

A Structural Constitutive Model for Viscoelastic Rheological Behavior of Human Saphenous Vein Using Experimental Assays

Rassoli Aisa, Abrishami Movahhed Arezu, Faturae Nasser, Seddighi Amir Saeed, Shafigh Mohammad

Abstract—Cardiovascular diseases are one of the most common causes of mortality in developed countries. Coronary artery abnormalities and carotid artery stenosis, also known as silent death, are among these diseases. One of the treatment methods for these diseases is to create a deviatory pathway to conduct blood into the heart through a bypass surgery. The saphenous vein is usually used in this surgery to create the deviatory pathway. Unfortunately, a re-surgery will be necessary after some years due to ignoring the disagreement of mechanical properties of graft tissue and/or applied prostheses with those of host tissue. The objective of the present study is to clarify the viscoelastic behavior of human saphenous tissue. The stress relaxation tests in circumferential and longitudinal direction were done in this vein by exerting 20% and 50% strains. Considering the stress relaxation curves obtained from stress relaxation tests and the coefficients of the standard solid model, it was demonstrated that the saphenous vein has a non-linear viscoelastic behavior. Thereafter, the fitting with Fung's quasilinear viscoelastic (QLV) model was performed based on stress relaxation time curves. Finally, the coefficients of Fung's QLV model, which models the behavior of saphenous tissue very well, were presented.

Keywords—Fung's quasilinear viscoelastic (QLV) model, strain rate, stress relaxation test, uniaxial tensile test, viscoelastic behavior.

I. INTRODUCTION

ONE of the main causes of death in developed countries is the coronary artery diseases, which are also known as silent death. The treatment of these diseases entails spending a considerable amount of money. One of the treatment methods for coronary artery abnormalities is to create a bypath for supplying blood to the heart through a coronary artery bypass surgery [1]. Various arteries or veins including a thoracic artery, brachial artery and saphenous vein and industrial prostheses are used in coronary bypass, carotid artery graft, and arteriovenous fistula surgeries to create a deviatory bypath [1], [2]. Few information is available regarding the mechanical properties of the human blood vessels that can be used in this surgery. Determining the mechanical properties of these tissues is therefore very important.

In general, tissues are composed of fibers; collagen fibers

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contribute to the hardness of tissue and elastin fibers to its elasticity. The composition of these two types of fibers determines the mechanical properties of tissue [3]. The blood vessel has a complex, layered structure. The middle layer (media) plays a more effective role in vessel properties than comparing to the innermost (intima) and outermost (adventitia) layers. The middle layer is composed of smooth muscle cells, elastin, collagen, and proteoglycan. Smooth muscle cells lie in the circumferential direction and let the vessel contract or expand in reaction to blood pressure. The elastin in middle layer leads to a distribution of blood pressure and collagens prevent the over-dilatation of the vessel [2]. To estimate the mechanical properties of the saphenous vein, Donovan et al. performed uniaxial tests in longitudinal and circumferential directions on this vein and obtained its tensional strength and module of elasticity [4]. They concluded that age, blood sugar, and hypertension affect the tensional strength of saphenous vein in the circumferential direction. Hamedani et al. also performed uniaxial tests on the human saphenous vein and found out that the saphenous tissue hardness is greater in longitudinal than circumferential direction and that tension in the transverse direction is more than in longitudinal direction. They, furthermore, compared the strength of this vein with that of the umbilical vein and concluded that saphenous vein is stronger than umbilical vein [5]. Paranjothi et al. performed inflation tests and came to the result that saphenous vein is inhomogeneous and compressible [6]. Brossollet and Vito performed biaxial tests on the canine saphenous vein and investigated the effect of freezing on this tissue [7]. They concluded that freezing and melting affect the smooth muscles but have no effect on collagen and elastin. Milesi et al. carried out tests on the veins of normal people and people with hypertension and demonstrated the difference of vein strength between normal people and people suffering from hypertension [8]. This finding can affect clinical results. Chamiot et al. performed uniaxial tests on the thoracic artery and radial artery and concluded that the strength of the thoracic artery is more than that of radial artery and the strain is greater in radial tissue than thoracic artery [9]. Andel et al. performed uniaxial tests with various strain rate on coronary arteries and thoracic artery. Comparing the results, they concluded that the thoracic artery has a higher strength than coronary arteries [10]. Holzapfel et al. have analyzed the elastic properties of various heart arteries with the assumption that they are multi-layered structures [11], [12]. Although the data of uniaxial test have been presented comprehensively,

these data do not provide precise information about the mechanical properties of materials. Soft tissues have viscoelastic properties since a high percentage of them is constituted of water. Therefore, investigating the viscoelastic properties of tissues is important.

