EXPERIMENTAL AND NUMERICAL STUDIES OF DIGITAL ARTERIAL ELASTICITY BY VOLUME OSCILLOMETRIC ANALYSIS

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ABSTRACT

Arterial elasticity is one of the indicators for the existence of cardiovascular diseases. The present study introduces the elasticity evaluation of digital artery by using a volume oscillometric technique. We conducted the experiment by analyzing an alternating signal of photoelectric plethysmograph during the continuous change of transmural pressure and resulting in the form of new pressure-volume relationship. In addition, the theoretical model based on the continuum mechanics and hyperelasticity of arterial wall was also simulated under the passive tension to predict arterial elasticity and clarify the experimental analysis. As the results of the experimental approach, the new pressure-volume relationship provided the sensible response of arterial wall to the transmural pressure. The change of this relationship associated with the age of subjects. While, the theoretical results demonstrated the ability of current model for the prediction of arterial elasticity using the volume oscillometric technique under the influence of pulse pressure.

Keywords: arterial elasticity, volume oscillometry, photoelectric plethysmograph

1. INTRODUCTION

The stiffening of arterial wall is caused by several factors such as the endothelial cell dysfunction, atheroma, elastin fragmentation, calcium deposition, etc (Lee and Oh 2010). This condition relates to the existence and development of cardiovascular diseases (CVD) (Vlachopoulos, Aznaouridis and Stefanadis 2010). One of the arterial properties which is regarded to be a CVD marker is arterial elasticity. Arterial elasticity mainly associates with the mechanical properties of elastin and collagen fibers in arterial wall. It is basically investigated by monitoring the arterial motion in circumferential direction. The instantaneous change of vessel circumference correlates with arterial pressure pulse in the form of pressure-diameter relationship or pressure-volume relationship. Using isolated arteries in vitro test can obtain those relationships by varying intravascular pressure (Carew, Vaishnav and Petal 1968). Moreover, several noninvasive methods have been proposed to evaluate arterial elasticity. For example, pulse pressure from sphygmomanometer (Franklin et al. 1997), pulse wave velocity from Doppler flow signals (Sutton-Tyrrell et al. 2005), indices derived from magnetic resonance imaging, MRI, and ultrasound imaging techniques and an augmentation index from applanation tonometry (Fantin et al. 2007). Another technique whose system is low-cost and easy to use is photoelectric plethysmography(PPG).

The system of PPG contains two essential components, an infrared light source and a photo sensor. The infrared light is absorbed by skin, bond, tissue and blood while the remaining light is detected at the photo sensor before transforming it into two signal components by the signal processing . The first signal is a steady signal, DC signal, which represents the absorption capability of skin, bone, tissue, venous blood and non-pulsatile arterial blood. Another is the alternating signal, AC signal, which represents the absorption due to pulsatile arterial blood. It also associates with the oscillation of vascular volume of arteries. The technique of using PPG for vascular elasticity analysis is conducted under the assumptions that surrounding tissues around vascular system are incompressible. The cuff pressure of the occluding cuff collapses the venous system. The continuous change of cuff pressure controls the vascular volume of arteries. Many researchers have utilized the DC signal of PPG coupled with the Lambert-Beer's Law to analyze arterial elasticity in the form of transmural pressure-relative volume change relationship (Ando et al. 1991, Kawarada et al. 1986). However, a conflict between the assumptions of their method and the actual DC signal has occurred. When cuff pressure is higher than systolic blood pressure, arterial blood flow disappears, then DC signal should be constant. However, the actual DC signal is not constant as in the assumptions. This phenomenon implies the influences of arterial surrounding tissues on the intensity of DC signal. In this study, therefore, we propose an alternative methodology to evaluate arterial elasticity using the AC signal instead of DC signal.

Furthermore, mathematical models derived from continuum mechanics and empirical data have been developed to describe the mechanical response of arterial wall (Kalita and Schaefer 2008). In this study, theoretical method based on the continuum mechanics of arterial wall is also employed to model and predict arterial elasticity in various conditions, especially the different level of pulse pressure. The theoretical results are expected to validate and clarify the assessment of arterial elasticity using the AC signal of PPG.

