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Tensile Characteristics and Behavior of Blood Vessels from Human Brain in Uniaxial Tensile Test

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The rupture of blood vessels in the human brain results in serious pathological and medical problems. In particular, brain hemorrhage and hematomas resulting from impact to the head are a major cause of death. As such, investigating the tensile behavior and rupture of blood vessels in the brain is very important from a medical point of view. In the present study, the tensile characteristics of the blood vessels in the human brain were analyzed using a quasi-static uniaxial tensile test, and the properties of the arteries and veins compared. In addition, to compare the tensile behavior and demonstrate the validity of the experimental results, blood vessels from the legs of pigs were also tested and analyzed. The overall results were in accordance with the histological structures and previous medical reports.

Key Words : Blood Vessel, Brain, Brain Vessel, Tensile Test, Visoco-elasticity

Nomenclature

E : Young's Modulus
A, B, a, b : Constants by Mechanical Properties
C_1, C_2 : Integral Constants
σ : Uniaxial stress
ε : Uniaxial strain

1. Introduction

Head injuries are the major cause of death in a car crash according to a statistical report by Luchter et al. (1996).

Normally, such deaths are caused by rupturing of the blood vessels in the brain due to the relative movement of the brain to the skull as a result of impact to the head or acceleration. This rupture of the brain blood vessels then leads to cerebral hemorrhage, subdural hematomas, and increased intracranial pressure (ICP), eventually resulting in death.

Although the human brain only accounts for 2% of the entire body weight, it consumes 20% of the total blood. As such, if the supply of blood ceases just for even 10 seconds, this can cause unconsciousness and serious pathological damage to the brain. When brain blood vessels are ruptured, the blood supply ceases and hematomas occur in the cranium between the brain and the skull. Fig. 1 shows a photograph of subdural hemorrhaging and hematomas resulting from the rupture of brain blood vessels after an impact to the head. Therefore, investigating the mechanical behavior of brain vessels has very important medical implications.

Lowenhielm (1978) developed a mathematical model of the brain blood vessels and evaluated

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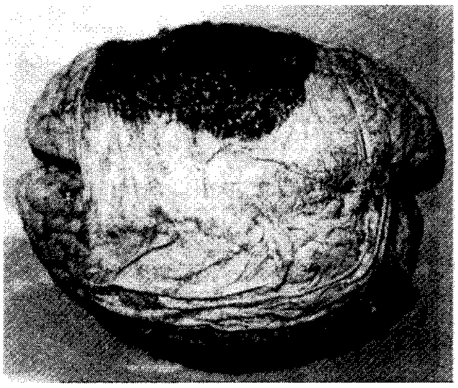


Fig. 1 Damaged brain as subdural hematoma by rupture of brain vessels

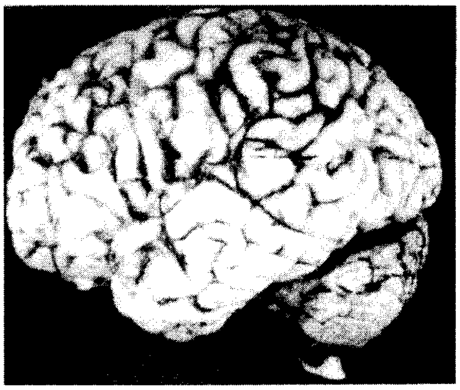


Fig. 2 Photograph of brain and vessels on brain · surface

the tolerance level for rupturing the bridging veins among the brian blood vessels in the case of head impact.

Fung (1981) also carried out a simple tensile test using biological soft tissues and developed experimental equations for the non-linear relationship between stress and strain from the experimental data.

Lee et al. (1989) performed a tensile test on bridging veins and reported that the main reason for subdural hemorrhaging is the rupture of the cerebral bridging vein.

Meanwhile, the current study performed a quasi-static uniaxial tensile test to investigate the mechanical properties of human brain arteries and veins excised from patients during brain surgery. Young's modulus(E), the maximum tensile stress, and maximum tensile strain were all evaluated from the tensile test. In addition, the differences between the mechanical behavior of the brain arteries and veins were analyzed to provide medical and pathological data on the brain blood vessels. Finally, as a comparison, the same test was also carried out on blood vessels from the legs of pigs.

