Mechanical Characterization of the Porcine Atrial Appendage Under Uniaxial Tension

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Abstract

1. Introduction

Stroke is the third leading cause of mortality in France and the leading cause of acquired disability (Al-Saady et al., 1999). About one-third of strokes are linked to atrial dysfunction, particularly atrial fibrillation (AF). AF often leads to thrombus formation in the left atrial appendage (LAA) due to blood stasis, caused by the irregular shape and trabeculations of this anatomical structure. Recent therapies, such as LAA closure, aim to prevent AF-related strokes, highlighting the importance of understanding its mechanical behavior and material properties.

Finite element (FE) models have been used to study the LA's mechanical response during AF, often assuming homogeneous wall properties and constant thickness (Zhang et al., 2008). However, to the authors' knowledge, only a few studies report experimental data on the LAA's tensile properties (Bellini et al., 2012; Di Martino et al., 2011; Javani et al., 2016; Jernigan et al., 2007). While hyperelastic models effectively capture the non-linear stress-strain behavior, there is no consensus on the most suitable constitutive model for this tissue. Approaches range from isotropic models like Neo-Hookean and Mooney-Rivlin to anisotropic models such as Holzapfel-Gasser-Ogden (HGO) and Fung SEFs, each reflecting different assumptions about the LAA's complex structure and function.

The goal of the current study is to characterize the mechanical behavior of the atrial appendage under uniaxial tension. In this context, the aim is to understand relationships between the global mechanical response of the tissue and its meso-scale architecture (trabeculations) and underlying microstructure.

2. Methods

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2.1 Uniaxial testing

Uniaxial tensile tests were conducted on n=96 samples taken from 24 fresh adult porcine hearts. Four samples were extracted from each heart (two per appendage: one proximal and one distal from the atria) with a square region of interest (ROI) of 15mm edge. The heterogeneity of each sample's geometry was analyzed through a 3D scan. Half of the samples were tested in the longitudinal direction (i.e. along the trabeculae's orientation) and the other half in the transverse direction. Experiments were conducted in a saline bath using a biaxial tensile machine equipped with a 20 N force sensor (Futek LSB205, 5lb). Two cameras (Alvium 1800 U-811, 8.1 MP) with macro lenses were positioned with a stereo angle of 20 to 25 degrees. Stereo digital image correlation (s-DIC) analyses were performed. A speckle pattern was sprayed using black paint to track the displacement field, which was computed with the software VIC 3D. The samples were subjected to 9 preconditioning cycles up to 35% strain, at a strain rate of 1%/s. Force, jaw displacement, and images were acquired at a frequency of 10Hz during a final 10th cycle.

2.2 Data analysis

The 1st Piola-Kirchhoff (PK1) stress was calculated as the ratio of the reaction force to the initial average cross-sectional area of the specimens. The engineering strain was defined as the ratio of the imposed displacement to the initial clamp-to-clamp distance.

An average stress-strain curve was calculated from the individual curves. The results were compared to the literature.

Left and right appendages were compared as well as proximal and distal samples. The anisotropy was quantified by comparing the mechanical responses of the samples tested in the longitudinal and transverse direction.

FE models were built in FEBio using the specific sample scans and the tensile experiments were reproduced. The local distribution of the strains in the numerical model was compared with the DIC data for a better understanding of the tissue heterogeneity on the mechanical response.

3. Results and discussion

Fung, HGO and second order Mooney-Rivlin models provide satisfying results when fitting the PK1 stress-strain curve of the FE models. In contrast, the Neo-Hookean model is less adapted to reproduce the strain-stiffening behaviour of this tissue.

These preliminary results demonstrate the capability of our tensile test set-up to characterize the mechanical response of the LAA tissue under uniaxial tension as the results are comparable with literature. The present work provides an overview of the variability in results obtained from experimental studies on LAA tissues. This variability can be attributed to the complexity of the tissue, including variations in its geometry and composition. Future studies will help clarify the extent to which these two factors impact the tissue's mechanical response. Sensitivity analyses will be conducted to explore the effect of the two following sources of uncertainty on the mechanical response of the LAA:

Orientation of the tissue. Characterizing the multiscale fibrous architecture of this tissue (trabeculae, muscular fibers, and collagen fibers) using micro-computed tomography would give insights on the structural organization of the tissue and enable to link it to the global mechanical behaviour.

Dimensions of the samples. The LAA exhibits significant geometrical heterogeneity. Accurately characterizing local thickness through the 3D scans will help explain variations in local strain and stiffness resulting from geometric factors.

4. Conclusions

This preliminary study highlights a notable disparity in the experimental characterization of the LAA's mechanical behavior. This tissue presents numerous experimental challenges, requiring an adapted protocol considering its heterogeneity and anisotropy. Enhancing our comprehension of the mechanical properties of the LAA is essential for developing predictive numerical models. Future work will address lack of available data in existing literature regarding pathological human LAA by performing biaxial tests on fresh tissues.

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