2. MATERIAL AND METHOD

2.1. Experimental Approach

A newly developed PPG system in which contains the infrared light source and the photo sensor was used to obtain AC, DC and cuff pressure, P_c, signals from the target site. These signals were transformed to be digital outputs with a 24-bit A/D converter of PowerLab4/26 (ML846, ADInstruments, Bella Vista, NSW, Australia). Figure 1 shows a typical example of PPG signals obtained from human finger. At the first appearance of AC signal, P_c is equal to systolic blood pressure, P_{sys}. Meanwhile, the point where the amplitude of AC signal is maximum indicates the equality between P_c and mean blood pressure, P_m. Transmural pressure, P_{tr}, which means the subtraction of P_c from P_m is zero at this stage. Thus, we can obtain P_m and P_{sys} from the connection between the AC signal and P_c of PPG.

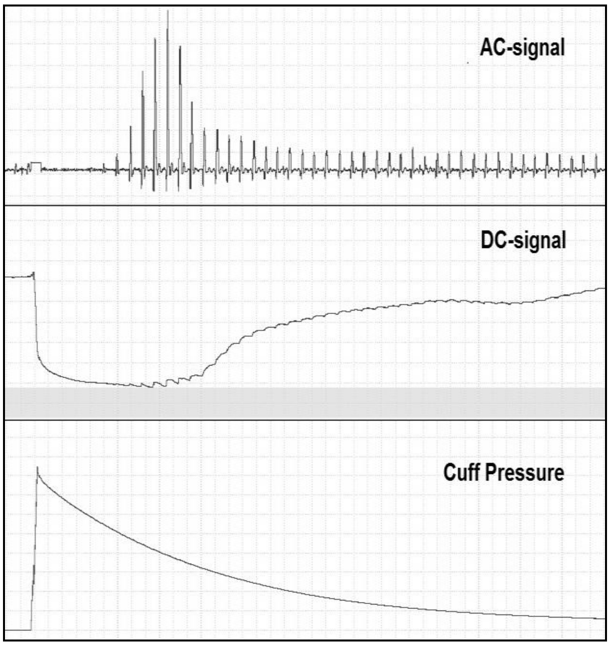

Figure1: The Signals Of Photoelectric Plethysmograph (AC, DC And P_c Signals)

Moreover, when P_c is equal or lower than P_m, the amplitude of AC signal reflects the volume difference between systole and diastole, ΔV. We therefore proposed the relative volume difference as a new index of vascular elasticity. The relative volume difference was defined as the volume difference at any P_{tr} normalized with that as zero P_{tr}, $\Delta V/\Delta V_0$. Then, we obtained the new pressure-volume relationship from the AC component of PPG signals in the form of P_{tr} – $\Delta V/\Delta V_0$ relationship.

We recorded the PPG signals from the right index finger of 40 subjects who were separated into six groups of subjects, eight females and eight males; 20-25 years old, five females and five males; 32-45 years old, six females and eight males; over 50 years old, at a temperature about 24±1 ^oC. After that, the output AC and P_c signals were used to calculate P_{sys}, P_m, P_{tr}, diastolic blood pressure, P_{dia}, pulse pressure, ΔP, and $\Delta V/\Delta V_0$ in order to obtain the relationship between P_{tr} and $\Delta V/\Delta V_0$.

Two way analysis of variance, Two-way ANOVA, was utilized to estimate the differences of P_m and ΔP among six groups of subjects. The P_m and ΔP were exhibited as mean values with standard deviation, SD. While, the relationships between P_{tr} and $\Delta V/\Delta V_0$ of each group were shown as the mean curves.