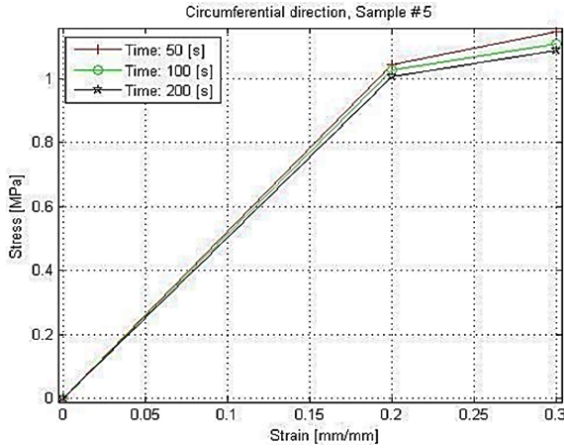


Fig. 1 Stress-strain curve obtained from stress relaxation test in circumferential direction

As far as the authors know, experimental measurements to develop a viscoelastic model for saphenous tissue haven't been considered before. The objective of the present study is to develop a viscoelastic model for a saphenous tissue. Stress relaxation tests are performed in longitudinal and circumferential directions on tissue samples, and Fung's quasilinear viscoelastic (QLV) model is generalized to saphenous tissue based on relaxation factor curves.

II. MATERIALS AND METHODS

A. Sample Preparation

Human saphenous samples were provided by Shahid Rajaei hospital in Tehran. The samples were residual parts of the veins of patients who underwent coronary bypass surgery. Samples were kept in normal saline solution and transferred into the laboratory. Tests were done within 2 or 3 hours after excision of the saphenous vein. Samples were first to cut cylindrically. To obtain the zero stress state and to free the residual strain in tissue, the samples were cut out of the cylindrical form. The extra tissues around veins, sutures of venules and venous valves were removed, and finally, rectangular samples were prepared for tests. Tests were performed at room temperature, as done by Kelly [13]. Similar to Silver's work, the normal saline solution was dripped onto tissue during tests to prevent it from drying [14].

B. Test Procedure

1. Equipment Description

The stress relaxation tests were done using a tension testing device, in which force sensors measure the tensile loads exerted by a micro stepper motor with a precision of 16 bits. This sensor can sense forces up to 14N. Test device has a

precision of 0.0025N. This device is provided with a digital micro-camera with a zooming capability of 300x, frequency of 30 Hz and resolution of 640x480. Data are transferred by controllers into a computer and saved there. To synchronize data, the data obtained from force sensors and camera are saved simultaneously with a frequency of 5Hz using code written in Python.

2. Loading Procedure

After setting each sample in the testing device, a preload of 0.01N was exerted in the axial direction on the sample to obtain a proper smooth form providing the conditions for a meaningful measurement. Five periodic loading cycles with a frequency of 0.2 and an amplitude of 0.5mm, which is equal to 10% of strain, were exerted on samples. Thereafter, displacements were exerted on samples with a rate of 0.2mm/s in longitudinal and circumferential directions. 20%, 30%, 40% and 50% strains were exerted and stress relaxation time curves were extracted and fitted for each strain. It is noteworthy that 60% strain was also exerted, but this strain was in some tissues more than the tissue strength in circumferential direction and tissues tore before reaching to this strain. Considering the tissue strength against exerted strains, 20% to 50% strains were tested and analyzed mathematically.

