Mechanical Response of the Human Aorta to the Delamination at Different Loading Velocities

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Abstract: Our study deals with the delamination strength of the human aorta. Rectangular strips of the aorta were obtained from three different locations – ascending thoracic aorta, descending thoracic aorta, and abdominal aorta. Peeling experiments were designed to take into account possible effects of arterial anisotropy and a rate-dependent mechanical response. The peeling was carried out at four different loading rates: 0.1, 1, 10, and 50 mms^{-1}. The experiments carried out with samples received from the ascending thoracic aorta and from the abdominal aorta did not show significant effect of the velocity on the delamination strength. On the other hand, the results suggest that in the thoracic region descending aorta delaminates at significantly higher force when teared at 50 mms^{-1} in comparison with the delamination conducted at speed of 0.1 mms^{-1}. This result was found for both circumferential and longitudinal orientation of samples.

Keywords: aorta; crack; dissection; peeling; strength.

1 Introduction

Aortic dissection is a life-threatening disease manifested by a separation of the layers of the aortic wall [1–3]. It occurs most frequently in the thoracic part of the aorta, but it can spread along its entire length. Although aortic dissection is relatively rare disease, the incidence is typically reported as ranging from 3 to 6 cases per 100 000 per year, the lethality of the dissection is rather high. According to [4], 37% of patients who reach the hospital alive die within the next 30 days, and approximately 20% of patients die before they receive medical intervention [5].

Our study seeks to deepen knowledge of the biomechanics of aortic delamination by means of the experimental investigation of the delamination strength of the human aortas. The peeling experiment is used to this end. It is a basic instrument utilized to show how the delamination strength depends on the anatomical site, loading velocity, and crack tip direction.

2 Methods

Segments of human aortas were obtained during regular autopsies conducted in the Department of Forensic Medicine and Toxicology at the Regional Hospital Liberec. The post-mortem use of human tissue was approved by the Ethics Committee of the Regional Hospital Liberec. Rectangular samples, approx. 8×40 mm, were cut from aortic segments. These segments were excised from the ascending as well as descending thoracic

aorta, and from the abdominal aorta. Rectangular samples were cut, aligned with both the longitudinal and circumferential direction of the vessel.

A method adopted to characterize the delamination properties of the aorta is the so-called peeling test. This experimental protocol was, in the context of the biomechanics of the aortic dissection, introduced by Sommer et al. in 2008 [1] and has been used in further studies focused on the delamination properties of arteries [6–8]. It resembles the mode I crack opening that is widely used in fracture mechanics, see Fig. 1.

The experiments were carried out with the help of the multipurpose tensile testing machine Zwick/Roell (Messphysik). Both the delamination force F (the force that is necessary to increase a tear length) and the tear length were recorded on a PC. The delamination force was measured by HBM U9C +/- 25N force transducers. The tear length was determined from the movement of the clamps, which was recorded at 1 μm resolution. This data was complemented with the recordings carried out by a built-in video-extensometer, which measured the distance between the marks made on the surface of the samples. To determine whether delamination strength depends on loading rate, the experiments were carried out with clamps' velocity set to 0.1, 1, 10, 50 mms^{-1}.

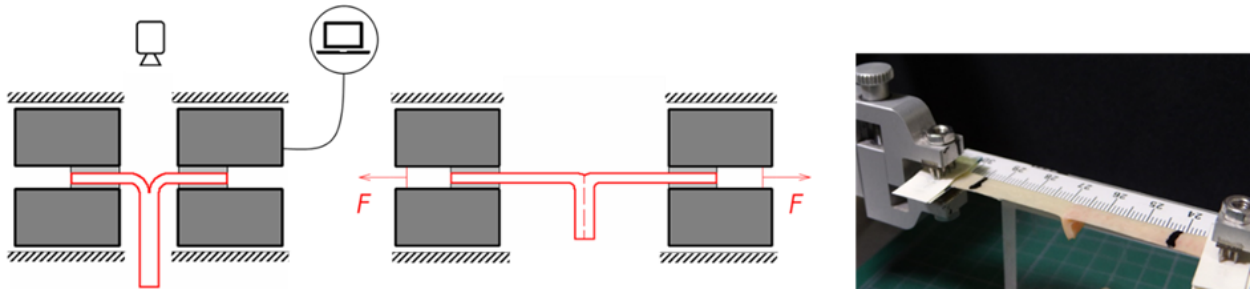

Fig. 1: Left panel illustrates the peeling experiment in which the force necessary to extend the crack that delaminates arterial layers is recorded. Right panel shows delaminated sample.

3 Results and discussion

Total number of conducted peeling experiments was 463. It consists of strips that were cut from 21 cadavers at three anatomic locations (thoracic ascending and descending, and abdominal) with two orientations (longitudinally and circumferentially) for peeling experiments carried out at four different speeds (0.1, 1, 10, and 50 mms^{-1}). This results in average number of 19 samples in each experimental group.

