High-Resolution Characterization of Deformation and Material Parameters In Vein Specimens

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Introduction:
Information of vein mechanics has many bioengineering applications. For instance, the design of artificial blood vessels (like arteriovenous grafts for hemodialysis) often requires the grafts to mimic the behavior of the native tissue, as well as the characterization of vein deformation due to interventions. While arterial mechanics are well understood, many aspects of vein mechanics remain to be explored. This study presents a novel pipeline for tissue response characterization by combining high resolution imaging via micro computer tomography (micro-CT) and image registration via hyperelastic warping [1] to measure local deformation of a vein specimen under physiological loads. The strain tensor is defined across the entire vein's geometry, which may contain complex anatomical features including non-uniform wall thickness, valves and bifurcations. Using strain information, the material properties of the tissue may be approximated by the optimization of a Finite Element (FE) simulation.

Materials and Methods:
A micro-CT compatible, hydrostatic pressure loading testing apparatus was built to image a freshly excised abdominal porcine vein (Fig 1., top panel) under two physiological loads: 0 and 30 mmHg. An Iodine-based staining protocol was optimized to obtain good contrast, while preserving the tissue [2]. Volumetric images of the stained vein sample acquired at a resolution of 17 microns were segmented to construct an FE mesh (Fig 1., center panel). Strain measurements via Hyperelastic Warping were obtained using two separate material parameter sets derived from aortic and saphenous vein tissue, respectively. The material parameters in a forward simulation, i.e., deforming the FE mesh with experimentally obtained boundary conditions and loads, were optimized to match the strain measured with Hyperelastic Warping, thus providing an estimate of the tissue constitutive behavior.

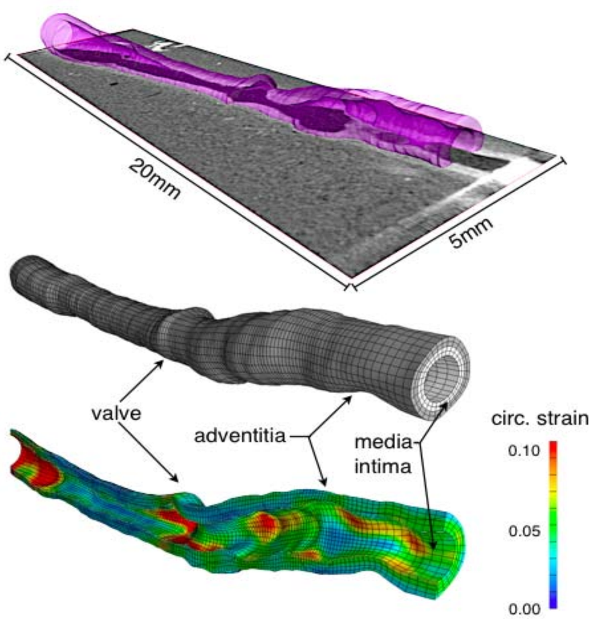

Figure 1. Top: volumetric information from segmentation. Middle: FE mesh showing bilayers and anatomical features of the vein sample. Bottom: circumferential strain from hyperelastic warping.

Results and Discussion:
In this application, the best tissue contrast with insignificant shrinking was obtained using 10% Lugol solution and a 3-hour soaking duration. The strains obtained from Hyperelastic Warping showed very little changes despite of material parameter variation (Fig 2., bottom panel). This consistency of results indicates that strain results depend mainly on image data, which reflects tissue response under load. The inverse problem provided quantifiable characterization of the abdominal porcine vein sample, which appeared to be stiffer than cardiac sinus tissue but less stiff than saphenous vein.

Conclusions:
A method for high-resolution strain measurements in vein specimens was presented demonstrating its potential application on material characterization. The iodine treatment resulted in stable contrast during imaging, which provided data with sufficient quality for segmentation and image registration. This pipeline shows promise for regional tissue characterization under different loads, tissue treatments, and geometries.

Acknowledgements:
Thanks to the Musculoskeletal Research Labs, and the Scientific Computing and Imaging Inst. at the University of Utah.

References: [1] Rabbitt R, et al. Proc SPIE (Vision Geometry IV), 1995; 2573:252 [2] Degenhardt K, et al. Circ Cardiovasc Imaging. 2010; 3(3):314-22