Mechanical characterization of Ascending Thoracic Aortic Aneurysms using 4D Ultrasound

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Introduction

Ascending Thoracic Aortic Aneurysms (ATAA) are a hazardous, asymptomatic condition that can lead to a life-threatening haemorrhage when ruptured.

Criteria for intervention planning relies currently on the maximum diameter (≥ 5.5cm) and growth rate (≥ 0.5cm/year), however, these criteria have proven to be inadequate. Therefore, the state of the aortic wall, i.e., the mechanical properties of the wall, could be a better predictor for rupture risk. **In this study the mechanical properties of the aortic wall are characterized using 4D (3D+time) ultrasound (US) *in vivo* and verified by bi-axial tensile testing *in vitro*.**

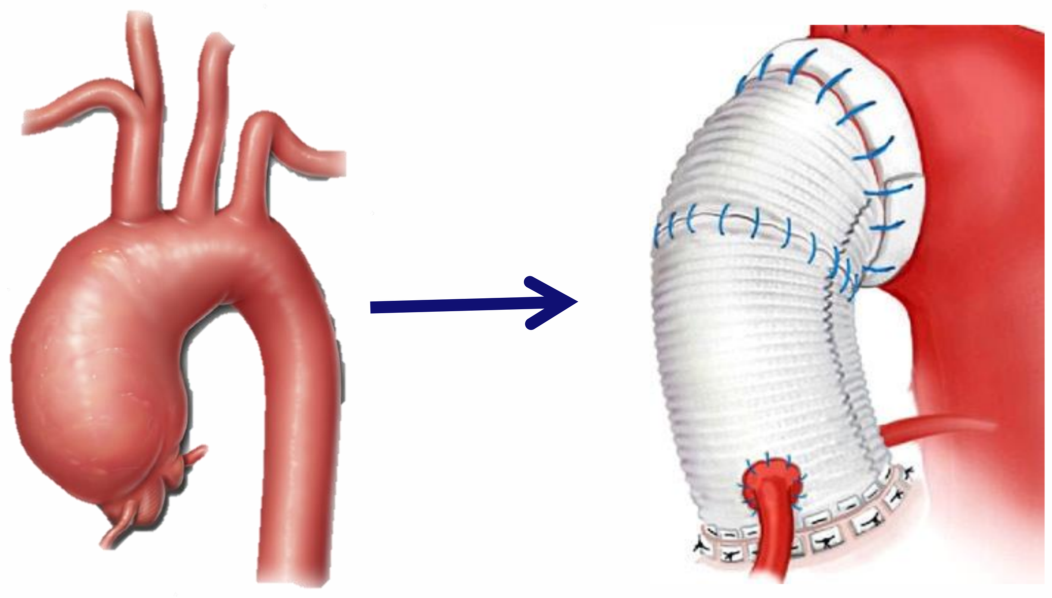


Figure 1: Human aorta with an aneurysm in the ascending aorta (left); Graft replacement of the aneurysm by a Bentall operation (right).

Methods

For 7 ATAA-patients 4D US data and intraluminal pressure were simultaneously captured perioperatively. The US data and pressures were the input for a finite element (FE) model and an elastography approach which both estimate the elasticity of the arterial wall.

Segmentation:

The 4D US data were segmented manually at end-diastolic and end-systolic pressure. After smoothing, the segmentation was used to obtain a mesh with in total 30.000 - 75.000 tetrahedral volume elements.

