EXPERIMENTAL AND ANALYTICAL STUDY OF RESIDUAL STRESS AND STRAIN IN THE LAMELLAR UNIT OF THE PORCINE AORTAS

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INTRODUCTION

It is well known that residual stress and strain exist in the artery wall. A ring-like specimen of an aortic segment springs open to form an arc when it is cut radially. This indicates that there existed compressive residual stress near the inner wall and tensile near the outer before the radial cut. Such residual stress reduces stress concentration which would appear in the inner wall of a pressurized vessel, and many studies suggest that circumferential stress in the aortic wall distributes uniformly in the radial direction *in vivo*.

The opened-up configuration is stress-free if the aortic wall is homogeneous. However, the wall is not homogeneous in a microscopic level: its media has a layered structure called lamellar unit which is a pair of elastic lamina (EL) and a smooth muscle rich layer (SML) [1]. Elastic modulus of elastin is about 0.6 MPa and that of relaxed smooth muscle is about 0.01 MPa [2]. Thus, the EL is supposed to be much stiffer than the SML. In fact, we recently found that the elastic modulus of the EL is about 2.5 times higher than that of the SML [3]. If the circumferential stress in the *in vivo* condition is the same between the two layers, residual stress of each layer in this direction should be different because the stress-strain relationships of the both layers differ. Such residual stress is not released fully by the radial cutting, but is released only in the area close to the cut surface. The stress release near the surface may cause hills and valleys on the surface due to the release of compressive and tensile stresses, respectively. In this study, we have developed a scanning micro indentation tester (SMIT), measured the surface topography and the stiffness distribution of the section, and estimated residual stress and strain in the lamellar unit with a finite element (FE) analysis.

MEASUREMENT OF SURFACE TOPOGRAPHY

Development of a Scanning Micro Indentation Tester (SMIT)

Scanning micro indentation tester is a tester to measure the surface topography and stiffness distribution of a specimen surface by pressing a cantilever tip against the specimen surface while scanning it like the atomic force microscope in the contact mode. The cantilever was made from a micro glass plate of 65 mm x 1 mm x 0.15 mm (Asahi Techno Glass Corp., Japan) by pulling it with a pipette puller (PP-83, Narishige Co., Ltd., Japan) to make its tip diameter 3–5 µm and bending it with a microforge (MF-90, Narishige Co., Ltd., Japan) at right angle at the point 4 mm from the tip. The cantilever was driven by a PZT actuator (AE505D1, Tokin Corp., Japan) and the displacement of its tip was measured with a confocal laser displacement meter (LT8100, Keyence Corp., Japan). The measurement was done in a bath filled with a physiological saline solution at room temperature. The specimen bath was set on a motor-driven XY stage (MINI60X, Sigma Koki Co., Ltd., Japan) to scan the point of measurement (Fig. 1). The contact point was determined at the point where the cantilever began deflecting, and a stiffness index α was obtained as the initial slope of the indentation-deflection curve. The index α was converted to elastic modulus E with the following formula obtained by calibrating the tester with silicone elastomers with known elastic moduli:

$$E \text{ (kPa)} = 1.88 \exp (2.54\alpha). \quad (1)$$

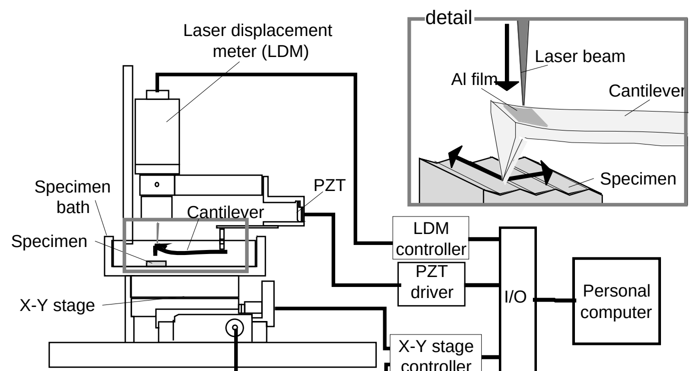


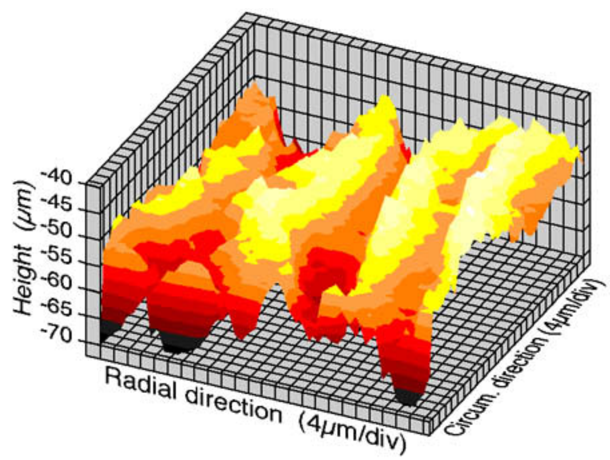
Figure 1. Schematic diagram of the scanning micro indentation tester (SMIT)

