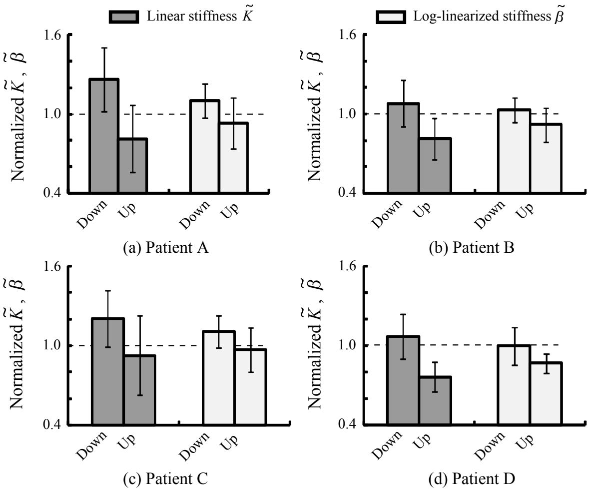

Fig. 4 Normalized stiffness parameters in up/down arm positions

In order to investigate estimation accuracy, the proposed model (with log-linearized arterial viscoelastic parameters) and stiffness parameter β [10] were compared with the coefficient of determination. For the arm position test data measured in Patient A, the mean value and standard deviation of the coefficient of determination R^2 for 20 periods of continued data (down and up) were calculated from each model. The results are shown in Fig. 3, which indicates that the estimation accuracy of our proposed model is significantly better, and that the standard deviation becomes smaller. Furthermore, a significant difference ($P < 0.001$) was found between two models.

Next, the values of $\widetilde{K}$ and $\widetilde{\beta}$ were normalized with the corresponding mean values for 50 seconds at rest, and the mean values and standard deviations with the up/down arm positions were calculated. The comparison results of all trials (Patient A – Patient D) are shown in Fig. 4, showing that the up/down differences in stiffness values estimated from the log-linearized model are smaller than those of the linearized model. Additionally, by comparing the model parameter variations in the up/down positioning, the up-down ratios were calculated. The calculated mean values and standard deviations in all trials are shown in Fig. 5. From these results, it can be confirmed that the up/down ratios for the log-linearized model is lower than that of the linear model, and that there is a significant difference ($P < 0.05$) between two models.

V. Discussion

In this study, to investigate the estimation accuracy, the proposed model (with log-linearized viscoelastic parameters) and the stiffness parameter β with the coefficient of determination were compared: the results indicated that the estimation accuracy of the proposed model is improved significantly as compared to that of the conventional model (not including viscosity), and that the standard deviation of the coefficients of determination for the proposed model is much smaller than that for the conventional model. It can be concluded that the proposed model including the viscosity parameter is useful for estimating the dynamic characteristics of arterial walls more precisely, as a significant difference ($P < 0.001$) was observed between both models.

Moreover, the proposed method was used to investigate vascular smooth muscle responses induced by changes in intravascular pressure with respect to arm position testing. The results confirmed that the value of $\tilde{K}$ fluctuates when the arm position changes, and that the variation of $\tilde{\beta}$ is small compared to that of $\tilde{K}$. Furthermore, the values of $\tilde{K}$ and $\tilde{\beta}$ were normalized with the corresponding mean values for 50 seconds at rest, and the mean values and standard deviations with the up/down arm positions were calculated. It can be considered that the variations of $\tilde{\beta}$ are smaller than those of $\tilde{K}$ in comparison with the up/down differences. Additionally, comparing the ratios of the up/down positioning, the ratio of the log-linearized model was lower than that of the linear model, and the significant difference ($P < 0.05$) was observed for mean values from all trials. As our study was conducted on patients under general anesthesia, it is considered that neurogenic vascular regulation mechanism factors (autochthonous impulses) such as tension were not responsive. Accordingly, it was found that the proposed method could reduce the influence of intravascular pressure fluctuation with the arm position test.

VI. Conclusion

In this paper, we proposed a novel model for the evaluation of vascular changes in the viscoelastic properties of arteries in consideration of intravascular pressure, known as the log-linearized arterial viscoelastic model. It was confirmed that the estimation accuracy of the proposed method was not strongly affected by intravascular pressure fluctuations during the arm position testing. The proposed method could be used to accurately evaluate the contractile function of vessel walls according to the vascular regulation mechanism.

In future studies, we plan to further consider the relationship between intravascular pressure and the neural vascular regulation mechanism. Research will be conducted to assess the additional validity of the proposed method by evaluating further experimental evidence.

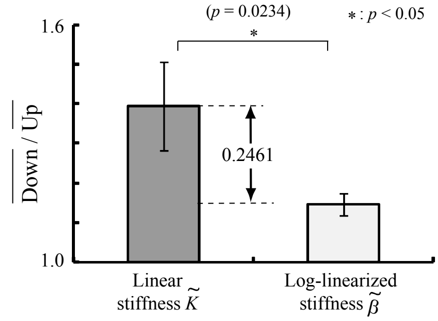

Fig. 5 Comparison between ratios of stiffness parameters in the up/down arm positions

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