2. Experimental Procedure

2.1 Vessel tissue preparation

Vessel tissue specimens were excised from the brain surface of patients undergoing brain surgery. The subjects were adults (male and female) aged between 35~55 and did not have any disease related to the brain blood vessels. After removal from the brain surface, the specimens were immediately stored in saline water(NaCl 131.55 g+water 15 L) in a storage box with ice at about 10±5℃ and carried to the laboratory for the tensile experiment. The test was performed within 8 hours to prevent any degradation or severe micro-deformation of the vessel tissue after excision from an in vivo state. Previous studies have reported that there is no degradation of human vessels within 8 hours at 5~37℃ in saline water (Thibault, 1997 ; Arbogast, 1997).

Fig. 3 Vessel specimens and suture before resection during brain surgery

While excising the blood vessels from the brain surface, the lengths of the specimens were measured in an in vivo state using a thread as the basis for the preconditioning procedure before

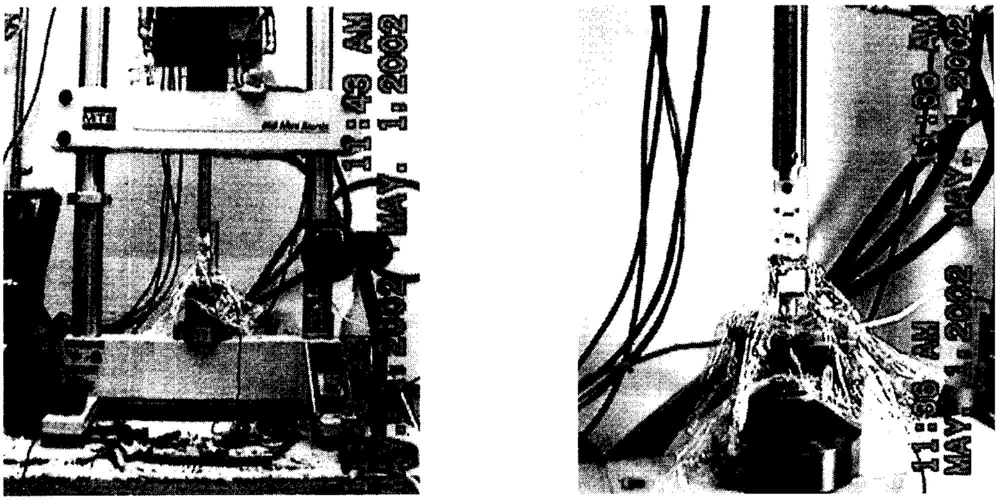

(a) Testing machine (b) Magnified photo of actuator and grip

Fig. 4 Photograph of testing machine

the tensile test. Figure 2 shows a photograph of the brain and the vessels on the brain surface, while Fig. 3 shows a photograph of the vessels before resection from the brain surface during brain surgery.

Blood vessels were also excised from the rear legs of juvenile yorkshire pigs (7~8 months old) and treated using the same procedures and conditions as the human tissue.

2.2 Preconditioning and testing

A hydraulic fatigue testing machine for biomaterials (MTS 858 Mini Bionix, 15 kN, MTS) was used for the tensile test of the blood vessels. To maintain an in vivo state, water was supplied using a spuit at intervals of 2 minutes during the tensile test. Previous researchers (Schatzmann et al., 1998 ; Carew et al., 2000 ; Eshel et al., 2001) have suggested preconditioning before testing to restore tissue in an in vitro state to an in vivo state, thereby reducing experimental errors, obtaining accurate data on soft tissue, and stabilizing the micro-tissue by rearranging the micro-fibers and cells into an in vivo state.

Therefore, in the current study, preconditioning was also performed, which involved 10 cycles and the length of the extension was based on the in vivo length so as to restore an in vivo state.

Next, the tensile test was performed and the strain rate was quasi-static at $0.04-0.27 s^{-1}$ based on the preconditioning rate.

