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

Abdugheni Kutluk
Graduate School of Engineering, Hiroshima University, Japan

Noboru Saeki
Graduate School of Biomedical Sciences, Hiroshima University, Japan

Ryuji Nakamura
Graduate School of Biomedical Sciences, Hiroshima University, Japan

Masao Yoshizumi
Graduate School of Biomedical Sciences, Hiroshima University, Japan

Toshio Tsuji
Graduate School of Engineering, Hiroshima University, Japan

Masashi Kawamoto
Graduate School of Biomedical Sciences, Hiroshima University, Japan

Teiji Ukawa
Nihon Kohden Corporation, Japan

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.

DOI: 10.4018/978-1-60960-559-9.ch040

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

blood pressure waveform, enabling more precise identification of the vascular changes seen with autonomic nervous system activity than was possible with the conventional method. The chapter explains the proposed method and discusses the results of experiments to validate the vascular viscoelastic index.

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. To quantify beat-to-beat changes in viscoelastic properties, time series of natural logarithmic blood pressure and radial strain are used for evaluation.

Figure 1 illustrates the proposed impedance model of the arterial wall. This model only represents the characteristics of the arterial wall in the arbitrary radius direction. Considering the relationship (Hayashi et al., 1980) of the exponential function by which the intravascular pressure $P_b(t)$ and strain $\varepsilon(t)$ relate to vascular diameter change in continuous time, arterial dynamic viscoelasticity can be expressed by the following equation:

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

where β and η represent the stiffness and 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:

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

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

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

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

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

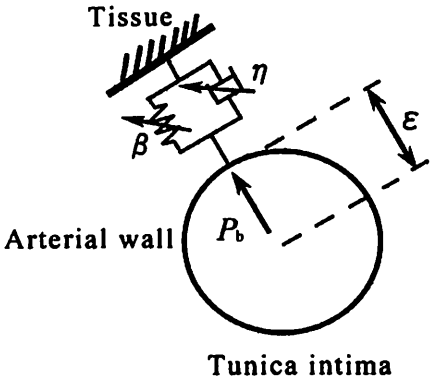
where $d\varepsilon(t) = \varepsilon(t) - \varepsilon(t_0)$ and $d\dot{\varepsilon}(t) = \dot{\varepsilon}(t) - \dot{\varepsilon}(t_0)$.

However, direct measurement of vascular strain is quite difficult. For this reason, plethysmogram is utilized instead of strain measurement, as follows (Sakane, Shiba, Tsuji, Saeki, & Kawamoto, 2005):

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

where $P_l(t)$ is the measured plethysmogram and A_0 is the mean value of absorbance $A(t)$ in one period

Figure 1. The arterial wall impedance model



(Sakane et al., 2005). Equation (4) can therefore be described using a plethysmogram:

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

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.

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

$\tilde{\beta}$ 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.

