Finite-element-assisted design of a bulge inflation experiment to reproduce the anisotropic in-vivo tensions in the ascending aorta

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Abstract

Introduction
Cardiovascular pathologies involving mechanical damage or rupture of the ascending aorta such as aneurysms or dissections are one of the most prevalent cause of mortality, affecting 5 out of 100 000 individuals/year (1). These events are driven by patient-specific mechanical and anatomical factors (degraded wall strength and cohesion, anatomy of the aortic arch) combined with an acute stressor often related to blood hypertension. In order to evaluate the risk of rupture for a given patient, a first step consists in quantifying the critical pressure at which the tension in the tissue overcomes the wall's strength. Previous studies (2) showed how the ultimate wall tension at failure can be determined by inflation experiments on fresh excised tissue (e.g. elective thoracic aneurysm surgery). In (2) and others, a circular ring was used for holding the tissue during the inflation. However, in order to obtain an accurate experimental model of aortic rupture, the bulge inflation test could be better designed if it reproduced more closely the anisotropic tension field of the pressurized aortic arch. Here we propose a numerical approach to design the shape of the ring that will reproduce the tension computed from a medical image and arterial pressure for a given patient.

Methods

We start with gated CT-scans of the patient obtained together with arterial pressures, at systole and diastole. Using inverse membrane elastostatics (3), the three components of the in-plane tension field at systole and diastole can be estimated despite the ignorance of the patient-specific constitutive behavior of the wall.

Next, a parametric Finite Element (FE) quarter model of the bulge inflation test was built in Python using the FenicsX library (4). The patch of tissue is described by a superellipse, so that its shape is controlled by the following parameters: radius along the x and y directions and roundness. These parameters effectively constrain the design of the clamping ring of the experimental setup. The sample is meshed with hexahedral 3D elements. A mixed

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formulation is used with Q2 (displacement) and P1 (pressure) elements to enforce incompressibility. A hyperelastic material with an GOH strain energy function (5) is used. The outer clamped surface was fixed, and a pressure was applied to the bottom surface until the circumferential tension reached the systolic value. A Newton solver was used to compute the displacement field, from which the 1st Piola-Kirchoff stress field was obtained. This stress field was integrated along the thickness to obtain the tension field.

Although the resulting tension field is mostly determined by the pressure, it is also weakly related to the constitutive behavior of the material. This influence becomes stronger when the membrane assumption becomes invalid, for instance for small patches of tissue when the radius cannot be considered as much larger than the thickness. Because the patient-specific constitutive data is not known a priori, we compute the response for 12 sets of constitutive parameters, representing the expected variability of the tested tissue (6).

Finally, an optimization procedure was used to find the set of shape parameters for the ring of the inflation experiment that minimizes the difference between the components of the tension field at the apex of the sample and the patient-specific tension in the right lateral wall of the ascending aorta obtained from medical images.

Results

The design procedure was demonstrated for a given clinical case. The tensions computed from the CT-scans were found to be anisotropic with a circumferential-to-axial ratio of 2.17 (diastole) and 2.25 (systole). The optimization procedure was able to converge to values close to this reference: 2.04 (diastole) and 2.38 (systole). The final ring shape had an elongated shape: the radii were 12 (axial) and 37 (circumferential) mm and the ring shape was close to an ellipse.

Discussion and conclusion

This study introduces a method to design a bulge inflation test that replicates the anisotropic tension field in the aortic wall, from a given patient-specific CT scan. Rapid prototyping could be used to quickly manufacture these rings, enabling patient-specific experiments.

The interest of this method lies in the fact that model assumptions like constant tissue thickness and the choice of constitutive parameters have limited influence on the final result due to the mechanical equilibrium between wall tension and pressure. Still, the stiffness ratio of the tissue between the circumferential and axial directions does influence the tension ratios to some extent. This stiffness ratio could be estimated clinically by extensibility measurements. Constraints could be added to the optimization procedure to restrict the sample area to the amount of available excised tissue.

This approach is a first step towards the development of an experimental model of aortic dissection with the aim of characterizing how the microstructure and existing medial defects affect the mechanical resistance and cohesion of the aortic wall, and how this impacts the critical pressure.

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