Multilayer Quasi-Linear Viscoelastic Characterization of Porcine Aorta Using Nanoindentation

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ABSTRACT

In a wide range of applications from traumatic injury to stent grafts, the arterial wall has been considered as a homogeneous single-layer vessel, ignoring the fact that arteries are composed of distinct anatomical layers with different mechanical characteristics. The multilayer nature of arteries has an important influence in the development of mathematical models to predict large deformations and injuries such as Traumatic Aortic Rupture (TAR). Most test methods used for characterizing the mechanical properties of arteries are dealing with the macroscopic properties of vessels. Recently nanoindentation techniques have been used to describe the local material properties of various tissues including vascular tissues. In this study, using a custom-made nanoindentation technique, changes in the mechanical properties of porcine thoracic aorta wall in the radial, circumferential, and longitudinal directions were characterized using a quasi-linear viscoelastic model. Cylindrical samples (8-10 mm long) were extracted from fresh porcine aortas. Successive indentation tests were performed within the aorta wall with intervals of approximately 100 µm. Results were categorized based on the normalized radial distance, where $r = 0$ represented the innermost layer and $r = 1$ the outmost layer. Indentation tests included a ramp-and-hold profile (10 ms and 30 s, respectively with 40 µm amplitude) and the reaction force was measured with a load cell connected to the indenter and the instantaneous Young's modulus (E) and reduced relaxation function G(t) were calculated accordingly. The results of 300 points will be reported in this study. The results in the radial direction were categorized into 10 regions based on r. Hierarchical cluster analysis showed that the results could be divided into two different groups of inner and outer halves. Additionally, paired t-test showed this difference was statistically significant for E and G_∞ ($p<0.001$). Overall, comparison of E and G_∞ of the outer half (70.27±2.47 kPa and 0.35±0.01) versus the inner half (60.32±1.65 kPa and 0.33±0.01) revealed that the outer half was stiffer and showed less relaxation. Therefore, it can be concluded that $r = 0.5$ acted as a cut-off for the heterogeneity of E in the radial direction. The results are summarized as a multilayer viscoelastic material model which can be used to investigate local mechanisms of aorta deformation, force transmission, tear propagation and failure. Many instances of partial aortic rupture occur (about 10 to 20%) in which the outermost layer of aorta does not rupture and the chance of survival of the patient is significantly increased. Considering aorta as a pressure vessel, the inner layers are exposed to higher stress levels than the outer layers. The results of this study revealed that the inner layer is more compliant than the outer one. Therefore, it can be concluded that, based on only pressure loading, the inner layer would sustain higher strains and would be more vulnerable to failure. In other words, failure in aorta would propagate from inner layers toward the outer layers.