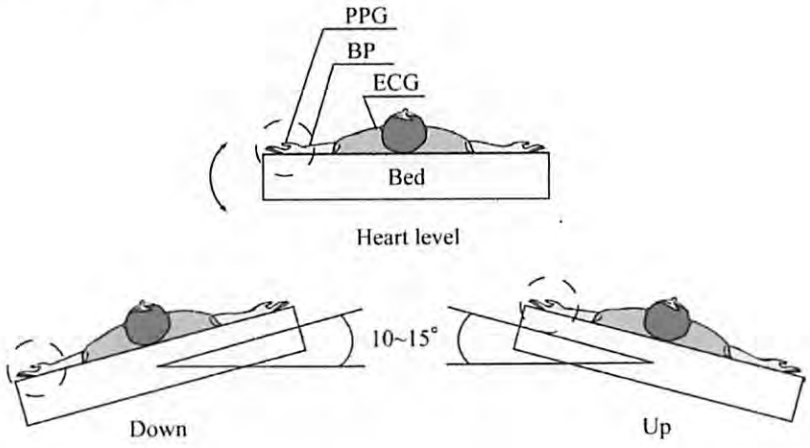
METHOD

In this study, the proposed method was used to investigate vascular smooth muscle responses (Bayliss, 1902) induced by changes in intravascular pressure with respect to arm position testing on four patients. Intravascular pressure variations were simulated according to a transmural pressure/vascular smooth muscle response evocation method (Takemiya, Maeda, Suzuki, Nishihira, & Shimoda, 1996) using up-and-down motion of the fingertip artery on the basis of 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 using arterial blood pressure and photoplethysmogram, and the intravascular pressure dependence was investigated (Figure 2). We used preoperative patients under general anesthesia as study subjects in order to prevent the vasomotor center in the hindbrain from functionalizing the neurogenic vascular regulation mechanism. The degree of dependence on internal-pressure is considered to be reduced if the variation in stiffness values and difference in resting values are decreased. Before starting the study, we obtained approval from our institutional Ethical Review Board and received written informed consent from each patient (Hiroshima University Hospital).

In the experiment, a bedside monitor (BSS-9800, Nihon Kohden Corp., Tokyo, Japan) was used to simultaneously obtain a biomedical signal electrocardiogram (ECG), arterial blood pressure (BP) and a photoplethysmogram (PPG) at 125 Hz. These data were 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. The filter properties used in this study included a second-order infinite impulse response (IIR) band-pass filter (14 – 28 Hz) 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 the interval between an R wave and the next R wave were considered a data set, and the viscoelastic parameters were estimated by 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. A higher contribution ratio indicates higher estimation ac-

Figure 2. Experimental setup



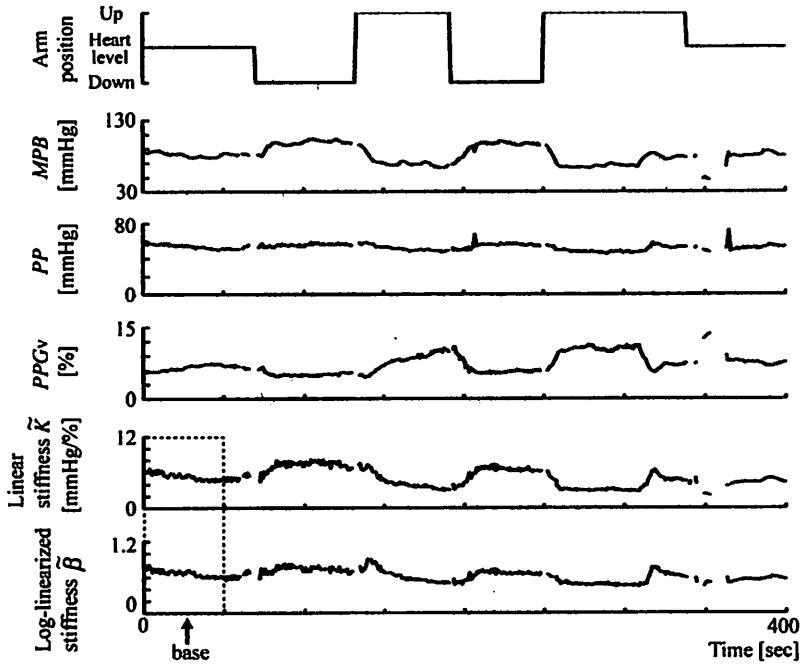
curacy in the proposed model. In this study, the proposed log-linearized model and the stiffness parameter were compared with the estimation accuracy during the arm positioning. The up/down variations for the proposed log-linearized model and the conventional linear model were then compared. Statistical analysis was performed using two-tailed t-test add-in software for Excel 2003, and the significance level was set at $P < 0.05$.

RESULTS

Figure 3 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 (Sakane, Tsuji, Tanaka, Saeki, & Kawamoto, 2004). 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 $\tilde{K}$ from the linear model, and the estimated stiffness parameter $\tilde{\beta}$ 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 R^2 was greater than 0.97. This is to remove the decrease in estimation accuracy due to the noise that occurs when the bed is moved. The results indicate that the variations in *MBP* and PPG_V showed remarkable changes when the arm was tilted. However, *PP* demonstrated no remarkable changes. Additionally, there were large changes (increases and decreases) in the stiffness parameter $\tilde{K}$ when the arm was raised and lowered; these changes showed the same tendency as *MBP*. On the other hand, the variations in $\tilde{\beta}$ were smaller than those in $\tilde{K}$.