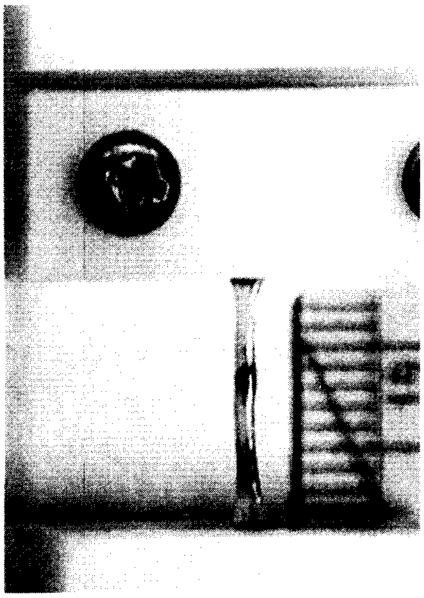
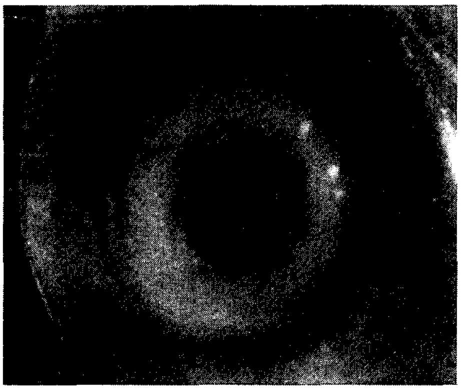


Fig. 5 Gripped artery specimen

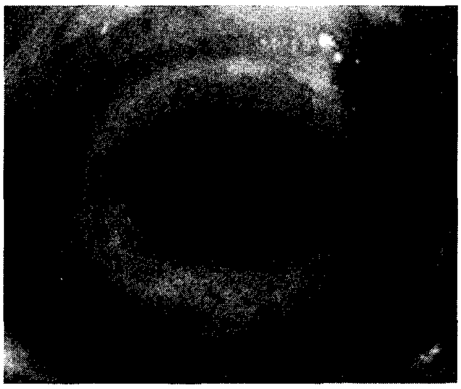
Figure 4(a) is a photograph of the MTS testing machine used for the tensile test and Fig. 4(b) shows a magnification of the actuator and grip part, respectively. Figure 5 shows a magnification of the grip part and a gripped blood vessel specimen. Special grips made of polyethylene were used for the tensile test of the soft tissue and sand

Table 1 Geometrical information of specimens

	Mean gage length (mm)	Mean area (mm^2)
Human brain artery	5.30	0.381
Human brain vein	5.68	0.389
Pig leg artery	6.25	0.820
Pig leg vein	6. 08	0.980



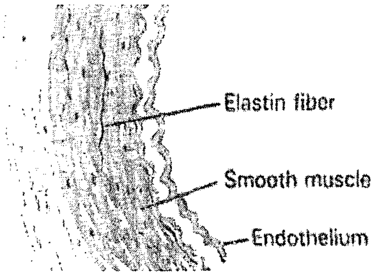
(a) Artery



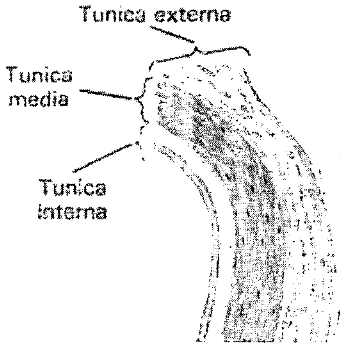
(b) Vein

Fig. 6 Photograph of cross section of brain vessels

paper (No. 2000) was attached on the gripping part to prevent the blood vessels from slipping out during the test. In addition, the surfaces of the blood vessels were stained at regular intervals to enable any stretching of the specimens to be observed with the naked eye, as shown in Fig. 4.



(a) Artery



(b) Vein

Fig. 7 Schematic sketch of vessels (Martini, 1989)

To calculate the stress after the tensile test, cross-sectional photographs were taken of the blood vessels using an optical microscope (CFM, Infinity Photo-Optical Co.) and CCD camera (SSC-M256, SONY), then a cross-sectional area was measured for each blood vessel using an image processing program (Scion Image Ver. Beta 4.02, Scion Corporation). Figure 6 shows the photographs of cross section of brain vessels and Fig. 7 shows a schematic sketch of vessels to compare the histological difference. As shown in Fig. 7, arteries contain more volumetric rate of elastin fiber and smooth muscle in the vessel wall than veins. The geometrical information of specimens is shown in Table 1.

3. Results of Tensile Test

Immediately after preconditioning, tensile tests for the human's and the pig's blood vessels were performed in order to derive stress and strain relationships.