C. Expansion of Fung's QLV Model

1. Modeling Based on Stress Relaxation Curves

In quasilinear viscoelastic theory, it is necessary to reduce stress relaxation functions and define the elastic model. Equation 2 expresses Fung's reduced relaxation function. This function is used for many tissues like ligaments. C is the relaxation factor. τ_1 and τ_2 are small and big time constants, respectively. E is the exponential integral function, as shown in (3). Elastic stress function, which is used for many biological tissues like meniscus, cartilage, tendon and ligament, has been shown in (4) [15], [16]:

$$\sigma(t) = G(t)T^{(e)} \quad (1)$$

$$G(t) = \frac{1 + C[E(\frac{t}{\tau_2}) - E(\frac{t}{\tau_1})]}{1 + C \ln(\frac{\tau_2}{\tau_1})} \quad (2)$$

$$E^Y = \int_Y^{+\infty} \frac{\exp(-z)}{z} dz \quad (3)$$

$$T^{(e)} = A\{\exp(B\varepsilon) - 1\} \quad (4)$$

These two functions are used for analysis of stress relaxation curves. Putting these functions in Fung's equation gives relation (5), which is used for fitting of curves.

$$\sigma(t) = \frac{[A \times (\exp(B \times \varepsilon) - 1)] \times [(2 + C \times \ln(\frac{\tau_2}{\tau_1}))]}{[1 + C \times \ln(\frac{\tau_2}{\tau_1})] + \left\{ \frac{[C \times E(\frac{t}{\tau_2}) - C \times E(\frac{t}{\tau_1})]}{1 + C \times \ln(\frac{\tau_2}{\tau_1})} \right\}} \quad (5)$$

where; A , B , C , τ_1 , and τ_2 are coefficients of transformation.

2. Modeling Based on the Curves of Relaxation Factor

The dimensionless parameter “relaxation factor,” which is defined as (6), is used in this method for analysis of stress relaxation curves. In this relation, σ_F is the final stress of tissue after complete relaxation and σ_P are the tissue stress at time zero (the beginning point of stress relaxation). The coefficients of Fung’s model are extracted in this method based on the curve of relaxation factor. The results of this fitting technique have less difference comparing to the results of the stress relaxation curve analysis and are exacter.

$$Q(t) = (\sigma(t) - \sigma_F) / (\sigma_P - \sigma_F) \tag{6}$$

III. RESULTS

To find the exact location of tissue after putting samples in the tensile test device, a very small force was exerted on them. Since it was not possible to protect the tissue against decay, some samples did not yield acceptable data. The average thickness of samples was considered to be 0.65mm. Separate stress-time curves were obtained for each sample after performing stress relaxation tests with various strains in longitudinal and circumferential directions. For precise modeling, the tissue linear or nonlinear behavior was investigated first. For this aim, the stress relaxation test was done for each sample with two different strains, and the stresses in each test were registered at 50, 100, and 200s and the stress-strain curves were drawn.

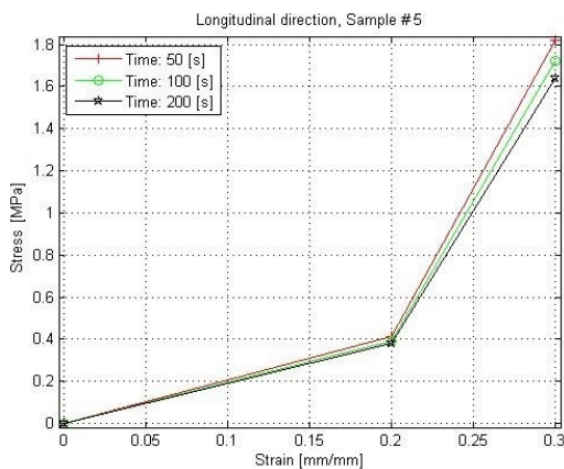


Fig. 2 Stress-strain curve obtained from stress relaxation test in longitudinal direction

Figs. 1 and 2 show the stress-strain curves of a sample for investigating the linear or nonlinear behavior of the tissue. As seen, the stress-strain curves drawn based on stress relaxation curves are nonlinear. This indicates the nonlinearity of viscoelastic behavior of tissue. Therefore, the behavior of tissue cannot be demonstrated with linear viscoelastic models, and one must use quasilinear or nonlinear models to explain the viscoelastic behavior of saphenous tissue. After making the nonlinear behavior of tissue clear, the stress-time curves were fitted to Fung’s QLV model in circumferential (Fig. 3)

and longitudinal (Fig. 4) directions separately using MATLAB software, and the model coefficients were obtained for each axis separately. As said before, modeling based on stress relaxation factor curves is exacter. These curves were obtained for each sample. Since there was a large number of data, data were shown as point cloud diagram in Figs. 3 and 4 for obtaining the average coefficients. The coefficients of Fung’s QLV model were obtained after fitting in MATLAB software (Tables I and II).