In order to investigate estimation accuracy, the proposed model (with log-linearized arterial viscoelastic parameters) and stiffness parameter β (Hayashi et al., 1980) were compared with the coefficient of determination. For the arm position test data measured in Patient A, the mean value and standard deviation of R^2 for 20 periods of continuous data (down and up) were calculated from each model. The results are shown in Figure 4, which indicates that the estimation accuracy of our proposed model is significantly better and

Figure 3. Estimated impedance parameters (Patient A)



that the standard deviation is smaller. A significant difference ($P < 0.001$) was found between the two models.

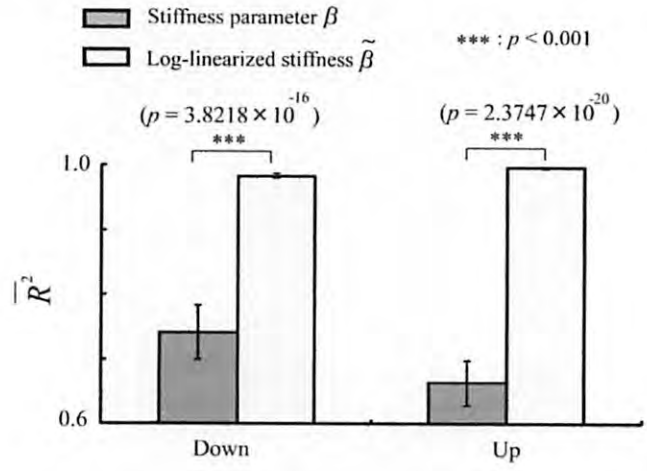
Next, the values of $\tilde{K}$ and $\tilde{\beta}$ were normalized with the corresponding mean values for 50 seconds at rest, and the mean values and standard deviations with the up/down arm positions were calculated. A comparison of the results of all trials (Patient A – Patient D) are shown in Figure 5 and indicate 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 Figure 6. From these results, we can confirm that the up/down ratio for the log-linearized model is lower than that of the linear model, and that there is a significant difference ($P < 0.05$) between the two models.

DISCUSSION

In this study, we investigated the estimation accuracy of the proposed model (with log-linearized viscoelastic parameters) relative to stiffness parameter β with the coefficient of determination. The results indicate that the estimation accuracy of the proposed model represents a significant improvement on 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 of the conventional model. We conclude that the proposed model, which includes the viscosity parameter, is useful for precisely estimating the dynamic characteristics of arterial walls, as a significant difference ($P < 0.001$) between the models was observed.

Moreover, the proposed method was used to investigate vascular smooth muscle responses induced by changes in intravascular pressure with

Figure 4. Coefficients of determination (Patient A)



respect to arm position testing. The results confirmed that the value of $\tilde{K}$ fluctuates when the arm position changes and that the variation in $\tilde{\beta}$ is small compared to that of $\tilde{K}$. 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 appears that the variations in $\tilde{\beta}$ 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 a 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 likely that neurogenic vascular regulation