Fig. 8 shows the results for the stress and strain measured for the human brain arteries after

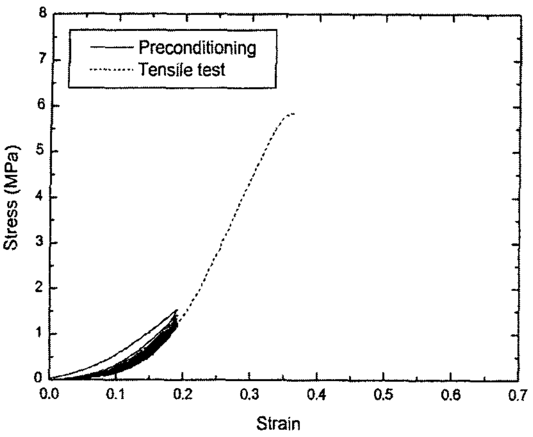


Fig. 8 Relationship between stress and strain of human's brain vessels

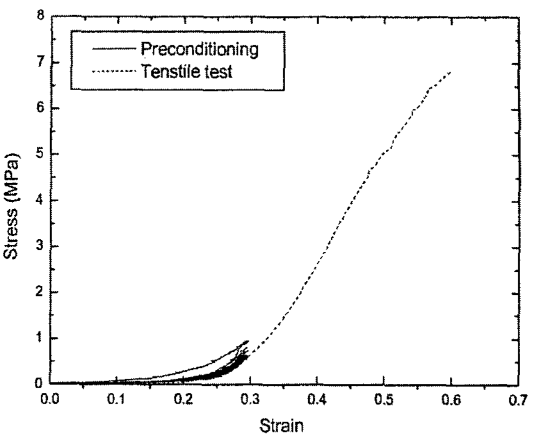


Fig. 9 Relationship between stress and strain of pig' s leg vessels

preconditioning and during the tensile test.

Typical viscoelastic behavior of stress relaxation was observed with each stretch cycle, followed by convergence as the number of strain cycles increased. This characteristic of hysteresis was due to internal friction among the micro-fibers making up the blood vessels. A graph of the stress and strain relationships exhibited an S-shaped curve, which is common for soft tissue. Additionally, the tensile graph increased along with the last cyclic curve of the preconditioning cycles at the initial part, as a result of the stress relaxation of the soft tissue and the viscoelastic material. The tensile graph also exhibited a toe region, which is a general characteristic of soft tissue, such as ligaments, muscle, and skin etc. (Fung, 1981).

Meanwhile, Fig. 9 shows the stress and strain relationships for the pig leg arteries after preconditioning and during the tensile test, which exhibited a similar trend to the human brain blood vessels, where stress relaxation and convergence were observed with each cyclic stretch. However, the maximum stress and strain for the pig leg arteries were higher than those for of the human brain arteries.

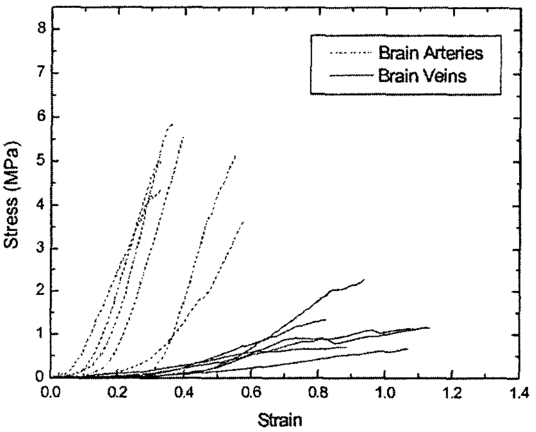


Fig. 10 Tensile behavior of blood vessels on human brains

Figure 10 shows the comparative results of the tensile tests on the human brain arteries and veins. Although there is relatively wide range of error in this experimental data of blood vessels, this error is a general trend for bio-material soft tissue because of histological imperfection and differences among samples as biological scatters. Therefore, the mechanical behavior of blood vessels in this study is reliable in spite of wide range of error. As shown in Fig. 10, the data for the veins and arteries exhibited sigmoidal curves and toe regions, general characteristics of biological soft tissue.

When comparing the characteristics of the arteries and veins, the arteries exhibited a lower maximum strain yet higher maximum stress than the veins. Normally, brain vessels are ruptured by brain deformation or the motion of the brain relative to the skull caused by impact to the head or sudden acceleration. Therefore, the current results indicate that arteries can be ruptured more easily than veins with the same amount of stretch due to deformation or relative motion of the brain, as arteries have a lower maximum strain than veins.