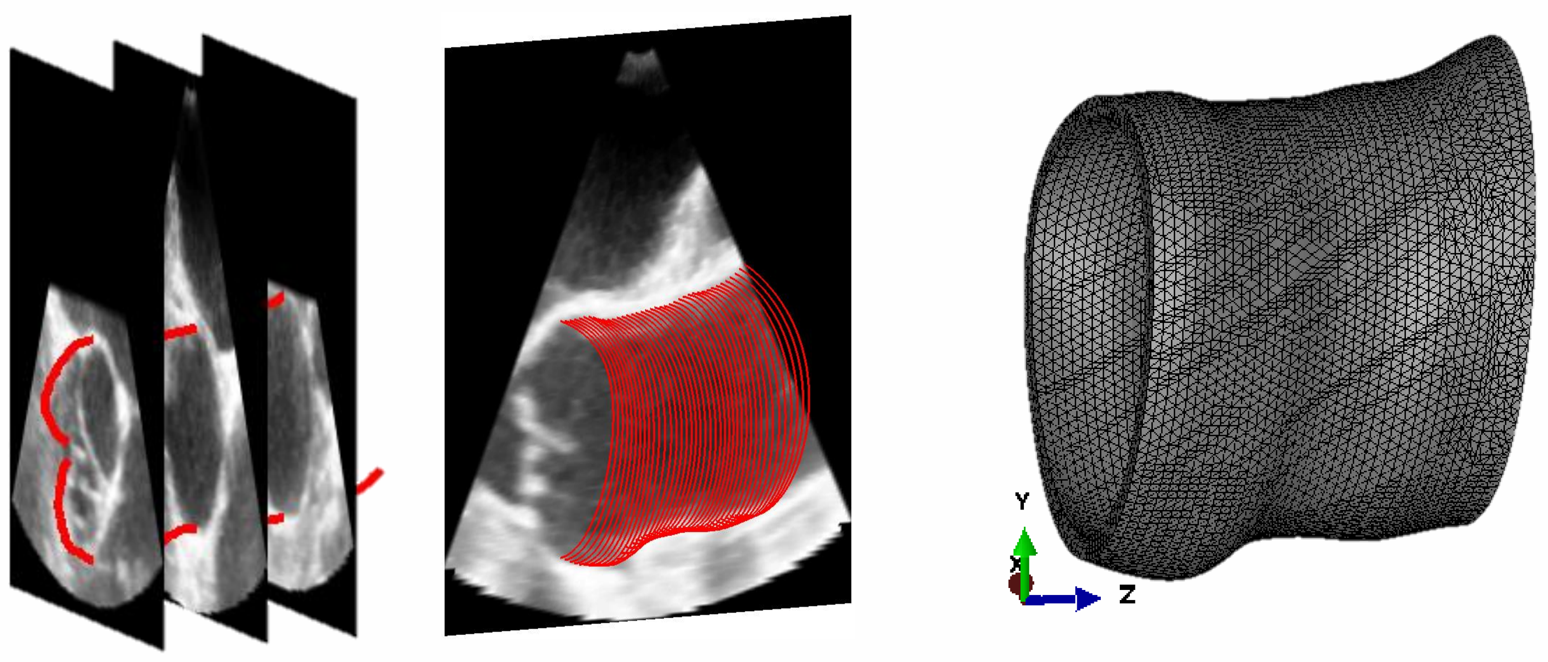
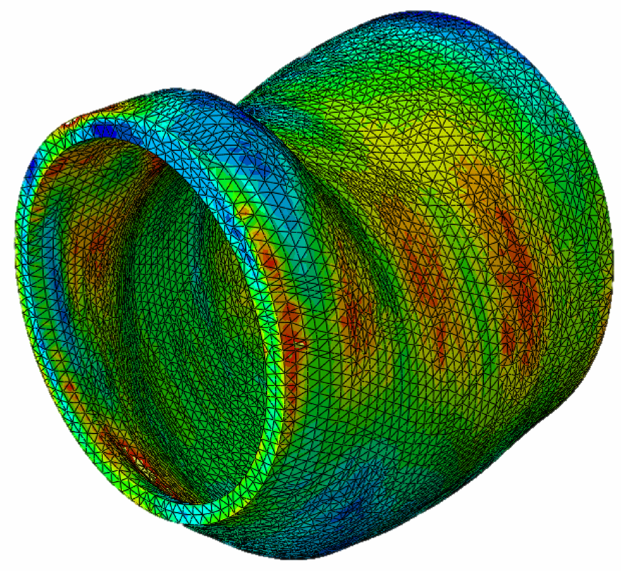


Figure 2: Result of manual segmentation after smoothing (left and middle), and the corresponding mesh is shown (right).

Material model:

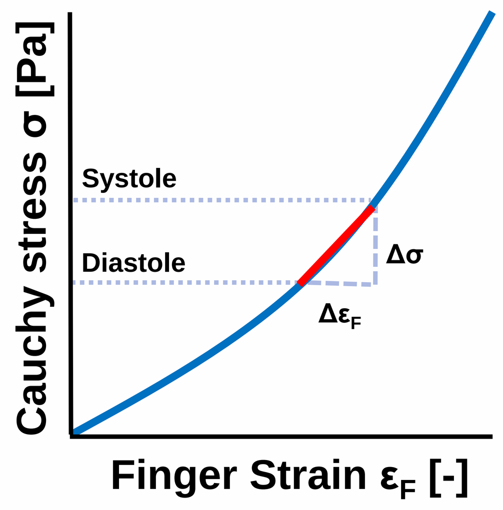
An incompressible Neo-Hookean model with an initial guess for the shear modulus is used to describe the arterial behavior for the pressure range present.

Finite Element Modeling:



In order to determine the initial stress at diastolic pressure, a backward incremental method is prescribed.

Finally, the shear modulus (**G_{FEM}**) is adjusted and optimized by a Gauss-Newton method until the displacements estimated by the FEM, resembled the displacements in the US data.

