MEASUREMENT OF HIGH STRAIN TENSILE FAILURE PROPERTIES OF CAROTID PLAQUE EMBOLUS ANALOGS

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Introduction

Acute ischemic stroke is a leading cause of death and morbidity [1]. Recent studies suggest that, in addition to embolus morphology, their mechanical properties contribute to complications in clot removal procedures [2,3]. In addition, thrombus low strain properties are well documented, and computational work has modelled the clot as a viscoelastic material [5,6]. High strain behaviour has yet to be characterized and is important to understand the high strain load profile of clots during mechanical thrombectomy. The goal of this project is to characterize the high strain tensile properties of carotid blood clot analogues and compare the results to a finite element, hyperelastic computational model.

Methods

Embolus analogues (EA) were created using human blood, following approved IRB protocols, with preliminary work done on bovine blood (IACUC approved). Briefly, extracted whole blood was anticoagulated with 0.32% wt. sodium citrate. Blood was separated via centrifugation and reconstituted to 214 x 10^6 platelets per mL and 40% vol. haematocrit. Blood was recalcified with 20 mM calcium chloride ($CaCl_2$) and 0.1 NIH Unit/mL thrombin from human plasma (BioPharm, Bluffdale, UT, USA). Carotid plaque samples were formed with an addition of 0.1 mg/mL human collagen Type 1. Recalcified blood was mixed and injected into "dog bone" tensile moulds with 16 mm length gauge section, following ATSM D638 standards, and allowed to coagulate at 37°C for 1 hour.

Once EAs were formed, the samples were attached to custom grips on a uniaxial load frame (Instron, Norwood, MA, USA) with a 5 N load cell. Once mounted, the specimen was loaded at a rate of 10% strain per second (based on sample gauge length) until sample fracture. From these data, a linear polynomial was fit to the curve prior to fracture to compute the modulus. The peak stress and strain were recorded. All samples were embedded in paraffin wax for histology and stained with a standard Carstairs protocol. All data analysis was performed using MATLAB's statistics toolbox (Mathworks, Natick, MA, USA).

To simulate the experiment, a Neo-Hookean elasticity model was applied to the interior of the clot with the gauge length left free to deform. Computations were run in COMSOL Multiphysics (Stockholm, SWE).

Results and Discussion

Nominal stress strain curves show strains of up to 250%, with highly linear behaviour. The measured mean elastic modulus was 5.43 ± 1.22 kPa, the maximum stresses were 10.2 ± 3.38 kPa, the maximum strains were 1.91 ± 0.29 with a linear R^2 value of 0.996. Bovine clots show a highly linear, elastic-like behaviour, similar to previous work (**Figure 1**). However, work by Boodt *et al.* [3] show a highly nonlinear compressive behaviour in clots, suggesting a compressive-tensile asymmetry. Work by Sugerman *et al.* shows similar tensile stiffnesses, however, reported strains at fracture were roughly 0.4 [7]. This method for loading clots in tension can be used to characterize the high strain properties of blood clots.

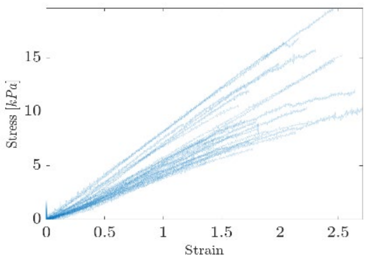

Figure 1: Nominal stress vs. strain curves for bovine tensile specimens, with cross-sectional area of 16 mm^2 in the gauge section.

References

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