2.2. Theoretical Approach

The theoretical approach of this study focused on the mechanical response of arterial wall due to pulsatile internal pressure. We combined the three layers of radial index arterial wall into one layer to simplify anatomical structure of arterial tube. The outer diameter of the tube was 1.54 mm (Bilge et al. 2006). The ratio of total wall thickness to outer diameter was 0.05. The initial length of the tube was 10 mm. This arterial tube confronted with pulsatile pressures which were given in the form of sinusoidal function to simplify the arterial pulsatile pressure as follows:

$$P(t) = P_m + P_{amp} \sin(2\pi ft) \tag{1}$$

where P(t) is the instantaneous pressure (mmHg), P_m is the mean level of pulsatile pressure (mmHg), P_{amp} is the amplitude of pulsatile pressure (mmHg) which is the half of constant ΔP, 60 mmHg, f is frequency (Hz) which associates with normal heat rate, 75 beats per minute and t is time (s). The pulsatile pressure was applied at the inner wall of the arterial tube. The outside pressure was assumed to be zero.

Arterial wall stress due to pulsatile pressure was calculated from the Laplace's Law. It provides the relationship between internal pressure and circumferential Cauchy stress as follows:

$$\sigma_c = (P_i - P_o)r/\omega \tag{2}$$

where σ_c is circumferential Cauchy stress (KPa) P_i is the internal pressure (KPa), P_o is the outside pressure (KPa), r is the radius of arterial tube (mm) and ω is the wall thickness of arterial tube (mm). The Cauchy stress tensor, σ, related to the second Piola-Kirchhoff stress tensor, S, by the following relationship:

$$\mathbf{S} = J\mathbf{F}^{-1}\boldsymbol{\sigma}\mathbf{F}^{T} \tag{3}$$

where F is the deformation gradient and J is the determinant of deformation gradient. In this study, arterial wall was considered to be hyperelastic material whose the relationship between stress and strain was derived in term of strain energy function, W, as follows:

$$\mathbf{S} = \partial W / \partial \mathbf{E} \tag{4}$$

where E is Green-Lagrange strain tensor. While the strain energy function of arterial wall was described by Fung model (Chuong and Fung 1983, Deng et a. 1994) as follows:

$$W = (C/2)\exp(Q) \tag{5}$$

$$\begin{aligned} Q = {} & b_1 E_{\theta\theta}^{\,2} + b_2 E_{zz}^{\,2} + b_3 E_{rr}^{\,2} + 2b_4 E_{\theta\theta} E_{zz} \\ & + 2b_5 E_{\theta\theta} E_{rr} + 2b_6 E_{zz} E_{rr} + b_7 (E_{r\theta}^{\,2} + E_{\theta r}^{\,2}) \\ & + b_8 (E_{\theta z}^{\,2} + E_{z\theta}^{\,2}) + b_9 (E_{zr}^{\,2} + E_{rz}^{\,2}) \end{aligned} \tag{6}$$

where C and b1 - b9 are material parameters. We firstly simplified the problem by neglecting shear stress and assuming arterial wall to be a very thin wall. Thus,

$$Q = b_1 E_{\theta\theta}^{\,2} + b_2 E_{zz}^{\,2} + 2b_4 E_{\theta\theta} E_{zz} \tag{7}$$

Material parameters, C, b_1, b_2 and b_4, of each group of subjects were obtained from the optimization by comparing with the $P_{tr} - \Delta V/\Delta V_0$ relationships of PPG measurement using the genetic algorithm. The theoretical results were also expressed as the $P_{tr} - \Delta V/\Delta V_0$ relationships.

Furthermore, the arterial model with the optimum material parameters was simulated under the different level of ΔP, 40, 50 and 60 mmHg, and resulted in the form of $P_{tr} - \Delta V/\Delta V_0$ relationships.

3. RESULTS AND DISCUSSION

3.1. Experimental Results

As the results of PPG measurement, the differences of P_m were found among six groups of subjects as in Figure 2. From the statistical analysis, over 50 years old subjects had the highest P_m in the group of women. The P_m of women tended to decrease when the age of subject decreased. These results corresponded to the study of Pearson et al. (1997). The increase in age induced the rises in systolic and diastolic pressure, especially in the range of 20 - 50 years old. However, the same level of P_m was seen in the different age of men. Moreover, the influence of gender on P_m was found in the 20-25 years old and over 50 years old subjects. Meanwhile, six groups of subjects had the similar level of ΔP as in Figure 2.

