Chapter 40
A Log–Linearized Viscoelastic Model for Measuring Changes in Vascular Impedance

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ABSTRACT

This chapter proposes a new nonlinear model, called a log-linearized viscoelastic model, to estimate the dynamic characteristics of human arterial walls. The model employs 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 determined by demonstrating 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 contribution ratios 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, in the same pattern as mean blood pressure. However, the changes seen in the proposed nonlinear viscoelastic parameter are smaller (P < 0.05) than those of the linear model. This result suggests that the proposed nonlinear arterial viscoelastic model is less affected by changes in mean intravascular pressure during arm position changes.

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INTRODUCTION

Blood vessels perform an essential function in human life by supporting the transport of oxygen and nutrients throughout the whole body. They also play a critical role in state changes such as vasoconstriction/vasodilatation blood volume adjustments (Nichols, & O’Rourke, 1998). Vascular state changes can usually be divided into two general categories: organic and functional change. In organic change (arteriosclerosis), the quality of collagen in the arterial wall changes with aging, and the reduced amounts of elastic fiber cause stiffness and poor wall condition (Faber, & Moller-Hou, 1952). Arterial walls demonstrate functional changes such as contraction and relaxation in response to various stimuli and stresses. If the peripheral aspect of a blood vessel becomes stiff due to organic changes, active vascular reactions to external stimuli are deadened, which activates autonomic nerves and in turn reduces circulation. Accordingly, if the dynamic characteristics of arteries could be measured quantitatively without unnatural stimulation, it would be possible to estimate the internal physiological conditions not only during surgical procedures but also during activities common to everyday healthcare, such as physical training and treatment for arteriosclerosis.

Therefore, modeling is useful for interpreting cardiovascular dynamics, 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 construct detailed descriptions of the characteristics of vascular smooth muscles, whose elasticity can be used as an index of the arterial wall (Greenfield, & Patel, D.J. 1962; Armentano, Simon, Levenson, Chau, Megnien, & Pichel, 1991; Bank, Wilson, Kubo, Holte, Dresing, & Wang, 1995). However, it is quite difficult to use such an invasive approach in 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 (Katayama, Shimoda, Maeda, & Takemiya, 1998), but these only addressed 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. This method aimed to estimate changes in the beat-to-beat conditions of blood vessels and ascertain vascular conditions from impedance changes in response to a physician’s surgical actions (Sakane, Tsuji, Tanaka, Saeki, & Kawamoto, 2004; Sakane, Tsuji, Saeki, & Kawamoto, 2004). However, the proposed linear model has the limitation of estimated stiffness parameters being dependent upon intravascular blood pressure; it has been experimentally confirmed that the relationship between vascular internal pressure and vascular diameter exhibits nonlinearity (Busse, Bauer, Schabert, Summa, Bumm, & Wetterer, 1979; Hayashi, Handa, Nagasawa, Okumura, & Moritake, 1980). For example, Hayashi et al. confirmed the nonlinearity of the pressure-radius curve through an in vitro experiment, and the proposed stiffness parameter was identified as an intravascular pressure-independent elastic modulus (Hayashi, Handa, Nagasawa, Okumura, & Moritake, 1980). However, this index is suitable only for evaluating elasticity and 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 (Wurzel, Cowper, & McCook, 1969).

In this chapter, we propose a novel log-linearized arterial viscoelastic model that considers the nonlinear relationship between arterial diameter and intravascular pressure (Busse, Bauer, Schabert, Summa, Bumm, & Wetterer, 1979), permitting beat-to-beat evaluation of advanced arterial dynamics such as stiffness and viscosity. In this model, intravascular pressure-independent arterial viscoelastic indices are estimated using the arterial displacement waveform and the logarithmic
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