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Research Paper

Further experimental evidence of the compressibility of arteries

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ABSTRACT

Further experimental evidence on the compressibility of arteries under normal physiological pressure range is provided using the experimental apparatus introduced in Yosibash et al., JMBBM 39(2014):339–354. We enlarged the experimental database by including almost twice the number of experiments, we considered a different artery – the porcine common carotid that allowed longer and larger diameters.

In the physiological pressure range of 50–200 mmHg, a relative volume change of 5% was obtained, lower compared to the sapheneous and femoral arteries (2–6%). Most of the arteries had a relative volume change of 1.5%.

The relative volume change is found to be almost linearly proportional to the pressure, and inversely proportional to the dimensions of the experimented arteries (especially the artery length). The smaller the artery tested, the larger the relative volume change (such a phenomenon was also realized in Yosibash et al., JMBBM 39(2014):339–354.).

We realized in recent past publications a flaw in the experimental protocol that results in an overestimation of the relative volume change (thus underestimating the bulk modulus). It is due to the consideration of experimental observations close to the zero pressure. Nontheless, in view of the experimental evidence, the pre-assumption of incompressibility in many phenomenological constitutive models of artery walls should be re-evaluated.

1. Introduction

Common constitutive models of arteries, aimed at predicting their passive response, are based on hyperelasticity assumption, pre-assuming the incompressibility of the artery tissue under physiological conditions, see e.g. the review (Holzapfel and Ogden, 2010). The motivation for this assumption is the high content of water in the artery wall, which is considered incompressible.

A definitive experimental-based answer on the level of compressibility in artery walls is therefore of biomechanical interest but not easily answered because of difficulties to

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measure accurately very small differences in volume under physiological pressure. In Yosibash et al. (2014) an accurate and calibrated experimental system was described for the measurement of volume changes in arteries under physiological conditions. These experiments were performed ex-vivo on porcine arteries harvested the same day or a previous day, loaded by internal pressure that well represents physiological conditions. Ten saphenous and femoral arteries were considered (one carotid artery also) which demonstrated experimentally a considerable volume change: for the physiological normal pressure range $\approx$50–200 mmHg the relative volume change was $\approx$2–6%. Recently, further studies demonstrating a considerable volume change in arteries were reported. Nolan and McGarry (2016) report on experiments on 13 excised circular disks of diameter of 10 mm from the descending aorta of six sheep. At an average stress of about 60 mmHg an average relative volume change $9\pm3\%$ is reported. This high compressibility at that low stress is probably overestimated possibly due to the excision and inaccuracies of the measurements of a small overall volume of the specimen (estimated to about 80 mm^3), but more importantly because of consideration of the very high volume changes at very low applied stresses.

These recent experimental observations demonstrate the compressibility of arterial wall tissues in three different artery types in two animals. Here we extend the experimental database and further investigate more quantitatively the compressibility of the arterial wall tissue by using the calibrated experimental apparatus described in details in Yosibash et al. (2014). In addition to the sapheneous and femoral arteries in Yosibash et al. (2014), we herein report on eighteen porcine common carotid arteries, thus enlarging both the type and number of specimens. The compressibility values observed in this study are compared to the ones in Yosibash et al. (2014). Furthermore, we investigate if pressurizing the arteries to 300 mmHg (above the physiological range as performed in Yosibash et al. (2014)) may have an influence on the relative volume change after removing the internal pressure and reapply it. We also investigate artifacts in the experimental observations that may be contributed to the size of the specimens, and what is the influence of wall thickness measurement error on the error in relative volume change.

2. Methods

2.1. The experimental apparatus

The experimental apparatus used for measuring artery's volume change in a "physiological" condition (inflating the lumen by inserting liquid to simulate the blood pressure, allowing the artery to expand) is based on the ideas in Di Puccio et al. (2012) and thoroughly described in Yosibash et al. (2014). It is briefly described here: the *test chamber* (see Fig. 1) was a PMMA tube, with an internal diameter of 32 mm, sealed at both ends by rigid plastic caps. Through the center of each cap a hollow small diameter metallic tube was inserted, enclosing the main part of the pressurized volume V_p. One cap was perforated at two locations, that were connected to plastic tubes. These needles were used to fill the test chamber with water and to allow the exit of air bubbles trapped inside the test chamber.

The artery specimen was tied to the metal hollow tubes inserted from either side of the test chamber with a pressure sensor inserted via a catheter into the tied artery. Colored water V_{in} was inserted through the hollow tube inflating the artery. The volume of the extruded water V_{ext} from the PMMA tube due to the inflation of the outer surface of the artery was measured. The setup of the testing apparatus and all its components are shown in Fig. 2.

The experimental apparatus was thoroughly calibrated. The various calibration tests are documented in Yosibash et al. (2014).

2.2. Experiment protocol

Porcine common carotid arteries were extracted from female pigs sacrificed for medical research not associated with the vascular system. Prior to excision, heparan sulfate was given to the sedated animal to prevent blood clots in the arteries. The excised specimens were kept in saline solution at 2–4 C° for at most 24 hours. The arteries were skeletonized (connective tissue removed around the arteries), cut to an appropriate length and attached to the metallic tubes by surgical thread. Colored water was then inserted into the lumen to remove trapped air and to check for leaks (by increasing the inner pressure to a value of $\approx$200 mmHg).

A preconditioning protocol was then followed by determining the amount of inlet water ($V_{in,200\ mmHg}$) that produced

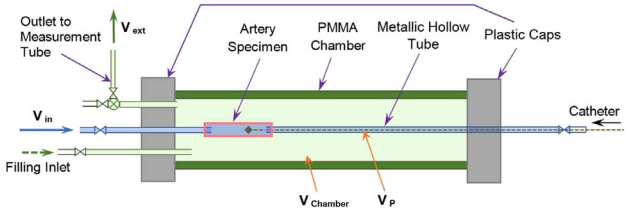

Fig. 1 – A schematic figure of the testing apparatus (from Yosibash et al. (2014)).

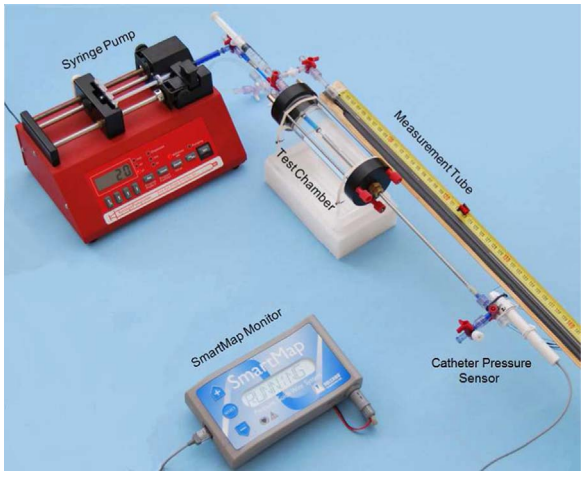

Fig. 2 – Photograph of the testing apparatus' components (from Yosibash et al. (2014).).