Measurement of strain distribution on human aortic wall surface with a plaque under uniaxial stretch

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Introduction

Mechanical properties of atherosclerotic plaque can have crucial effects on plaque rupture which may result in myocardial and cerebral infarctions. The final goal of this study is to identify the mechanical properties of plaques based on strain-field analysis of the intimal surface and to assess the risk of rupture.

In this study we evaluated the strain distribution on the luminal surface of a human aortic wall using a set of uniaxial loading tests and digital image correlation (DIC) technique. Furthermore we assessed the mechanical properties of a normal region to predict the mechanical properties of the plaque.

Method

We preserved a thoracic aorta of an 84-year-old male in a freezer for 4 days. After thawing, we cut the aorta with a plaque into a 20×25 mm rectangle and removed the adventitia. The research protocol was approved by the Research Ethics Committee of University Hospital, Fukuoka University.

We used a strip-like 2×18 mm specimen for a uniaxial loading test to identify the mechanical properties of the aortic wall. This experiment setup is similar to our previous studies(2).

On the surface of the specimen, a pair of dark spots, which was apart by 44% of the grip-to-grip distance initially, was traced during loading. Images from the loading test on this specimen were processed in the software DIPP Motion Pro 2.24 (DITECT) to convert the grip-to-grip stretch to the specimen’s one. Then the stress-strain relationship of the normal specimen was calculated from the force-displacement relationship.

With an assumption of incompressible and isotropic material, we used an Ogden hyperelastic material model with a single pair of material constants (See Eq. (1)). Under uniaxial loading condition, the material constants in the Ogden model were determined using its curve fitting function in Igor Pro 6 (WaveMetrics).

\[ \tau = \mu (\lambda_{xx}^{\alpha-1} - \lambda_{xx}^{\alpha-1/\alpha}) \]

(1)

with an incompressibility constraint

\[ \lambda_{xx} \lambda_{yy} \lambda_{zz} = 1 \]

(2)

where \( \mu \) and \( \alpha \) are the material constants and \( \lambda_{ii} \) is stretch in "i" direction(2).

The rectangle specimen was scanned by X-ray CT to identify calcified locations.

Specimen was sprayed with black ink to create dark spots on its surface for the strain analysis with a DIC technique. Two cameras (Canon, EOS 60D) were used to record the stretch, one perpendicular to intimal side and the other recording the specimen’s side-view.

The specimen was fixed between two grippers in the circumferential direction of the aorta. A 5-cycle of preconditioning with 10% strain and final stretch of 33% were carried out in a 37°C physiological saline bath. The specimen was stretched with a strain rate of 0.01/s using two step-motor driven stages. After the experiment, the specimen was cut into strips with a width of 2 mm and images were taken from the cut surfaces in order to produce the profile of the specimen.

Results

Figure 1(a) shows the specimen in its gripped condition and the straight line where one of circumferential cuts after the experiment was carried out. Actual profile of the vascular wall and the plaque for this cut is presented in Fig.1 (b).

Figure 1(c) shows the distribution of strains in circumferential and axial directions for the region
shown in Fig.1 (a). The result shown here is for the strain of 6.3% or the displacement of 0.98 mm between the two grippers.

Fig.2 shows nominal stress-strain relationship of the normal specimen.

![Fig.1](image1)

(a) Gripped specimen at zero strain and the region of DIC analysis (dimensions are in millimeters). (b) The actual profile of analyzed region derived from post-experimental cut. (c) Distributions of circumferential and axial strains of the aorta along the line in the circumferential direction (See Fig. 1(a)).

![Fig.2](image2)

Fig.2 Nominal stress-strain relationship of the normal region

**Discussion**

Comparing the DIC analysis results in Fig. 1(c) and the specimen profile in Fig. 1(b), strain peaks occur near the plaque shoulder. One reason for the strain concentration at these locations may be a large curvature of the surface. The fibrous cap has the lowest amount of strain in both directions. One reason for the small strain of this region may be that the plaque surface is out of the plane of the surrounding regions.

One needs to determine the main cause of the small strain at fibrous cap: out-of-plane nature of the region or its high stiffness.

We are planning to use finite element method to determine the mechanical properties of the vascular wall and the plaque based on DIC strain results. In the analysis we will use the material constants of the normal region as shown in Fig. 2.

**Conclusion**

We measured the the strain on the intimal surface of human aorta with a plaque under uniaxial stretch by using DIC technique, and obtained nonuniform distribution along the shoulder of the plaque.

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**Reference**