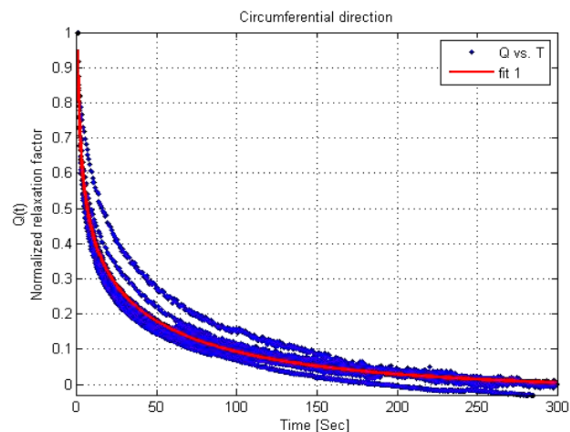


Fig. 3 The relaxation factor-time curve, fitting to Fung’s model, circumferential direction

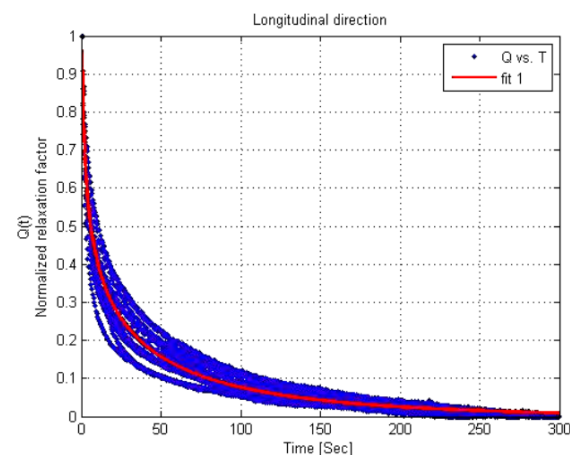


Fig. 4 The relaxation factor-time curve, fitting to Fung’s model, longitudinal direction

IV. DISCUSSION AND CONCLUSION

The behavior of many biological tissues, which are independent of strain rate, is explained with the viscoelastic mechanical model. The classic linear viscoelastic models have a similar specific frequency and hence cannot demonstrate the ineffectiveness of strain rate in biological tissues. Furthermore, the stress-strain relationship in biological tissues is usually very nonlinear, and their structure is greatly nonisotropic. Fung’s quasilinear viscoelastic theory was developed due to such behavior of soft tissue. This theory is widely used for demonstration of tissue behavior. The stress

dependence on time (loading history) and strain (total deformation) are separated in classical formulation of QLV model and the (time dependent) stress relaxation response is linear, while the stress-strain relationship remains nonlinear. Stress has a linear relation to time and strain in QLV theory. Considering this, a linear viscoelastic model, which is not dependent on loading frequency, can demonstrate the behavior of soft tissue constituents very well.

TABLE I

THE COEFFICIENTS OBTAINED FROM THE FITTING TO FUNG'S MODEL BASED ON RELAXATION FACTOR CURVE IN CIRCUMFERENTIAL DIRECTION

Coefficient	Fitting of point cloud curve	Average	Standard deviation	Error
A	5.928	5.82	0.511555276	0.127888819
B	0.04658	0.07578875	0.041177014	0.010294253
C	0.09449	0.103314375	0.014568921	0.00364223
η_1	0.03836	0.053856875	0.031063841	0.00776596
η_2	246.2	231.25	55.49574158	13.87393539

TABLE II

THE COEFFICIENTS OBTAINED FROM THE FITTING TO FUNG'S MODEL BASED ON RELAXATION FACTOR CURVE IN LONGITUDINAL DIRECTION

Coefficient	Fitting of point cloud curve	Average	Standard deviation	Error
A	5.504	5.52805	0.43314	0.09685
B	0.04441	0.07539	0.0407	0.0091
C	0.1219	0.15809	0.17637	0.03944
η_1	0.02035	0.0627	0.02564	0.00573
η_2	158.6	179.554	60.989	13.6376

The final objective of this study is to present a viscoelastic model compatible with tissue behavior and also to present the best and most precise method of testing tissues similar to saphenous tissue (regarding strength and dimensions). As explained before, Fung's QLV model was used for fitting stress relaxation curves. Fung's QLV model was investigated in two ways, first by modeling based on stress relaxation time curve and second based on relaxation factor-time curve. The results indicate that fitting based on relaxation factor is more precise and yields better results.

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