Figure 5. Normalized stiffness parameters in up/down arm positions

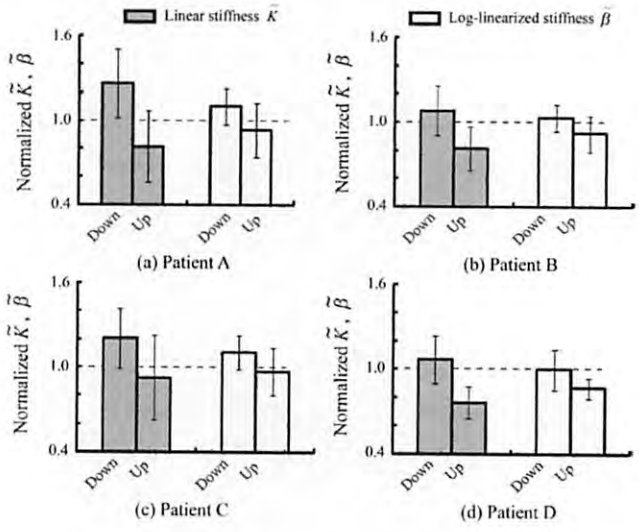
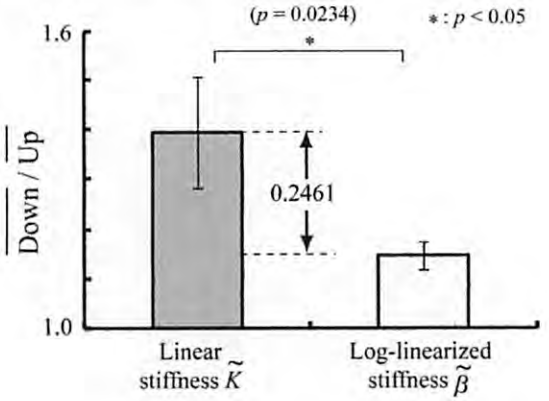


Figure 6. Comparison between ratios of stiffness parameters in the up/down arm positions



mechanism factors (autochthonous impulses) such as tension were not responsive. Accordingly, we found that the proposed method could reduce the influence of intravascular pressure fluctuation during the arm position test.

CONCLUSION

In future studies, we plan to further consider the relationship between intravascular pressure and the neural vascular regulation mechanism. Additional experiments will be conducted to assess the validity of the proposed method.

ACKNOWLEDGMENT

This work was supported by the Regional Innovation Creating System Enterprise for Ministry of Economy, Trade and Industry (RIETI) of Japan.

REFERENCES

Armentano, R. L., Simon, A., Levenson, J., Chau, N. P., Megnien, J. L., & Pichel, R. (1991). Mechanical pressure versus intrinsic effects of hypertension on large arteries in humans. *Hypertension, 18*(5), 657–664.

Bank, A. J., Wilson, R. F., & Kubo, S. H. (1995). Direct effects of smooth muscle relaxation and contraction on in vivo human brachial artery elastic properties. *Circulation Research, 77*, 1008–1016.

Bayliss, W. M. (1902). On the local reactions of the arterial wall to changes of internal pressure. *The Journal of Physiology, 28*, 220–231.

Busse, R., Bauer, R. D., Schabert, A., Summa, Y., Bumm, P., & Wetterer, E. (1979). The mechanical properties of exposed human common carotid arteries in vivo. *Basic Research in Cardiology, 74*, 545–554. doi:10.1007/BF01907647

Faber, M., & Moller Hou, G. (1952). The human aorta. Part V: Collagen and elastin in the normal and hypertensive aorta. *Acta Pathologica et Microbiologica Scandinavica, 31*, 377–382. doi:10.1111/j.1699-0463.1952.tb00205.x

Greenfield, J. C., & Patel, D. J. (1962). Relation between pressure and diameter in the ascending aorta of man. *Circulation Research, 10*, 778–781.

Hayashi, K., Handa, H., Nagasawa, S., Okumura, A., & Moritake, K. (1980). Stiffness and elastic behavior of human intracranial and extracranial arteries. *Journal of Biomechanics, 13*, 175–184. doi:10.1016/0021-9290(80)90191-8

Katayama, K., Shimoda, M., Maeda, J., & Takemiya, T. (1998). Endurance exercise training increases peripheral vascular response in human fingers. *Japanese Journal of Physiology, 48*(5), 365–371. doi:10.2170/jjphysiol.48.365

Nichols, W. W., & O'Rourke, M. F. (1998). *McDonald's blood flow in arteries: Theoretical experimental and clinical principles*, 4th ed. London.

Sakane, A., Shiba, K., Tsuji, T., Saeki, N., & Kawamoto, M. (2005). Non-invasive monitoring of arterial wall impedance. *Proceedings of the First International Conference on Complex Medical Engineering*, (pp. 984-989). Takamatsu, May 2005.

Sakane, A., Tsuji, T., Saeki, N., & Kawamoto, M. (2004). Discrimination of vascular conditions using a probabilistic neural network. *Journal of Robotics and Mechatronics, 16*(2), 138–145.

