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Diameter-Related Variations of Geometrical, Mechanical, and Mass Fraction Data in the Anterior Portion of Abdominal Aortic Aneurysms

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WHAT THIS PAPER ADDS

Irreversible dilation of abdominal aortic aneurysms (AAAs) results in larger aortic diameters. The present study investigates variations of AAA data with increased AAA diameter. Patient specific geometrical, mechanical, and biochemical data were analyzed and correlated with relevant maximum AAA diameters, which are reported for the first time in the literature. For geometrical parameters, maximum intraluminal thrombus thickness, wall thickness, and AAA expansion rate were measured and showed changes of AAA geometries for different diameters. Biomechanical investigations focus on biaxial responses and dissection properties of AAA tissues that play a key role in aneurysmal development and rupture. Biochemical tests quantify dry weight percentages of elastin and collagen within the AAA wall, which are closely related to the tissue microstructure. The present findings may advance understanding of the effects of AAA enlargement on patient specific vascular tissue properties.

Objective: Maximum aortic diameter is an important measure in rupture prediction of abdominal aortic aneurysms (AAAs). Analyzing the variations of geometrical, material, and biochemical properties with increased AAA diameters advances understanding of the effect of lesion enlargement on patient specific vascular properties.

Methods: 96 AAA samples were harvested during open surgical aneurysm repair. Geometrical factors such as the maximum intraluminal thrombus (ILT) thickness, wall thickness, and AAA expansion rate were measured. Biaxial extension and peeling tests were performed to characterize the biaxial mechanical responses and to quantify the dissection properties of aneurysmal tissue. Mass fraction analysis quantified the dry weight percentages of elastin and collagen within the AAA wall. Linear regression models were used to correlate geometrical, mechanical, and mass fraction data with maximum AAA diameter.

Results: Both ILT thickness and AAA expansion rate increased and were positively correlated with maximum AAA diameter, while there was a slight increase in wall thickness for AAAs with a larger maximum diameter. For the biaxial mechanical responses, mean peak stretches and maximum tangential moduli in the circumferential and longitudinal axes did not correlate with maximum AAA diameters. However, the quantified energy to propagate tissue dissections within intima-media composites showed a significant inverse correlation with maximum AAA diameter. Elastin content decreased significantly with increasing AAA diameter.

Conclusion: Larger AAA diameters are associated with thicker ILTs, higher AAA expansion rates, and pronounced elastin loss, and may also lead to a higher propensity for tissue dissection and aneurysm rupture.

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INTRODUCTION

An abdominal aortic aneurysm (AAA) is a localized and irreversible dilation of the aorta.[1,2] The pathogenesis of AAA, which involves a complex series of events, has not yet been fully clarified.[3] Continuous AAA growth may lead to wall rupture, a catastrophic event frequently associated with high mortality and serious life threatening morbidity if not addressed.[4—6] Currently, no technique or criterion available can provide a reliable patient specific prediction of the AAA rupture risk. Typically, patients with an AAA diameter ≥5.0 cm in women and ≥5.5 cm in men undergo surgical repair.[7—9] However, this "maximum diameter

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criterion" is unreliable, as indicated by previous studies.[8–11] In particular, it neglects the potential rupture risk for smaller AAAs.[12]

Rupture of an AAA occurs when the peak wall stress exceeds the local wall strength at any location. A refined understanding of the biomechanical properties of vascular tissues during AAA pathological progression may help to better explain the rupture mechanism due to tissue growth and remodeling from a biomechanical point of view. As AAA dilation is irreversible, there is a need to investigate the changes in the material properties of AAA tissues with respect to continuously increasing diameters. Such correlations re-evaluate the role of the maximum AAA diameter criterion in clinical rupture risk assessment.

The aim of the present study was to investigate how patient specific (mechanical and biochemical) properties vary with the maximum AAA diameter in patients before surgery. In particular, for individual AAA samples the maximum intraluminal thrombus, wall thicknesses and AAA expansion rate were measured and correlated with the maximum AAA diameter. The biaxial mechanical responses and the dissection properties of AAA tissue were determined quantitatively in order to investigate variations in biomechanical conditions in the aneurysm. Finally, dry weight percentages of elastin and collagen within the AAA wall were identified for different AAA diameters.