This conclusion matches well with the previous pathological reports, which found that arteries were more likely to rupture than veins in the case of intracranial hemorrhaging due to brain deformation resulting from impact to the head.

Conversely, the higher maximum stress exhibited by the arteries, compared to the veins, has advantages in supporting severe stress conditions due to high blood pressure. In particular, the slopes of the curves for the arteries were steeper than those for the veins, representing that the arteries had a higher Young's modulus(E) than the veins. This possibly resulted from the differences between the histological composition of the arteries and veins, such as the volumetric rate of elastin. In general, arteries contain more elastin in the layers of the vessel wall than veins, as shown in Fig. 7.

As such, it is supposed that the histological differences contributed to the different mechanical behavior of the arteries and veins in the tensile test, and the higher Young's modulus for the arteries enabled the support of more blood pressure.

Figure 11 shows the results of the tensile test on the pig leg arteries and veins, which exhibited similar characteristics to the human brain arteries and veins, where sigmoidal curves and toe regions were observed as with soft tissue. When comparing the lengths of the toe regions in Figs. 10 and 11, the human and pig veins had longer toe regions than the human and pig arteries. The toe region indicates the stress threshold for soft tissue, and the difference in the lengths of the toe regions was likely due to the differences in the composition and micro-structure of the artery and vein tissue.

From the results of the quasi-static tensile

Table 2 Tensile properties of blood vessel

(a) Human's brain arteries

Human's arteries	Young's modulus (MPa)	Maximum stress (MPa)	Maximum strain
No. 1	25.039	5.821	0.356
No. 2	27.236	5.553	0.394
No. 3	40.854	5.096	0.549
No. 4	18.317	5.023	0.333
No. 5	17.073	4.279	0.318
No. 6	16.927	3.605	0.575
Average	21.916	4.819	0.408

(b) Human's brain veins

Human's veins	Young's modulus (MPa)	Maximum stress (MPa)	Maximum strain
No. 1	6.013	2.273	0.938
No. 2	2.739	1.350	0.826
No. 3	1.140	1.155	1.131
No. 4	1.808	1.126	1.083
No. 5	0.775	0.707	0.885
No. 6	1.199	0.680	1.069
Average	1.722	1.085	0.994

(c) Pig's leg arteries

Pin's arteries	Young's modulus (MPa)	Maximum stress (MPa)	Maximum strain
No. 1	25.105	7.705	0.480
No. 2	26.843	7.689	0.420
No. 3	24.229	6.846	0.603
No. 4	25.907	6.216	0.310
No. 5	22.490	6.019	0.728
No. 6	28.542	5.589	0.412
Average	25.521	6.693	0.479

(d) Pig's leg veins

Pig's veins	Young's modulus (MPa)	Maximum stress (MPa)	Maximum strain
No. 1	12.098	3.338	0.892
No. 2	9.697	3.073	1.035
No. 3	7.020	2.643	0.841
No. 4	7.086	2.414	1.066
No. 5	6.953	2.181	0.902
No. 6	3.352	1.849	1.155
Average	7.689	2.578	0.974

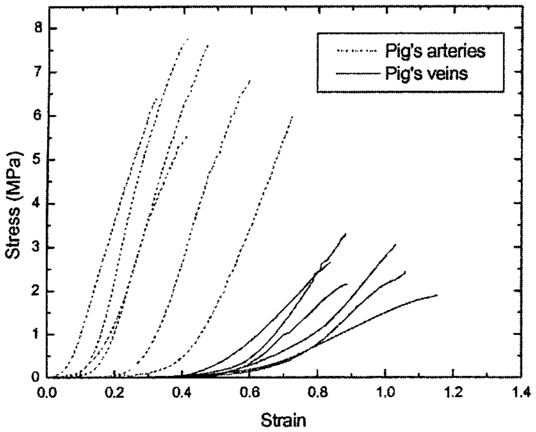


Fig. 11 Tensile behavior of blood bessels of pig legs

test on the human and pig blood vessels, certain mechanical properties were measured and calculated quantitatively. Table 2 shows the mechanical properties for each type of blood vessel. Tables 2(a) and (b) list the properties of the human brain arteries and veins, respectively, while Tables 2(c) and (d) list the properties of the pig leg arteries and veins, respectively.