Figure 3. illustrates the relationships between P_{tr} and $\Delta V/\Delta V_0$ of six groups of subjects. The results showed that $\Delta V/\Delta V_0$ nonlinearly declined when P_{tr} increased. This informed that arteries were stiffer with the advancing P_{tr}. The groups of 20-25 years old and 32-45 years old subjects had the same characteristic of $P_{tr} - \Delta V/\Delta V_0$ curves, while the $P_{tr} - \Delta V/\Delta V_0$ curves of over 50 years old subjects explicitly differed from those curves of 20-25 years old and 32-45 years old subjects. The higher level of $\Delta V/\Delta V_0$ values at any P_{tr} of over 50 years old subjects, compared with those of 20-25 years old and 32-45 years old subjects, implied the lower elasticity of arterial blood vessel in human finger of the older subjects, especially subjects whose age beyond 50 years old. These results agreed with other methods in the study of Jayasree, Sandhya and Radhakrishnan (2008) and Kelly et al. (1989). Therefore, the $P_{tr} - \Delta V/\Delta V_0$ relationship would be one of the arterial elasticity markers as well. In addition, men and women had the same shape of $P_{tr} - \Delta V/\Delta V_0$ curves in all three groups of age. These results reflected that the different P_m between men and women, especially in 20-25 years old and over 50 years old subjects, did not influenced on the $P_{tr} - \Delta V/\Delta V_0$ relationship. Thus, using the $P_{tr} - \Delta V/\Delta V_0$ relationship would eliminate the effect of P_m on the arterial elasticity evaluation by using the AC signal of PPG.

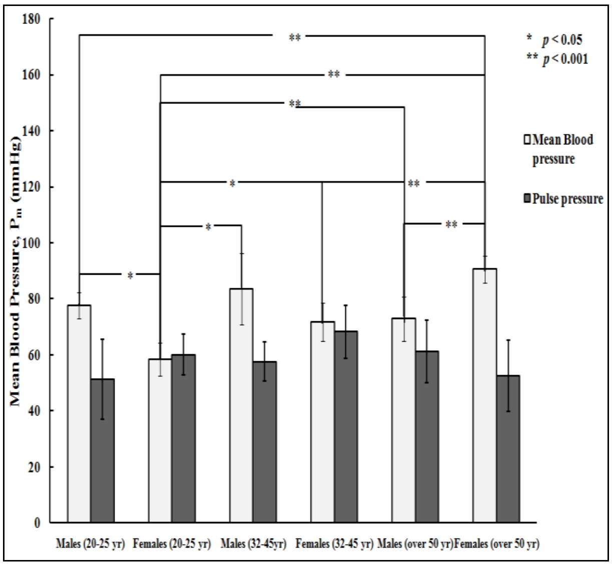

Figure 2: Mean Blood Pressure (White) And Pulse Pressure (Black) Of Six Groups Of Subjects From PPG Measurement

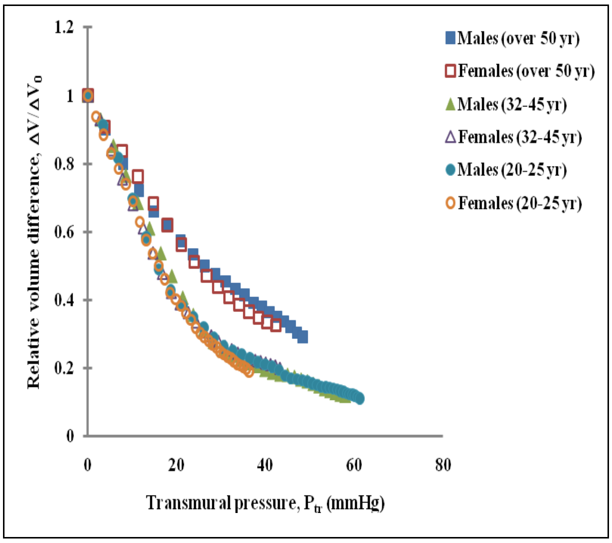

Figure 3: The Relationship Between Transmural Pressure And Relative Volume Difference From PPG

