Ultrasound Image-based Estimation System for Arteriosclerosis of *in vivo* Blood Vessel

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***Abstract*—With aging, mechanical properties of blood vessel degrade as that strength and elongation decrease. However its stiffness (stress/strain) increases. Also progression rate of hardening of vessel depends on individual. It is urgent task to establish inspection technique with those strength parameters for hardening progression. This report presents that a technique for estimating sclerosis of *in vivo* blood vessel with ultrasound B-mode image. The method is based on *in vivo* stiffness (Eth) calculated from variations in vessel diameter with changes in systolic and diastolic blood pressures. In addition, we obtained a correlation between Eth and strength (σ_u) from the results of tensile and internal pressure tests using some animal arteries specimens including human. Therefore, we can estimate *in vivo* Eth and σ_u of artery using B-mode image and the correlation curve. To simplify measurement of diameter changes, prototype software was developed. To examine the validity of this technique, clinical data was collected at some hospitals. The results indicated that Eth and σ_u are useful symptom indices for arteriosclerosis, particularly for identifying the beginning of sclerosis in patients in their early twenties.**

Keywords--B-mode image, blood vessel, in vivo strength, image analysis, preventive medicine

I. INTRODUCTION

With aging, property of blood vessel wall changes both morphologically and mechanically. And the progression rate of hardening depends on individual. Mechanical changes include thickening of arterial walls, alteration of arterial elasticity, contraction of smooth muscle, increased sensitivity to pharmacological stimulation and increased arterial viscoelasticity, i.e., arteriosclerosis [1]. A report by the Japan Ministry of Health, Labor and Welfare indicated that cardiac and cerebrovascular diseases were the main cause of one-third of deaths in Japan. Cardiac diseases, such as myocardial infraction, and cerebrovascular diseases are directly related to arteriosclerosis [2]. Arteriosclerosis is a disease of the arterial walls, in which clinical symptoms are typically only seen when the disease is advanced. Therefore, it is essential task to detect arteriosclerosis by early diagnosis methods in order to prevent the progression of this condition.

To establish a noninvasive method for estimating sclerosis of *in vivo* arteries, we first examined the relationship between mechanical properties (stiffness and strength) and diameter changes in blood vessels due to heartbeats. Secondly, prototype software that is capable of measuring small diameter changes based on 30-image/s by ultrasound B-mode imaging was developed. The system was applied clinically during a feasibility study that may become a routine health examination item in the near future.

II. ESTIMATION OF STIFFNESS FOR *IN VIVO* AERTERY

A. *Definition of elastic stiffness for blood vessel*

Hardening of blood vessels is a sign of aging in humans, and is the result of degradation of elongation and strength from a mechanical viewpoint. Figure 1 shows a schematic stress-strain relationship of arteries. The curves, for both young and older adults, exhibit non-linear relationships due to the viscoelastic nature of blood vessels. In addition to strength reduction with increasing age, the curve becomes steeper. For this nonlinear relationship, the definition of a generalized mathematical expression for calculating stiffness, $d\sigma/d\varepsilon$, of blood vessel is complex. Several reports describing the mechanical properties of *in vivo* arteries have been published [3, 5-8]. In the present report, because the variations in blood vessel diameter are very small, 3~15% of the diameter (0.2~1.2 mm) due to systolic (Ps) and diastolic (Pd) blood pressures in the resting state, we defined a linear relationship between stress and strain, $d\sigma/d\varepsilon$=Eth, designated *in vivo* stiffness. The equation is based on a hollow thick-walled cylinder model subjected to internal pressure, as the ratio of thickness (t) and diameter (D) of the human artery, approximately t/D=0.1~0.15, is given by,

$$\text{Eth} = \sigma_\theta/\varepsilon_\theta \quad (1)$$

$$\sigma_\theta = \{(\underline{R}_i^2 + \underline{R}_o^2)p_s - (R_i^2 + R_o^2)p_d\}/(R_i^2 - R_o^2),$$ F

$$\varepsilon_\theta = \Delta R_i / R_i, \quad \Delta R_i = \underline{R}_i - R_i$$

