Disponible en ligne sur
ScienceDirect
www.sciencedirect.com

Elsevier Masson France
EM|consulte
www.em-consulte.com

IRBM

IRBM 37 (2016) 158–164

Original Article

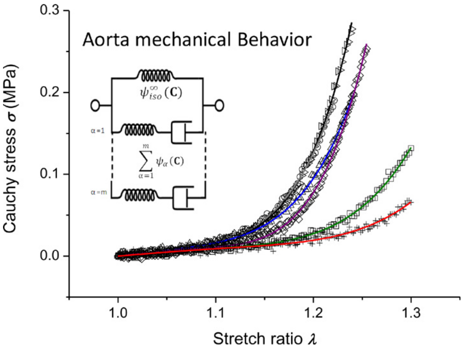
Hyper-Viscoelastic Behavior of Healthy Abdominal Aorta

E.-J. Courtial [a,b,c], L. Fanton [d], M. Orkisz [b], P.C. Douek [d], L. Huet [c], R. Fulchiron [e,*]

[a] *Univ Lyon, Université Lyon 1, CNRS, Ingénierie des Matériaux Polymères, UMR5223, F-69622, Villeurbanne, France*
[b] *Univ Lyon, CREATIS; CNRS UMR 5220; Inserm U1044; INSA-Lyon; Université Lyon 1, 69621 Villeurbanne, France*
[c] *Département recherche et innovation, Segula Matra Technologies, Bron, France*
[d] *Univ Lyon, CREATIS; CNRS UMR 5220; Inserm U1044; INSA-Lyon; Université Lyon 1; Hospices Civils de Lyon, 69621 Villeurbanne, France*
[e] *Univ Lyon, Université Claude Bernard Lyon 1, CNRS, Ingénierie des Matériaux Polymères, UMR5223, F-69622, Villeurbanne, France*

Received 15 September 2015; received in revised form 2 February 2016; accepted 8 March 2016

Graphical abstract



Abstract

The aim of the present study was to define biomechanical parameters of the healthy human abdominal aorta, usable to develop materials for the aortic phantom production. Such phantoms used in the training of endovascular treatment must describe the same morphology and mechanical behavior properties as the patient's aorta. To accurately identify these biomechanical parameters, *ex vivo* experiments in uniaxial tensile and dynamic simple shear tests were performed on six human healthy abdominal aortas (6 males, between 12 and 69 years old). A solid generalized Maxwell model including Yeoh expression for the elastic part was used to describe the hyper-viscoelastic behavior of the aorta. The results obtained from uniaxial tensile tests show an exponential-like increase in stiffness, which can be described by three hyperelastic parameters (C_1, C_2 and C_3). From dynamic shear experiments, the viscous part of the global biomechanical behavior was expressed in a specific angular-frequency range (1 to 315 rad/s). Three Maxwell elements (β_1, β_2, and β_3) put on three constant times ($\tau_1 = 0.003$ s, $\tau_2 = 0.03$ s, and $\tau_3 = 0.3$ s) respectively, were necessary to describe it. As this relatively high number of viscoelastic parameters may be difficult to control in the development of materials, we suggest defining the viscous behavior with the global viscosity η_0 that combines the viscoelastic contributions of each Maxwell element. In conclusion, four biomechanical parameters: C_1, C_2, C_3 and η_0, must be considered for the development of materials used in the aortic phantom production.

Keywords: Abdominal aorta; Hyper-viscoelasticity; Yeoh model; Aortic phantom; Generalized Maxwell model

---

[*] Corresponding author.

E-mail addresses: edwin.courtial@hotmail.fr (E.-J. Courtial), laurent.fanton@creatis.insa-lyon.fr (L. Fanton), maciej.orkisz@creatis.insa-lyon.fr (M. Orkisz), philippe.douek@creatis.univ-lyon1.fr (P.C. Douek), laurent.huet@segula.fr (L. Huet), rene.fulchiron@univ-lyon1.fr (R. Fulchiron).

http://dx.doi.org/10.1016/j.irbm.2016.03.007

1. Introduction

Arterial biomechanics has been intensively studied, and substantial progress has been achieved in understanding basic arterial structure and its influence on mechanical behavior [1]. It is now widely accepted that the arterial tissue undergoes large deformations and that its behavior is highly nonlinear, dissipative, and anisotropic [2]. The knowledge of patient-specific biomechanical properties is of paramount importance, because they influence the response of the artery to therapeutic interventions. The increase of endovascular therapies over the past decade has led to a wide use of medical devices such as aortic phantoms [3,4]. Numerous studies have attempted to produce aorta phantoms, which have the same morphology and mimic the nonlinear viscoelastic (hyper-viscoelastic) behavior of the actual aortic tree [5,6]. Rigorously speaking, a patient-specific aortic phantom would be composed of healthy and diseased areas. Unfortunately, complicated procedures and difficulty to obtain human artery specimens have led to a paucity of experimental data concerning the hyper-viscoelastic behavior of healthy aortas. Consequently, aortic phantoms are mostly developed with materials able to mimic the diseased-artery mechanical behavior [3,7].