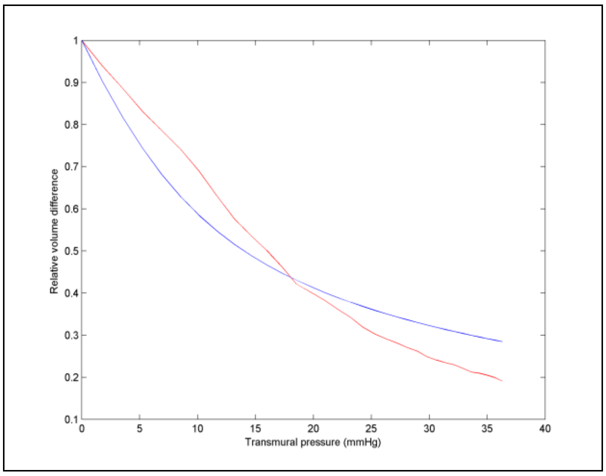

Figure 4: The Comparison Of P_{tr} – $\Delta V/\Delta V_0$ Relationship Between Experimental (Red Line) And Theoretical (Blue Line) Results Of 20-25 Years Old Women.

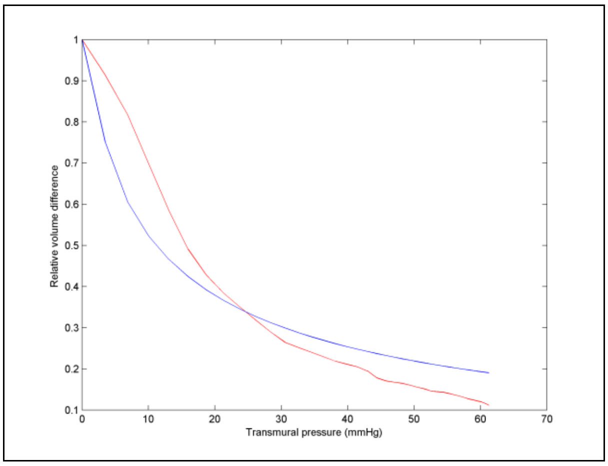

Figure 5: The Comparison Of P_{tr} – $\Delta V/\Delta V_0$ Relationship Between Experimental (Red Line) And Theoretical (Blue Line) Results Of 20-25 Years Old Men.

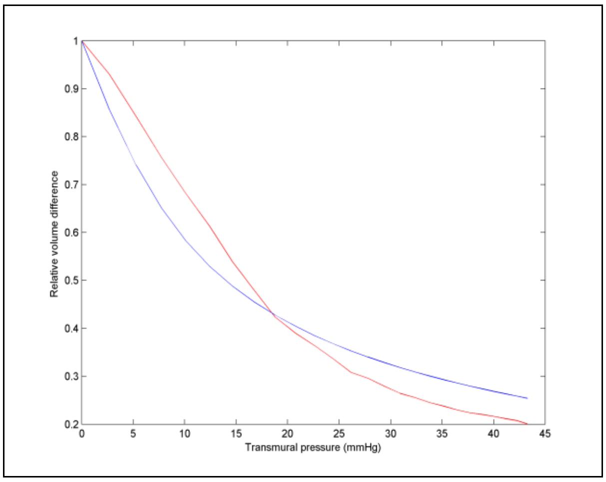

Figure 6: The Comparison Of P_{tr} – $\Delta V/\Delta V_0$ Relationship Between Experimental (Red Line) And Theoretical (Blue Line) Results Of 32-45 Years Old Women.