rom the condition of no volume-change between Ps and Pd pressures, it is also given as,

$$(R_i^2 - R_o^2) = (\underline{R}_i^2 - \underline{R}_o^2) \quad (2)$$

where σ_θ and ε_θ are circumferential stress and strain at the inner wall, R_i and R_o are the inner and outer radius of blood vessel respectively. Underline means the diameter at the systolic pressure, p_s. The values of R_i, R_o, $\underline{R}_i$, and $\underline{R}_o$ in Eq. (1) can be measured using ultrasound B-mode motion image. And critical burst pressure (Bp) of *in vivo* artery can be estimated as a hollow cylinder model subjected to inner pressure,

$$Bp=\sigma_u(R_o^2-R_i^2)/(R_o^2+R_i^2) \quad (3)$$

In case of the size, R_i=3.5, R_o=4.0 mm, i.e. Bp =0.133σ_u, MPa.

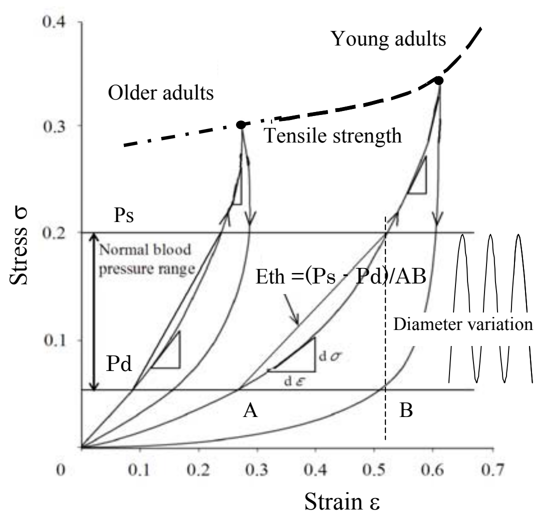

Figure 1. Schematic stress-strain curves showing change in mechanical properties of artery with aging; Eth increases and σu decreases.

On the other definition of elastic stiffness, there is a non-dimensional equation known as beta parameter, β* expressing by natural logarithm of Ps/Pd. The equation [1] is

$$\beta^* = \ln(p_s / p_d)/[(\underline{R_i} - R_i)/R_i] = \ln(p_s / p_d)/\Delta R_i \quad (4).$$

To establish an estimation technique of strength of *in vivo* blood vessel using ultrasound motion images, we examined the relation between ultimate strength (σ_u) and Eth by tensile and liquid pressure tests for *in vitro* specimens (human common carotid artery, ox, big, sheep, tube of silicon and rubber specimens); step-by-step loading and rupture finally [4]. In determining ΔRi, the microscopic change in the specimen's diameter due to inner-pressure was measured using optical-image expanded. Then, the Eth was compared with other four equations (E_p, E_{inc}, V_E, and β*) in terms of stiffness reported in references [5-8]. Finally, we confirmed that the stiffness estimated by Eq. (1) is approximately equivalent to the tensile and internal pressure data [4,9] between resting blood pressure rages. Other four parameters (Ep, Einc, V_E, and β*) differed from the tensile stiffness. From a practical viewpoint, it is concluded that Eq. 1 is reasonable as an index parameter to express progression of arteriosclerosis within the resting blood pressure. A correlation curve between Eth and σ_u was obtained from human and sheep arteries specimens.

B. *An ultrasond image-based estimation system*

Figure 2 shows the prototype system for estimating sclerosis of artery using B-mode imaging. For measurement, ultrasound gel is applied to the skin surface of the subject's neck and a linear-type ultrasound transducer (7.5 MHz) is used. Subsequently, B-mode motion images of the subject's common carotid artery are seen on the monitor of the ultrasound equipment (540×420 pixels, 0.0713 mm/pixel in the case of SonoAce PICO). Because sclerosis of artery proceeds in localized areas, we measured stiffness distribution with regular intervals of 3~5 mm for nine positions. A prototype software allows real-time measurement of both carotid arteries within 3~5 minutes.