Young's modulus was defined as the maximum slope of the stress and strain curve before yielding. And average values of each property were calculated after discarding maximum and minimum values, considering a large error range of bio-material specimen. As shown in Table 2, the average Young's modulus for the human brain arteries was 21.916 MPa, which was about 12.7 times higher than that for the human brain veins.

In addition, the average maximum stress for the human arteries was 4.819 MPa, which is about 4.4 times higher than that for the human veins, although the maximum strain for the human arteries was 0.4 times lower than that of the human veins. The pig blood vessels exhibited similar results to those for the human blood vessels.

When comparing the human and pig arteries, there were no significant differences in the various average values, quantitatively. However, the Young's modulus for the pig leg veins was about 4.5 times higher than that for the human brain veins, plus the maximum stress for the pig veins was 2.4 times higher than that for the human veins, yet the average maximum strain was almost the same at 0.974 and 0.994, respectively.

4. Empirical Formulation

Fung (1981) suggested an experimental equation for a proportional relationship between Young's modulus and stress at a point on the curve for a non-linear relationship between stress and strain from the toe region to the yield point. The first-order linear differential Eq. (1) suggested by Fung (1981) represents the non-linear elastic behavior of biological soft tissue based on a uniaxial tensile test.

$$E_i = A\sigma + B \quad (\sigma \geq 0) \qquad (1)$$

As such, the definition of Young's modulus at any point on the curve can be represented by Eq. (2).

$$E_i = \frac{d\sigma}{d\varepsilon} \quad (\varepsilon \geq 0) \qquad (2)$$

Equation (1) can be represented by Eq. (3) using Eq. (2)

$$\frac{d\sigma}{d\varepsilon} = A\sigma + B \qquad (3)$$

By the separation of variables and integration, Eq. (3) can be represented as following :

$$\int \frac{d\sigma}{\sigma + \frac{B}{A}} = \int A d\varepsilon \qquad (4)$$

$$\ln\left(\sigma + \frac{B}{A}\right) = A\varepsilon + C_1 \qquad (5)$$

where C_1 is constant and Eq. (5) can be modified to Eqs. (6) and (7) with an exponential function.

$$\sigma + \frac{B}{A} = e^{(A\varepsilon + C_1)} \qquad (6)$$

$$\sigma + \frac{B}{A} = C_2 e^{A\varepsilon} \qquad (7)$$

where C_2 is constant. Based on the condition $\sigma = 0$ at $\varepsilon = 0$ in the tensile test, C_2 can be B/A. Thus, Eq. (7) can be simplified into Eq. (8).

$$\sigma = a(e^{b\varepsilon} - 1) \quad (\sigma \geq 0,\ \varepsilon \geq 0) \qquad (8)$$

where a and b are constants determined from the experimental data and become the mechanical properties of the tensile behavior of biological soft tissue.

Therefore, the data curves for the stress and strain relationship were fitted according to Eq. (8) by the nonlinear least square fitting method using Microcal Origin Ver 6.0 (Microcal Software, Inc.).

Figures 12 and 13 represent the results of the curve fitting of the nonlinear elastic behavior of the human and pig blood vessels from the toe region to the yield point. As shown in these figures, the fitted curves agreed well with the experimental data.

Table 3 shows the values of the constants *a*

Table 3 Values of constant *a* and *b*, and statistical results of nonlinear curve fitting for each blood vessels

(a) Human's brain arteries

Human's arteries	a	b	χ^2	R^2
No. 1	0.041	14.653	0.0093	0.988
No. 2	0.027	9.702	0.0008	0.996
No. 3	0.003	16.398	0.0082	0.987
No. 4	0.100	13.267	0.0090	0.993
No. 5	0.146	13.067	0.0167	0.985
No. 6	0.951	6.169	0.0206	0.985
Average	0.079	12.672	–	–

(b) Human's brain veins

Human's veins	a	b	χ^2	R^2
No. 1	0.007	7.265	0.0007	0.988
No. 2	0.074	3.411	0.0005	0.992
No. 3	0.020	5.726	0.0042	0.984
No. 4	0.033	3.338	0.0001	0.995
No. 5	0.035	5.217	0.0017	0.979
No. 6	0.098	3.382	0.0001	0.998
Average	0.037	4.434	–	–