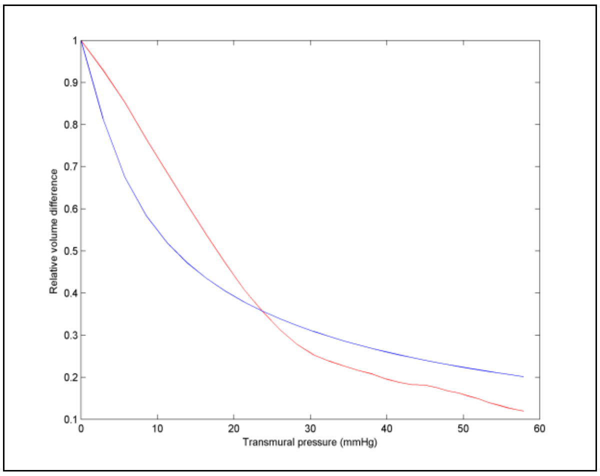

Figure 7: The Comparison Of P_{tr} – $\Delta V/\Delta V_0$ Relationship Between Experimental (Red Line) And Theoretical (Blue Line) Results Of 32-45 Years Old Men.

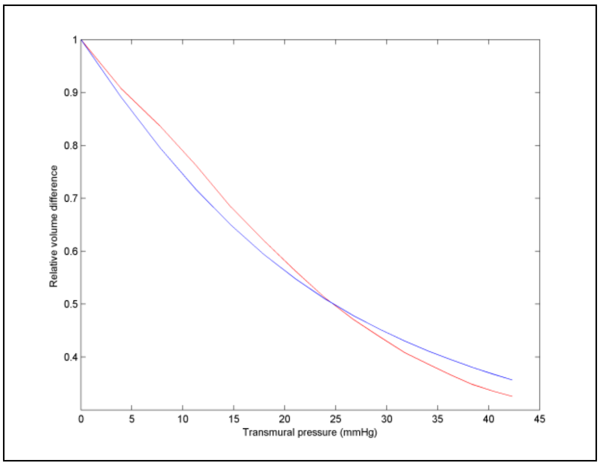

Figure 8: The Comparison Of P_{tr} – $\Delta V/\Delta V_0$ Relationship Between Experimental (Red Line) And Theoretical (Blue Line) Results Of Over 50 Years Old Women.

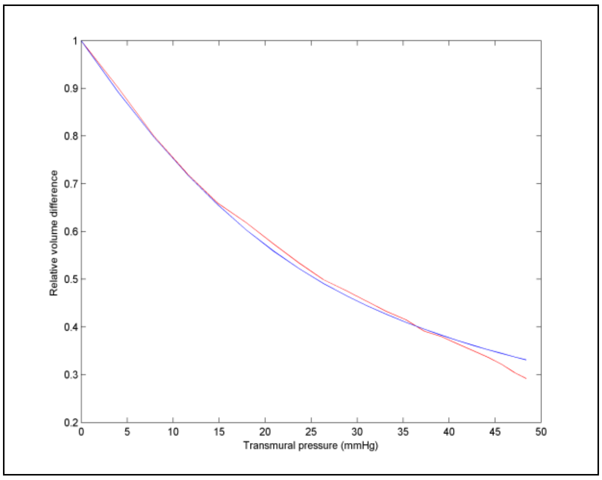

Figure 9: The Comparison Of P_{tr} – $\Delta V/\Delta V_0$ Relationship Between Experimental (Red Line) And Theoretical (Blue Line) Results Of Over 50 Years Old Men.

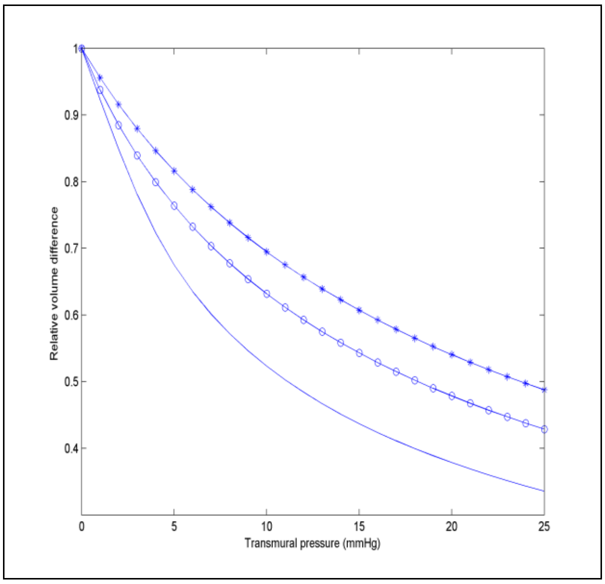

Figure 10: The P_{tr} – $\Delta V/\Delta V_0$ Relationships Of 20-25 Years Old Men With Different Level Of ΔP, 40 (*),50 (o) And 60 (-) mmHg.