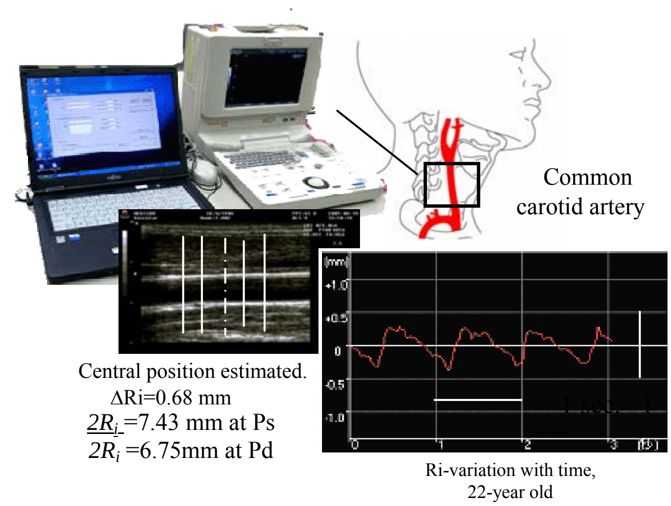

Figure 2. A system developed for estimating strength of *in vivo* artery using B-mode ultrasound image; variation of *Ri* wtith time is shown.

III. RESULTS AND DISCUSSION

Figure 3 shows the correlation between Eth and σ_u, which allows estimation of *in vivo* σ_u of arteries by B-mode imaging using the equation obtained from curve fitting,

$$Bp = 7.0431\,Eth^6 - 109.69\,Eth^5 + 689.2\,Eth^4 - 2234.5\,Eth^3 + 3951.8\,Eth^2 - 3727.9\,Eth + 1975.4$$
$$0.1MPa \le Eth \le 4.0MPa \quad (5)$$

For example, tensile strength (σ_u) is 0.8 MPa (Bp=798 mmHg) when *in vivo* Eth from ultrasound image is 0.5 MPa (average for age 60-70 years as shown in Fig. 4). If σ_u is below a lower threshold (σ_u=0.2 MPa), the probable value of Bp is 200 mmHg when *in vivo* Eth is larger than 3~4 MPa, and this might indicated a potential risk to patient health.

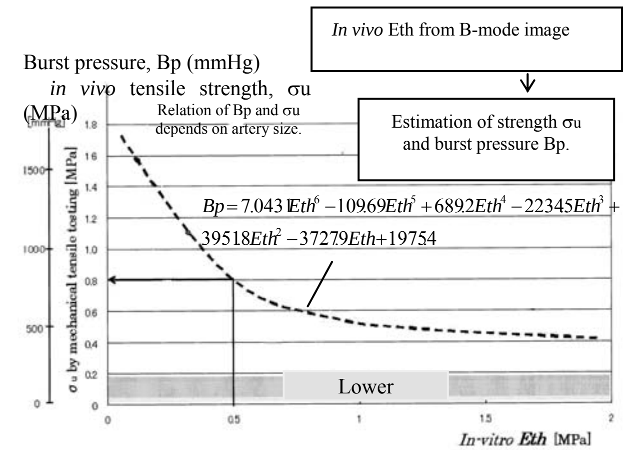

Figure 3. Correlation between Eth and strength (σu) obtained from tensile and internal pressure tests of human common carotid artery specimens.

Figure 4 shows the dependence of Eth on the age of test subjects (159 males and 51 females) for right and left common carotid arteries. In this graph, the scale of critical burst pressure predicted from the relationship in Fig. 3 was confirmed. Differences in Eth for the right and left common carotid arteries are visible for both young adults and older adults as well as gender (male or female) at the same age, but the trend is prominent for older adults and male. According to this figure, it cannot be demonstrated that Eth for a particular (right or left) artery is always larger; rather, it varies by individual. Thus, measuring Eth for both common carotid arteries during diagnosis of arteriosclerosis is necessary.

