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Experimental verification of the healthy and atherosclerotic coronary arteries incompressibility via Digital Image Correlation

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Abstract So far there is no study to measure the Poisson's ratio of the human coronary arteries in order to verify their incompressibility regardless of being healthy or atherosclerosis. It has been reported that atherosclerosis alters the elastin content of the arterial wall which is responsible for the elastic behavior of the arterial wall and helps tissue to reserve its initial shape after contracting or stretching. It is believed that the arterial walls are almost incompressible with nonlinear anisotropic mechanical response under axial or circumferential loading. Although the elastic modulus and Poisson's ratios were both originally stemmed from the linear solid mechanics, they can be employed to address the linear elastic mechanical properties of the arterial wall under small deformation/strain. To date, many studies assumed the arterial wall as an incompressible material whether via a direct mechanical measurement or a fluid simulation study in the arterial wall, despite there is no enough supporting evidence. The present study was planned to discover this issue in detail using Digital Image Correlation (DIC) technique to lively measure the induced strains of 9 healthy and 8 atherosclerotic human coronary arteries at two different longitudinal strain rates, i.e., 5 and 20 mm/min. The Poisson's ratio of the arterial walls, thereafter, were measured as a value of transverse strain with respect to the longitudinal strain. The results revealed the mean Poisson's ratio of 0.49098 and 0.49330 for the healthy and atherosclerotic arterial walls, respectively, under the strain rate of 5 mm/min. Furthermore, the Poisson's ratio of 0.49156 and 0.49702 were seen in the

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healthy and atherosclerotic arterial walls, respectively, under the strain rate of 20 mm/min. The results well verified the incompressibility of the coronary arterial walls regardless of being healthy or atherosclerotic under the both strain rates.

Introduction

Cardiovascular disease is a wide range of clinical disorders responsible for a high rate of deaths throughout the world.[1] Atherosclerosis is ranked as the most hazardous shapes of the cardiovascular disease causes by dehydrated food, smoking, pollution, stress, etc., which can alter the elastin and collagen content of the arterial wall (microstructure) and, consequently, the mechanical properties of the arterial wall.[2–4] Atherosclerotic plaque is also enabled to block the blood occlusion in the arteries and, as a result, invokes a significant variation not only in the hemodynamics of the blood flow but also the mechanical properties of the arterial wall.[5–7]

So far there are many studies have been measured the mechanical properties of the arterial wall using different mechanical approaches, such as linear,[8] nonlinear isotropic[9] and anisotropic[10] solid mechanics via constitutive equations.[11] However, the arterial tissue can be considered as an incompressible material which is in common among almost many of the studies have been conducted so far. However, up to now there is no agreement with this assumption and, therefore, there is a need to set an experimental study to confirm that. In the past, most studies considered the arterial wall as an isotropic elastic material. In characterizing the linear mechanical properties of the arterial walls several researchers have employed the postulation of arterial walls' incompressibility.[12,13] Although this assumption may significantly abridge the mechanical behavior of the arterial wall, this would provide a more simplified mechanical behavior of the arterial wall with fewer constants, such as elastic modulus as well as Poisson's ratio. In addition, so far there is no experimental evidence to prove the incompressibility of the human coronary arterial wall. Lawton et al.[14] showed that the aortic strips were behaved like an incompressible material under different stretch ranges. The canine carotid arteries were also found to be incompressible through an internal pressurization test.[15] It is well known that an impeccably incompressible material under a hydrostatic stress tolerates no comparative alteration in distance among material elements. Although it would be difficult to consider a soft tissue as an incompressible material, because all materials display some degree of compressibility. However, in some especial conditions the behavior of these materials under strains can be approximated as an incompressible material. It is known that a nearly incompressible material would not show a considerable deformation and, as a result, would have the Poisson's ratio of 0.5. That is, the value of the axial/longitudinal strain must be nearly two times of the transverse strain. Hasegawa et al.[16] proposed a non-invasive ultrasound technique to experimentally measure the Poisson's ratio of the carotid artery and abdominal aorta. Their method employed a high spatial resolution technique to measure the both in axial and radial directions of the arterial wall and their results finally reported the value of 0.46 as the Poisson's ratio of the arterial wall. Carew et al.[17] subjected a group of 11 thoracic aorta segments of the dogs to a series of internal pressure and their results reported the Poisson's ratio of closely to 0.5. Thereafter, the longitudinal and circumferential strain of the tissues due to internal pressure were measured accurately to prove the incompressibility (Poisson's ratio of 0.5) of the arterial wall.[18,19]

To this end, most studies measured the elastic modulus, computed the hyperelastic parameters, or analyzed the nonlinear anisotropic response of the arterial tissues Therefore, there is not much result on the Poisson's ratio of these tissue under various strain rates, namely 5 and 20 mm/min. In addition, those studies measured the Poisson's ratio mostly have been performed on the animal models. Therefore, this study was designed to explore the Poisson's ratio of the healthy and atherosclerotic human coronary arteries via Digital Image Correlation (DIC) technique under the strain rates of 5 and 20 mm/min. The results would provide a verification for the current assumption employed by many studies on the Poisson's ratio of the coronary arterial walls not only in the healthy but also in the diseased condition.

Materials and methods

Experimental testing and Digital Image Correlation (DIC) technique

The coronary arteries were collected during autopsy from eight healthy and nine atherosclerotic male individuals having the mean age of 38.12 $\pm$ 9.89 and 63.73 $\pm$ 16.23 years, respectively. The samples were tried to be gathered as fresh as possible with less than 5-h post-mortem to minimize the post-mortem tissue degradation. Although there is an age difference among the tissue samples, the age difference may hardly affect the amount of Poisson's ratio among the coronary arteries. In addition, the reports in this case well stated that the age difference may not significantly affect the mechanical properties of the coronary arterial walls.[8,20] In order to figure out whether the obtained tissues are healthy or atherosclerosis, picro Sirius red staining of the cap was done and the tissues were imaged using polarized light microscopy images (Olympus, Tokyo, Japan). The atherosclerotic arterial wall is