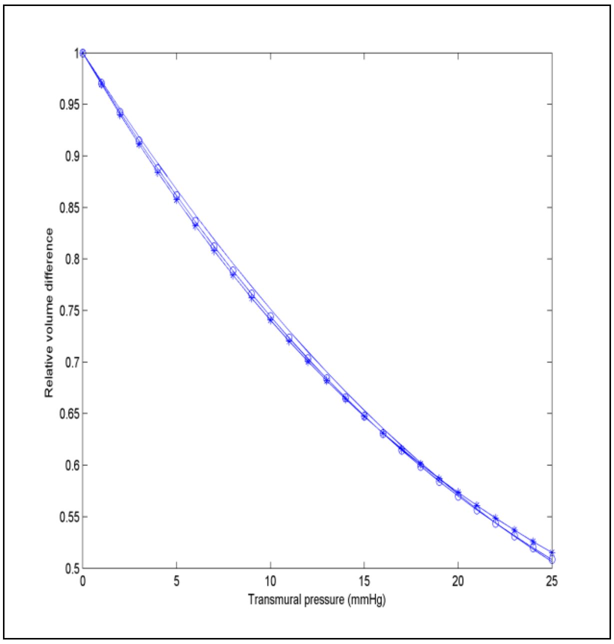

Figure 10: The P_{tr} – $\Delta V/\Delta V_0$ Relationships Of Over 50 Years Old Men With Different Level Of ΔP, 40 (*),50 (o) And 60 (-) mmHg.

3.2. Theoretical Results

According to theoretical approach, the relationships between P_{tr} and $\Delta V/\Delta V_0$ of six groups of subjects are shown in Figure 4-9. These results were obtained from the optimum material parameters of individual group. They showed that $\Delta V/\Delta V_0$ decreased when P_{tr} increased in all groups of subjects as same as the experimental results. These results indicated that Fung model which described the hyperelasticity of arterial wall was able to provide the reasonable response of arterial wall. It also generated the similar trend of P_{tr} – $\Delta V/\Delta V_0$ relationship as the experimental results from PPG measurement. Although there were some differences between experimental and theoretical results in the groups of 20-25 years old and 32-45 years old subjects, theoretical results had the good fit curves with the experimental results in over 50 years old subjects (Figure 8 and 9). These results demonstrated that the current theoretical model was more efficient to predict the elasticity of stiff artery than that of flexible artery. Meanwhile, the difference between experimental and theoretical results might be caused by the limitation of 2D computation and the exponential term of the Fung model.

Figure 10 presents the example result of theoretical model under the influence of ΔP. The difference of P_{tr} – $\Delta V/\Delta V_0$ relationships in 20-25 years old men was found when the level of ΔP was changed. This relationship shifted downwards when the level of ΔP increased. However the effect of ΔP was difficult to see in older subjects as the example of P_{tr} – $\Delta V/\Delta V_0$ relationships in over 50 years old men in Figure 11. Because the blood vessel of older subjects had lower elasticity, the small magnitude of ΔP change could not induce the much different response of the stiff wall. We therefore suggest that the level of ΔP mainly affects the arterial elasticity evaluation in the flexible artery.