(c) Pig's leg arteries

Pig's arteries	a	b	χ^2	R^2
No. 1	0.021	8.518	0.0161	0.985
No. 2	0.145	11.139	0.0010	0.992
No. 3	0.670	9.498	0.0258	0.983
No. 4	0.050	15.219	0.0188	0.981
No. 5	0.017	12.463	0.0155	0.987
No. 6	0.157	13.164	0.0476	0.978
Average	0.093	11. 566	–	–

(d) Pig's leg veins

Pig's veins	a	b	χ^2	R^2
No. 1	0.004	6.339	0.0002	0.984
No. 2	0.004	8.838	0.0027	0.982
No. 3	0.001	12.598	0.0001	0.992
No. 4	0.002	9.447	0.0015	0.993
No. 5	0.007	6.258	0.0020	0.994
No. 6	0.002	7.668	0.0006	0.996
Average	0.003	8.073	–	–

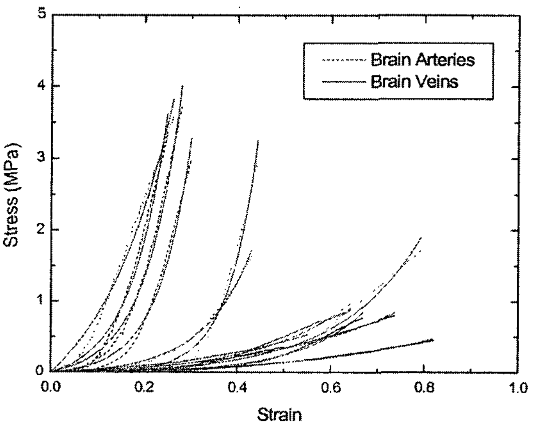


Fig. 12 Nonlinear curve fitting according to experimental equation of human's brain vessels

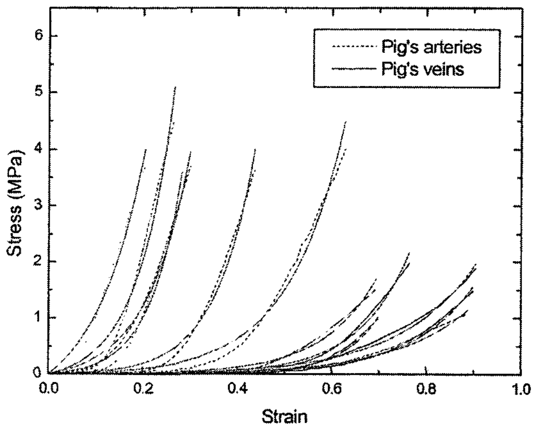


Fig. 13 Nonlinear curve fitting according to experimental equation of pig's leg vessels

and *b*, and the statistical results of the nonlinear curve fitting. When comparing the human blood vessel data in (a) and (b) of Table 3, the average values for the constants *a* and *b* for the arteries were higher than those for the veins. In addition, as shown in Tables (c) and (d), the pig blood vessels exhibited similar characteristics to the human blood vessels.

Comparing the human and pig arteries, there was no significant difference between the average values for the constants *a* and *b*. However, when comparing the human's and the pig's veins, a significant difference was found between the average values for the constants *a* and *b*.

Accordingly, the constants *a* and *b* would appear to represent significant material properties for human and pig blood vessels. Therefore, the experimental equations in this study may be useful for predicting rupture due to tension in the case of brain deformation resulting from impact to the head and for analyzing medical and pathological problems related to intracranial hemorrhaging. Besides, these results will be able to supply experimental data to develop dummy systems to investigate head and brain injury (Kim et al., 1997).

5. Conclusions

(1) Consistent with biological soft tissue, the stress and strain relationship for the blood vessels from the human brain was represented by the visco-elastic behavior of stress relaxation and sigmoidal curves. In particular, human and pig arteries were found to be stiffer than human and pig veins due to differences between the histological structures.

(2) Although the arteries exhibited a higher maximum stress than the veins, the maximum strain for rupture of the arteries was lower than that for the veins. This result accords with previous pathological reports on intracranial hemorrhaging.

(3) Experimental equations representing the tensile behavior were derived from the basis of experimental data. These equations can be used to simulate the mechanical behavior of blood vessels and analyze medical problems related to blood vessel injury and disease.

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