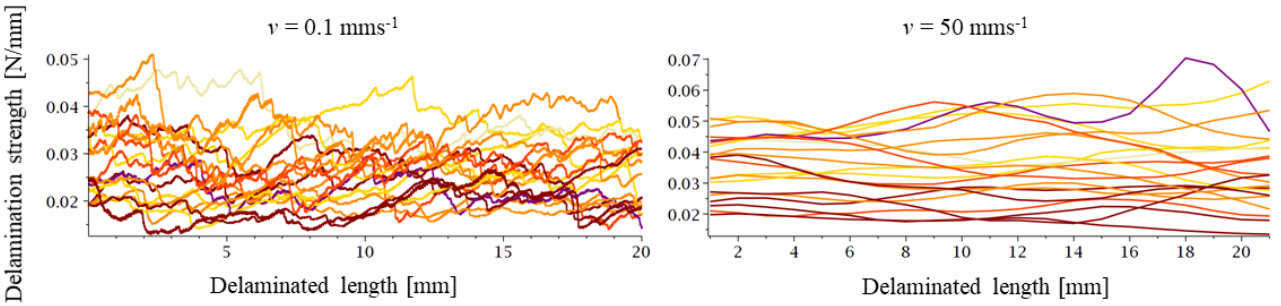

Fig. 2: Left panel depicts force-displacement relationships recorded in the peeling experiments carried out with longitudinal samples of the human descending thoracic aorta at the clamps' speed 0.1 mms^{-1} whereas records obtained at 50 mms^{-1} speed are depicted in the right panel. The sampling rate of 20 Hz was used in both cases which explains why the left panel shows curves exhibiting significant oscillations whereas the right panel shows rather flattened curves. Results are presented for 20 mm of the delamination length (distance through which a crack propagated).

Fig. 2 depicts examples of records obtained in the peeling experiment. Left panel in Fig. 2 shows delamination force as a function of a crack length how it was determined at slow loading velocity (0.1 mms^{-1}), whereas the right panel depicts responses obtained at the highest speed of clamps (50 mms^{-1}). Both records correspond to data obtained in the descending thoracic aorta where delamination strength seems to be depending on loading rate.

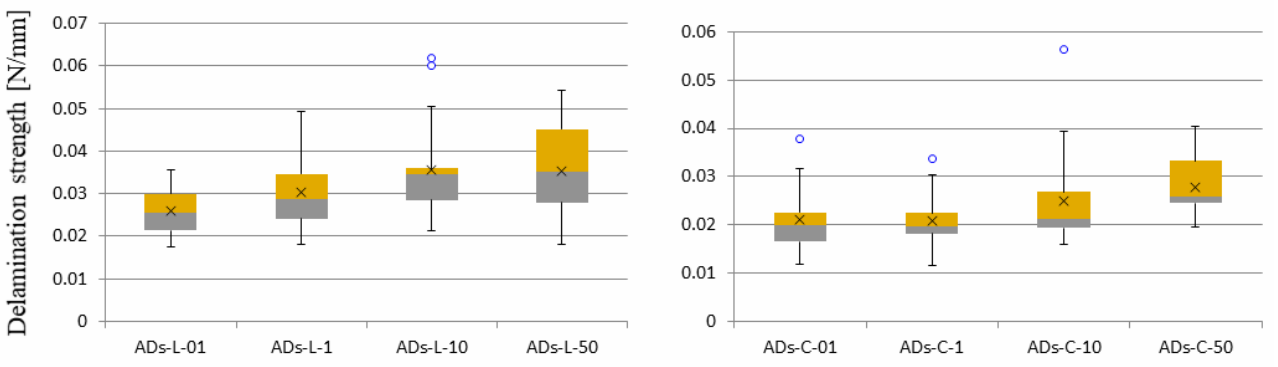

Fig. 3: Box plots of medians of the delamination strength determined with longitudinal samples (left panel) and with circumferential samples (right panel). In both longitudinal and circumferential response, 0.1 ms^{-1} differs significantly from 50 mms^{-1}.

To be more specific, neither ascending thoracic samples nor samples excised form abdominal aorta did show a dependence on the loading rate. On the other hand, results recorded in experiments conducted with samples from descending thoracic aorta show statistically significant differences in average delamination strength. Fig. 3 documents it in the box plots. The left panel shows results for longitudinal samples and the right panel contains results determined with samples oriented circumferentially. Data were evaluated by means of analysis of variance in the form of Kruskal-Wallis test which was followed by Dunn test to determine pairwise differences. Their results confirmed that medians in case of longitudinally oriented samples groups differ significantly (Kruskal-Wallis $p < 0.01$), and that delamination strength obtained at 0.1 mms^{-1} differs from the strength measured at 10 mms^{-1} (Dunn test $p < 0.01$), and at 50 mms^{-1} (Dunn test $p < 0.01$), and that also response at 1 mms^{-1} differs significantly from 10 mms^{-1}. Differences computed for 1 mms^{-1} and 50 mms^{-1} were at the border (p = 0.055). In the circumferential response, significant differences were determined in 0.1 mms^{-1} vs. 50 mms^{-1} (Dunn test $p < 0.01$), 1 mms^{-1} vs. 50 mms^{-1} (Dunn test $p < 0.01$), and in comparison between 10 $mms^{-1}$and 50 mms^{-1} (Dunn test $p = 0.04$).

4 Conclusions

Present contribution delivers preliminary results of our project that deals with the delamination strength of the human aorta. In this project, our goal is to evaluate anisotropy, inhomogeneity, age-related changes, and loading rate dependence in the peeling properties of the aorta. In this article, an effect of the loading velocity is the main subject. This effort is justified by a fact that general mechanical response of our arteries is viscoelastic thus it cannot be rejected with experimental confirmation that viscous or rate-dependent effects play a role in a propagation of discontinuity.

Our data suggests that delamination strength may depend on the loading velocity. However, this effect seems to be site specific. Neither ascending thoracic samples nor samples excised form abdominal aorta did show a dependence on the loading rate. On the other hand, results recorded in experiments conducted with samples from descending thoracic aorta show statistically significant differences in average delamination strength.

It is not clear at present, why different results at different anatomical sites were obtained. Further research is needed to elucidate it. One possible explanation could arise in microstructural observations. Especially quantitative histological studies could be helpful to this end. This is our plan how we would like to continue in our research.

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