MATERIALS AND METHODS

Material

96 patients (mean age 70 ± 12 years) who underwent open surgical aneurysm repair from November 2008 to November 2012 at the clinical department of vascular surgery, Medical University of Graz, Austria were included. Use of the material was approved by the ethics committee of the Medical University of Graz. All samples, including intraluminal thrombi (ILTs) and thrombus covered walls, were harvested from the anterior part of the aneurysm (for the particular location see the sketch in Di Martino et al.[13]). The samples were stored in Dulbecco's Modified Eagle's Medium within the operating room immediately after retrieval. Biomechanical analysis was performed without delay after transport to the biomechanics laboratory at Graz University of Technology. The mean duration from storage to test was 2 ± 1 hours.

Geometrical factors

Computed tomography angiography protocol. Computed tomography angiography (CTA) examinations were undertaken on a 128 row dual source CT scanner with the patient in the supine position during a single breath hold (SOMATOM Definition AS; Siemens Healthcare, Munich, Germany). The scanning parameters were as follows: slice thickness 2 mm, increment 1.5 mm, tube voltage 100–120 kV. For contrast enhanced CTA a bolus of 100 mL non-ionic iodinated contrast medium (Iopromidum, Ultravist 300, 300 mg iodine/mL; Bayer Schering Pharma, Berlin, Germany) was injected intravenously (4 mL/second) via an 18 gauge catheter placed in the antecubital vein followed by 40 mL saline flush. Multiplanar reconstruction images of the abdominal aorta were routinely produced in the axial, sagittal, and coronal planes with 2 mm slice thickness. All image data sets were stored on the picture archiving and communication system.

CTA analysis. Dual energy data were post-processed on a workstation (Multimodality Workplace, Siemens Healthcare) running Syngo software (version VA 11; Siemens Healthcare). Diameters were measured from the outer to outer wall of the aneurysm using electronic calipers with a zoom function by a single experienced observer. The maximum diameter of the infrarenal aorta was measured as the maximal external cross sectional measurement in any plane using electronic calipers at right angles to the image slices using a set protocol on the workstation, as described in the literature.[14]

AAA expansion rate. The AAA expansion rate, defined as an increment of the maximum transverse AAA diameter per year, was obtained from consecutive CTA scans, as described above, measuring at the correlating aortic level, as identified by the neighboring anatomical structure (i.e., vertebrae, ribs). The difference between consecutive CTA examinations was divided by the interval between CT scans (minimum of 12 months) and growth described as mm/year. As the growth rate was not part of a standardized measurement and follow up protocol, no data from sequential ultrasound investigations were included.

Wall and ILT measurements. The maximum ILT thicknesses were measured at three different locations of the thickest part for each ILT sample and then averaged. The mean thickness of the thrombus covered wall was measured by a PC controlled video extensometer with a full image charge coupled device camera (for details of the measurement protocol see the studies by Sommer et al.[15] and Tong et al.[16]).

Biomechanical tests

Biaxial extension tests were performed to characterize the mechanical responses of the intact thrombus covered wall at the applied (engineering) stress of $P_{\theta\theta} = P_{LL} = 150$ kPa. Details of the specimen preparations and the experimental protocol for biaxial extension tests have been described in a previous study.[17]

Peeling tests quantitatively determine the energy required to propagate a dissection within a tissue.[16] Rectangular strips were cut with a uniform dimension of 18.0 × 6.0 mm (length × width) and further given an initial cut (incision of about 2.0–3.0 mm in length) using a surgical scalpel in order to better control the initiation of the tissue failure. Subsequently, two "tongues" were obtained and mounted onto a PC controlled, screw driven, high precision tensile testing device. The tests were executed in phosphate buffered saline solution at 37.0 ± 1.0 °C and the extension