Sakane, A., Tsuji, T., Tanaka, Y., Saeki, N., & Kawamoto, M. (2004). Monitoring of vascular conditions using plethysmogram. *Journal of the Society of Instrument and Control Engineers, 40*(12), 1236–1242.

Takemiya, T., Maeda, J., Suzuki, J., Nishihira, Y., & Shimoda, M. (1996). Differential digital photoplethysmographic observations of finger vascular exponential response to the arm position changes in humans. *Advances in Exercise and Sports Physiology, 2*(2), 83–90.

Wurzel, M., Cowper, G. R., & McCook, J. M. (1969). Smooth muscle contraction and viscoelasticity of arterial wall. *Canadian Journal of Physiology and Pharmacology, 48*, 510–523.

KEY TERMS AND DEFINITIONS

Arterial Wall Impedance (Vascular Impedance): A relationship between pulsatile pressure and pulsatile flow recorded in an artery feeding a particular vascular bed. Also known as the impediment to flow at the input of a vascular bed where pulsatile flow is involved (aorta and arteries).

Arteriosclerosis: (also known as atherosclerosis) a stiffening of the arteries. Arteriosclerosis is a chronic disease characterized by abnormal thickening and hardening of the arterial walls with resulting loss of elasticity.

Collagen: A protein found in blood vessels that is much stiffer than elastin.

Endothelial Cells: A specialized type of epithelial cell which forms the inner lining of blood vessels.

Intravascular Pressure: The amount of pressure exerted on the walls of blood vessels by the blood.

Mechanical Impedance: A measure of how much a structure resists motion when subjected to a given force. It relates forces with velocities acting on a mechanical system.

Photoplethysmography (PPG): A simple and low-cost optical non-invasive technique that can be used to detect blood volume changes in microvascular tissue beds.

Smooth Muscle: Found in many places; within the tunica media layer of large and small arteries, veins, lymphatic vessels, the urinary bladder, uterus, etc.

Viscoelastic: The property of materials that exhibit both viscous and elastic characteristics when undergoing deformation.

Voigt Model: Consists of a Newtonian damper and Hookean elastic spring connected in parallel.

Senior Editorial Director:	Kristin Klinger
Director of Book Publications:	Julia Mosemann
Editorial Director:	Lindsay Johnston
Acquisitions Editor:	Erika Carter
Development Editor:	Myla Harty
Production Coordinator:	Jamie Snavely
Typesetters:	Mike Brehm, Jennifer Romanchak and Deanna Jo Zombro
Cover Design:	Nick Newcomer

Published in the United States of America by
Medical Information Science Reference (an imprint of IGI Global)
701 E. Chocolate Avenue
Hershey PA 17033
Tel: 717-533-8845
Fax: 717-533-8661
E-mail: cust@igi-global.com
Web site: http://www.igi-global.com/reference

Library of Congress Cataloging-in-Publication Data

Early detection and rehabilitation technologies for dementia: neuroscience and biomedical applications / Jinglong Wu, editor.
p. ; cm.
Includes bibliographical references and index.
Summary: "This book provides a comprehensive collection for experts in the Neuroscience and Biomedical technology fields, outlining various concepts from cognitive neuroscience and dementia to neural technology and rehabilitation"-- Provided by publisher.
ISBN 978-1-60960-559-9 (hardcover) -- ISBN 978-1-60960-560-5 (ebook) 1. Dementia--Diagnosis. 2. Neurologic examination. I. Wu, Jinglong, 1958-
[DNLM: 1. Dementia. 2. Brain--physiopathology. 3. Diagnostic Techniques, Neurological. 4. Early Diagnosis. WM 220]
RC521.E27 2011
616.8'3--dc22

2010054442

British Cataloguing in Publication Data
A Cataloguing in Publication record for this book is available from the British Library.

Early Detection and Rehabilitation Technologies for Dementia:

Neuroscience and Biomedical Applications

Jinglong Wu
Okayama University, Japan

Medical Information Science
REFERENCE