Method of the Measurement

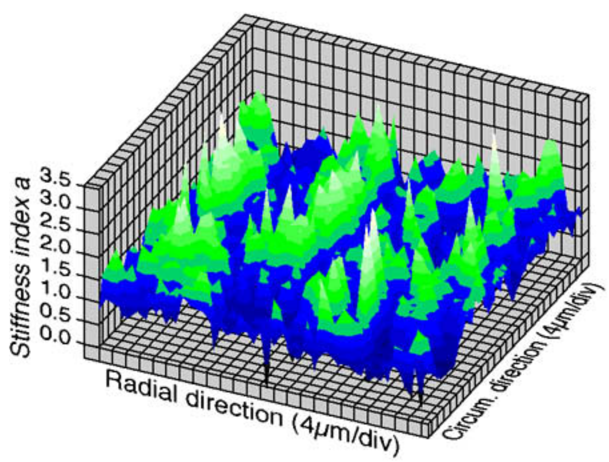
Rectangular specimens of 5 x 10 mm (2–3 mm thick) were excised from porcine descending thoracic aortas. Macroscopic residual stresses are removed during excision. Each of the specimens was embedded in an agar gel with low gelling temperature (30~31°C, Nacalai Tesque, Japan) and sliced with a tissue sectioner (Microslicer DTK-1500, Dosaka EM Co., Ltd., Japan) in the saline to obtain the surface perpendicular to the circumferential direction. The specimen with its bath was then mounted on the XY stage of the SMIT for the surface measurement.

Surface Topography and Stiffness Distribution

The surface of the section shows hill and valley pattern perpendicular to the radial direction (Fig. 2). The distance between the peaks and the peak height were ~25 and ~8 μm, respectively. The elastic modulus estimated from α was ~180 kPa at the peak and ~52 kPa at the bottom. On a separate study, we observed the change in thickness of EL and SML in response to radial compression of the whole wall and found that the elastic modulus of EL is 2.5 times higher than that of SML [3]. Thus, we suppose the hill must be EL and the valley SML, *i.e.*, EL may be compressed and SML stretched in the lamellar unit.



(a) Surface topography



(b) Distribution of stiffness index α

Figure 2. A set of data obtained with the SMIT for a section perpendicular to the circumferential direction of a porcine thoracic aorta. Measured area, 100μm×100μm.

ESTIMATION OF RESIDUAL STRESS AND STRAIN

Deformation of the cut surface following the slicing was analyzed with a 2D FE model as shown in Fig. 3. Circumferential–radial (θ–r) section was modeled under the plane strain condition. Following assumptions were made: 1) each layer is homogeneous and has uniform thickness before slicing; 2) EL is 6 μm thick and uniformly compressed, while SML is 22 μm thick and uniformly stretched before slicing; 3) EL and SML are linearly elastic with the elastic modulus of 180 and 50 kPa, respectively; 4) layers are connected to each other and nearly incompressible with the Poisson's ratio of 0.49; 5) the model is constrained in all directions at its bottom and in radial (horizontal in the figure) direction at both sides. Deformation and the stress and strain distributions following the slicing, *i.e.*, upon the release of constraints on the top surface, were obtained for various levels of residual stress and the model height. Analyses were performed with ABAQUS ver.5.8 (HKS, Inc.) at Center for Information and Media Studies, Nagoya Institute of Technology.

An example of the analysis is shown in Fig. 3. As observed in Fig. 2, EL became hill and SML valley. The peak height was one half of the measured value (4μm), although residual stresses applied to the model were much larger than those estimated to be in ring-like segments of the aortas in no load condition (~±10 kPa). Residual stress was fully released only in the region adjacent to the surface: more than 10% of the stress before slicing resides in the region deeper than 6μm from the surface. These results indicate that the lamellar unit may have large residual stress and/or shear moduli of EL and SML are much smaller than those estimated for homogeneous material.

CONCLUDING REMARKS

Fairly large stress may still reside in the opened-up segment, which had been believed to be stress-free. Microscopic viewpoint is necessary to reveal the mechanical environment of the smooth muscle cells in the aortic media.

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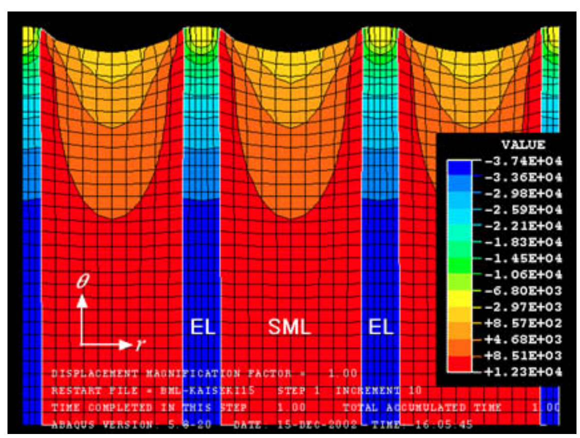

Figure 3. Deformation and distribution of the circumferential residual stress in a FE model after the release of constraints on the top surface (height, 60 μm; initial residual stress, -37.8 kPa for EL and 10.5 for SML; initial residual strain, -0.21 for EL and 0.21 for SML).