

RESIDUAL STRESS AND STRAIN IN THE LAMELLAR UNIT OF THE AORTA: EXPERIMENT AND ANALYSIS

Takeo Matsumoto, Taisuke Goto, and Masaaki Sato
Biomechanics Laboratory, Tohoku University, Sendai, Miyagi, Japan
For correspondence: takeo@biomech.mech.tohoku.ac.jp (T.M.)

INTRODUCTION

If one cut a ring-like segment of an aorta radially, it usually springs open to become an arc. It has been pointed out that this happens because circumferential stress in the aortic wall distributes uniformly in the radial direction *in vivo*, and as a result, the segment at no load has compressive residual stress near the inner wall and tensile near the outer. 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). Recently, we found that the EL is much stiffer than the SML (Goto, 2002). Thus, 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 differ. Such residual stress is not released fully by radial cutting, but is released in the area close to the cut surface, causing hills and valleys on the surface due to compressive and tensile stresses, respectively. In this study, we have developed a scanning micro indentation tester (SMIT) to measure the topography and the stiffness distribution of the cut surface, and estimated residual stress and strain in the lamellar unit.

SCANNING MICRO INDENTATION TESTER (SMIT)

It is a tester to measure the surface topography and stiffness distribution of a specimen surface by pressing a cantilever tip against the surface while scanning it like the atomic force microscope in the contact mode. The cantilever was made by pulling a micro glass plate of 65mm x 1mm x 0.15mm to make its tip diameter 3–5 μm and bending it at right angle at the point 4mm from the tip. The cantilever was driven by a PZT actuator and the displacement of its tip was measured with a laser displacement meter. The specimen bath was set on a motor-driven XY stage to scan the point of measurement. 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 formula E (kPa)= $1.88\exp(2.54\alpha)$ obtained by calibrating the tester with silicone elastomers with known elastic moduli.

MEASUREMENT OF SURFACE TOPOGRAPHY

Rectangular specimens of 5x10 mm (2–3 mm thick) were excised from porcine descending thoracic aortas. Macroscopic residual stresses are removed during excision. Each of the specimens was sliced with a vibrotome 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. The surface of the section shows hill and valley pattern aligned with the circumferential direction (Fig. 1). 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 and found that the elastic modulus of EL is 2.5 times higher than that of SML (Goto, 2002). 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.

ESTIMATION OF RESIDUAL STRESS AND STRAIN

The stress distribution required to restore the hill and valley pattern to the plane where the specimen was cut corresponds to the residual stress distribution. Such distribution was estimated on a 2D simplified model based on the data shown in Fig. 1. Following assumptions were made: 1) lamellar unit is made of two layers EL and SML with uniform thickness; 2) the thickness of EL and SML are 6 and 22 μm , respectively; 3) the height of each layer is uniform and the difference between the two is 8 μm ; 4) EL and SML are linearly elastic with the elastic modulus of 180 and 52 kPa, respectively; 5) residual stress is released upon cutting to the depth l_0 ; 6) shear stress and lateral deformations are negligible. To estimate the depth l_0 , thin slices with various thickness were removed from the surface with the vibrotome while measuring surface topography with the SMIT. The height difference between hills and valleys did not decrease unless the thickness was smaller than 70 μm . Thus, we roughly estimated l_0 to be 70 μm . The model analysis showed that the residual stress and strain increased with the decrease in l_0 , and that the residual stress is at least -10 kPa for the EL and 3kPa for the SML and the residual strain is at least -6% for the EL and 5% for the SML. These values are almost comparable to those estimated to be in ring-like segments of the aortas in no load condition. Fairly large stress may still reside in the opened-up aortic wall, which had been believed to be stress-free. Microscopic viewpoint is necessary when studying mechanical environment of the smooth muscle cells in the aortic media.

REFERENCE

Goto, T. et al (2002). *Proc 14th Bioeng Conf/JSME, in press.*

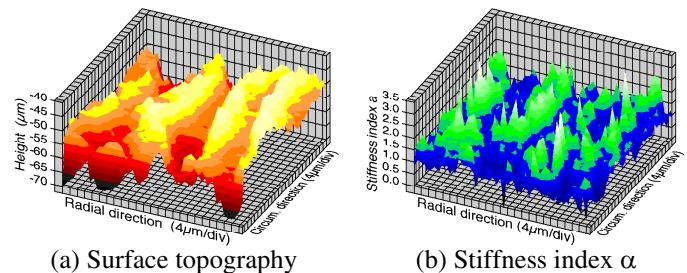


Figure 1: An example of data obtained with the SMIT for a section perpendicular to the circumferential direction of a porcine thoracic aorta. Measurement area, 100 μm x 100 μm .