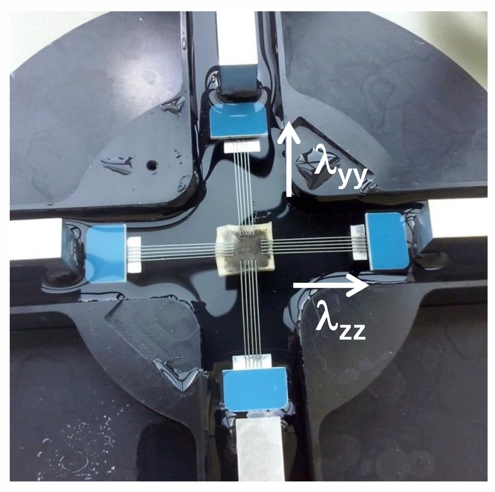


Elastography Approach:

Secondly, in a more direct, elastography approach, the geometrical data and pressure were used to estimate shear modulus (**G_{ELASTO}**) directly, using LaPlace's law.

Bi-axial Tensile Testing:

The diseased aortic tissue was collected after graft replacement surgery and verification of the *in vivo* characterization was performed *in vitro* using biaxial tensile tests. An axial pre-stretch of 1.25 was applied to samples of aortic tissue, and was subsequently stretched to 1.45 to capture the total stress-strain behavior. Finally the corresponding shear modulus (**G_{TT}**) was calculated.



Results

The results of this study showed a good agreement between the two *in vivo* US-based methods (Fig. 3), and characterized a mean incremental shear modulus of G_{FEM}=227±98 kPa and G_{ELASTO}=231±98 kPa.

Comparing the *in vivo* US-based methods with the *in vitro* verification showed a good agreement for 5 out of 7 patients.

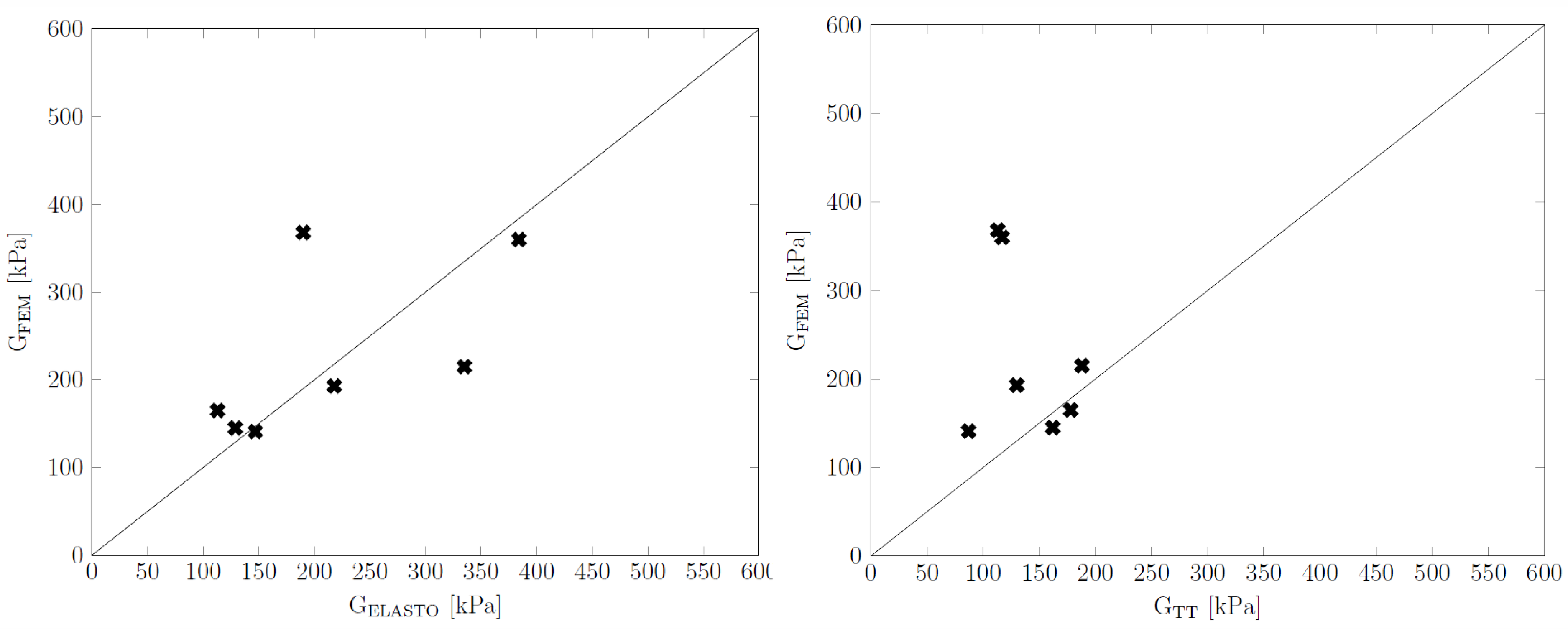


Figure 3: Incremental shear modulus of FEM vs. Elastograhy (left); Incremental shear modulus of FEM vs. Biaxial tensile tests (right).

Future work

The future work of this study is to include more patients and compare the results of this study with healthy volunteers to relate the material properties of the ATAA to the progression of the disease towards rupture.

Increasing the complexity of the material model will also be considered.