4. CONCLUSION

The novel method to quantify arterial elasticity using the AC signal of PPG and the first step of theoretical approach based on the continuum mechanics of arterial wall were proposed in this paper. According to using AC signal of PPG measurement, we obtained the P_{tr} – $\Delta V/\Delta V_0$ relationship which presented the reasonable response of arterial wall to the continuous change of P_{tr}. This P_{tr} – $\Delta V/\Delta V_0$ relationship could reflect the variation of arterial elasticity due to the increase in age of subjects. Moreover, the effect of P_m would be negligible when we analyzed arterial elasticity by this novel method. As the results of theoretical approach, the current theoretical model provided the response of arterial wall to the pressure similar to natural artery. This theoretical model also clarified the effect of pulse pressure on the P_{tr} – $\Delta V/\Delta V_0$ relationship that should be regarded in the analysis of arterial elasticity by using AC signal of PPG, especially in the flexible artery. However, the theoretical model will be improved in order to increase the efficiency of arterial elasticity prediction and evaluation by using the volume oscillometric technique

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REFERENCES

Ando, J., Kawarada, A., Shibata, M., Yamakoshi, K. and Kamiya, A., 1991. Pressure-volume relationships of finger arteries in healthy subjects and patients with coronary atherosclerosis measured non-invasively by photoelectric plethysmography. *Japanese Circulation Journal*, 55, 567-575.

Bilge, O., Pinar, Y., Özer, M. A. and Gövsa, F., 2006. A morphometric study on the superficial palmer arch of the hand. *Surgical and Radiologic Anatomy*, 28, 343-350.

Carew, T. E., Vaishnav, R. N. and Patel, D. J., 1968. Compressibility of the arterial wall. *Circulation Research*, 23, 61-68.

Chuong, C. J. and Fung, Y. C., 1983. Three-dimensional stress distribution in arteries. *ASME Journal of Biomechanical Engineering*, 105, 268-274.

Deng, S. X., Tomioka, J., Debes, J. C. and Fung, Y. C., 1994. New experiments on shear modulus of elasticity of arteries. *American Journal of Physiology*, 266, H1-H10.

Fantin, F., Mattocks, A., Bulpitt, C. J., Banya, W. and Rajkumar, C., 2007. Is augmentation index a good measure of vascular stiffness in the elderly?. *Age and Aging*, 36, 43-48.

Franklin, S. S., Gustin, W., Wong, N. D., Larson, M. G., Weber, M. A., Kannel, W. B., and Levy, D., 1997. Hemodynamic patterns of age-related changes in blood pressure. *Circulation*, 96, 308-315.

Jayasree, V. K., Sandhya, T.V. and Radhakrishnan, P., 2008. Non-invasive studies on age related parameters using a blood volume pulse sensor. *Measurement Science Review*, 8, 82-86.

Lee, H. and Oh, B., 2010. Aging and arterial stiffness. *Circulation Journal*, 74, 2257-2262.

Kalita, P. and Schaefer, R., 2008. Mechanical model of artery walls. *Archives of Computational Methods in Engineering*, 15, 1-36.

Kawarada, A., Shimazu, H., Yamakoshi, K. and Kamiya, A., 1986. Noninvasive automatic measurement of arterial elasticity in human fingers and rabbit forelegs using photoelectric plethysmography. *Medical & Biological Engineering & Computing*, 24, 591-596.

Kelly, R., Hayward, C., Avolio, A. and O'Rourke, M., 1989. Noninvasive determination of age-related changes in the human arterial pulse. *Circulation*, 80, 1652-1659.

Pearson, J. D., Morrell, C. H., Brant, L. J., Landis, P. K. and Fleg, J. L., 1997. Age-associated changes in blood pressure in a longitudinal study of healthy men and women, *Journal of Gerontology: MEDICAL SCIENCES*, 52A, M177-M183.

Sutton-Tyrrell, K., Najjar, S. S., Boudreau, R. M., Venkitachalam, L., Kupelian, V., Simonsick, E. M., Havlik, R., Lakatta, E. G., Spurgeon, H., Kritchevsky, S., Pahor, M., Bauer, D. and Newman, A., 2005. Elevated aortic pulse wave velocity, a marker of arterial stiffness, predicts cardiovascular events in well-functioning older adults. *Circulation*, 111 (25), 3384-3390.

Vlachopoulos, C., Aznaouridis, K. and Stefanadis, C., 2010. Prediction of cardiovascular events and all-cause mortality with arterial stiffness: a systematic review and meta-analysis. *Journal of the American College of Cardiology*, 55, 1318-1327.

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