The biomechanical behavior of healthy aortas can be described from *in vivo* or *ex vivo* experiments. With regards to *in vivo* experiments, it is difficult to identify the hyper-viscoelastic behavior due to the complexity of the technique [8] and the limits of medical imaging. In this case, it is virtually impossible to quote a study including reliable data that could be used in aortic phantom development. Some authors resort to *ex vivo* experiments in order to accurately study the biomechanical behavior of the aorta. Nevertheless, the majority of them focus only on the relationship between elastic properties and aortic region [9–11], age [12,13], or disease characteristics [14–16]. They omit the dissipative part which is an important component of the global biomechanical behavior.

The identification of constitutive models able to describe the aorta behavior, and of their parameters, allowed biomedical engineers to develop materials exhibiting mechanical behaviors tending toward this of healthy or diseased aortic tissues [5,7]. Nonetheless, in constitutive equations based on a detailed physical description of the tissues [17,18], the number of parameters generally becomes very large so that they may be difficult to determine. Therefore, the material macrostructure of the aorta phantom is often different [19] compared to the actual aorta [20]. More simply, the use of a phenomenological model [21] with a smaller number of parameters makes it possible to validate materials formulations.

The aims of this study are to contribute quantitative data on the hyper-viscoelastic behavior of healthy abdominal aortas (AA) based on uniaxial tests and dynamic shear methods, and to propose a phenomenological constitutive equation suitable to describe this behavior, while keeping a relative simplicity. For each artery tested, we provide parameter values of a selected phenomenological model, namely generalized Maxwell solid model that can be used by biomedical engineers and device manufacturers to investigate better treatment methods and develop artery-specific devices.

Table 1
Data for the human abdominal aorta samples tested.

Age	BMI (Body Mass Index)	Sample name	Cause of death
12	20	a12b20	Unknown
39	18	a39b18	Unknown
50	36	a50b36	Unknown
57	28	a57b28	Road traffic accident
68	18	a68b18	Cardiac arrest
69	25	a69b25	Cardiac arrest

2. Materials and methods

2.1. *Tissue specimens*

This study was approved by the Hospital and University Ethics Committees of Lyon (France). Healthy abdominal aortas were collected from 6 deceased human subjects (6 males, between 12 and 69 years old) at the time of their autopsy at the Institute of Forensic Medicine. Subject population data, namely age and body-mass index (BMI $= m/h^2$, where m is the body mass in kilograms, whereas h is the body height in meters), as well as the corresponding sample names are presented in Table 1. The name of each sample is built as follows: aXXbYY, where XX is the age, and YY is the BMI, e.g., a12b20 corresponds to a 12-year-old subject with BMI equal to 20. Specimens were removed between iliac arteries and the lower mesenteric artery. All tissues were stored in 0.9% NaCl physiological saline solution at 4 °C. Then, all the mechanical measurements were performed in isothermal conditions at ambient temperature. Testing was done within 36 hours of death to preserve freshness.

2.2. *Constitutive model*

In the present work, a phenomenological model was chosen to limit the number of adjustable parameters, while keeping the best possible description of the behavior. Therefore, a hyper-viscoelastic model, namely the generalized Maxwell solid model, was selected. This model can be represented by a parallel assembly of a solid branch composed of an isolated spring and a number m of viscoelastic liquid branches, each of them composed of a spring and a dashpot in series. In this model, the function ψ that describes the free-energy variation of a transformation in isochoric and isothermal conditions is given by [22]:

$$\psi(\mathbf{C}) = \psi_{iso}^{\infty}(\mathbf{C}) + \sum_{\alpha=1}^{m} \psi_{\alpha}(\mathbf{C}) \tag{1}$$

where $\psi_{iso}^{\infty}(\mathbf{C})$ is the strain-energy function characterizing the equilibrium state of the solid represented by the isolated spring, $\mathbf{C}$ the right Cauchy–Green strain tensor and m the number of relaxation times (which are defined by the ratio between the corresponding dashpot viscosity and spring modulus). This left-side term of equation (1) can be experimentally assessed by