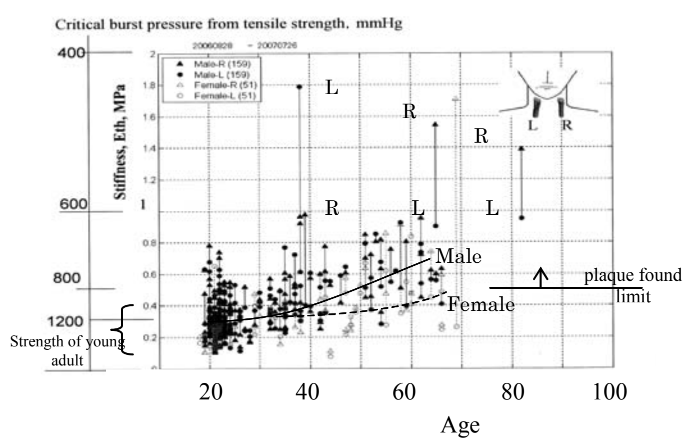

Figure 4. Clinical investigation data showing dependence of age, gender and location (right or left) of common carotid artery on stiffness; special investigation is required if Eth is over 2.0 MPa (under 400 mmHg).

From clinical viewpoint, it can also note that the method is detectable slight change in arteriosclerosis. Furthermore, the result of the regulated examination (carotid sonography) indicated that some examinees with over Eth=0.5 MPa were found visible small plaques. Thus a screening test could be estimated using the Eth index.

Figure 5 shows the results for *in vivo* Eth in a 64-year-old female. From this figure, Eth has slight dependence on location, with the maximum Eth being 1.01 MPa (Bp=548 mmHg by Eq. 5). The result suggests necessity of a complete examination based on the rule of carotid sonography inspection. This is the proposed procedure to estimate the strength of *in vivo* arteries. It is effective to use the mechanical strength of arteries as an index of sclerosis development.

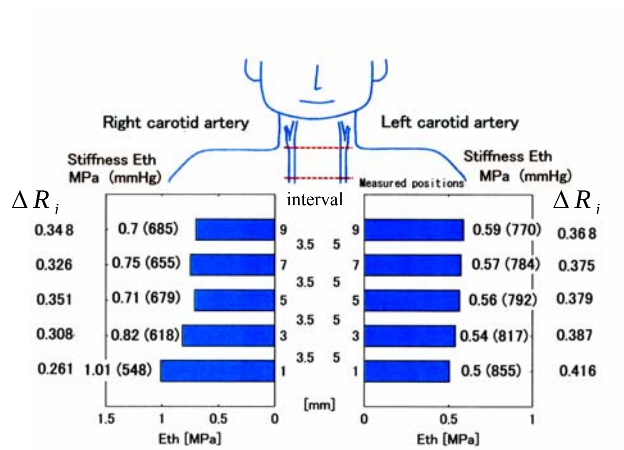

Figure 5. Distribution of stiffness (Eth) showing sclerosis progression of the common carotid artery, measurement of 4~5-mm inerval.

IV. Concluding Remarks

Hardening of blood vessels is a sign of aging in humans, which is the result of degradation of elongation and strength. It is urgent task to establish inspection technique with those strength parameters for hardening progression.

A new system for investigating the risk of arteriosclerosis by measuring *in vivo* stiffness, Eth, of carotid artery is proposed. This method is based on *in vivo* Eth, as calculated from the variations in carotid artery diameter at systolic and diastolic blood pressures using moving B-mode images of a couple of seconds. On the other hand, we found a relationship between Eth from the radial bulge of artery and mechanical strength from the results of tensile and internal pressure tests for *in vitro* artery specimens. Thus, we can predict *in vivo* artery strength as index of arterial sclerosis development. From clinical results, it indicate that material properties such as Eth, tensile strength and burst pressure are useful symptom indices for arterial sclerosis, particularly for identifying the beginning of sclerosis that during the early twenties because the method is detectable slight change in stiffness of vessel. Since this technique only uses conventional inspection data (ultrasound moving images and blood pressures) without special equipment, we believe that this technique will become part of routine health examinations.

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