

DEVELOPMENT OF TOUGHNESS EXHAUSTION MODELS FOR VASCULAR TISSUE RUPTURE

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INTRODUCTION

Vascular tissue rupture is a common phenomenon associated with many catastrophic cardiovascular diseases including coronary plaque rupture, aortic dissection and aortic aneurysm rupture. An early biomechanical model relating the fibrous cap thickness, the stress amplitude and the size of the lipid pool suggested that high stresses occur at the plaque shoulders and is more severe with thin cap and large lipid pool [1]. This paradigm has dominated the biomechanical comprehension and prognosis of the disease. Peak stress based failure criteria were proposed, such as yield stress for aortic tissue and ultimate tensile strength for carotid plaque [2]. However, clinically observed ruptured plaques reveal that in about 25% - 30% of cases, the ruptures do not occur at the shoulders [3] and can manifest at low stress. Certain groups have proposed conventional fatigue models for vascular tissue such as endurance [4, pig coronary arteries]. Our hypothesis is that toughness is the principal property governing vascular tissue rupture and that diseased vessels present microstructure alterations (calcifications, medial degeneration) that constitute flaws that can induce a rupture.

METHODS AND RESULTS

In Fracture Mechanics, the fracture toughness (the work required to propagate a crack opening of unit area in J/m^2), replaces the conventional Ultimate Tensile Strength (UTS) as a failure criterion [5]. The concept was transposed to living tissue in the 1970's but remained scarcely used. For a two-dimensional specimen in traction along direction y , toughness can be calculated with the Rice's J-integral [5]: $J = \int_{\Gamma} (w dy - T_i \partial u_i / \partial x ds)$, where w is the strain energy density (J/m^3) within a closed contour Γ , T_i the traction vector components (N/m^2), u_i the displacement vector components on the contour itself (m).

A custom guillotine fracture toughness testing device was built and attached to an Enduratec tester configured for simple uniaxial testing (Fig 1). The guillotine attachment design consists mainly of a razor blade mounted on the testing arm of the test apparatus. Porcine ascending aortas were collected from a local slaughterhouse. The specimens were affixed to a temperature-controlled fatigue apparatus that stretches

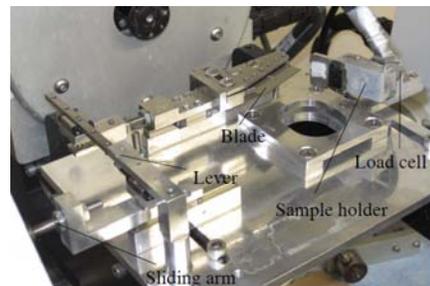


Fig 1 Custom soft tissue toughness tester

the strip's by a physiologic stretch ratio $\lambda = 1.15$. A typical force-displacement curve is also illustrated with the work area shown shaded for the toughness calculation (Fig 2). Typical values of toughness obtained for aortic tissue are in the range of 0.7-0.9 KJ/m² and 152.21J/m² for mitral valve tissue.

In analogy with the endurance S-N curve, a toughness exhaustion J-N curve is proposed and modeled with exponentially decreasing functions (Fig 3, [6]). The shape of the experimental J-N curves can be fitted with a relation of the form $J=J_0\exp[-kN+a]$, with J_0 the static toughness. Preliminary results for healthy porcine aortic tissue give $k=-3.332 \times 10^{-7}$ and $a=0.06175$. The threshold value J^* at which the tissue would rupture needs to be computed for the physiological loading conditions of interest.

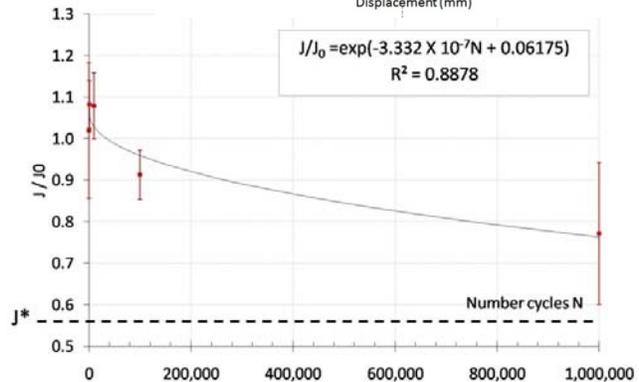
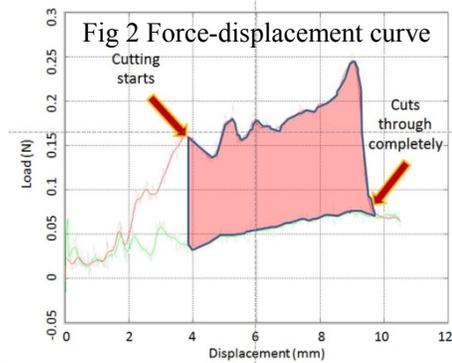


Fig 3 Exhaustion curve for vascular tissue

We are currently using a micro/nano indenter from Nanovea (Model M1) with a blunt conico-spherical tip with a 10 μm diameter with a load of 400 mN and load rate of 4 mN/s. The work during tip penetration is: $W_p = \int F dh_s$, where h_s is the displacement. For a cone tip with apex include angle ϕ , the fracture toughness is calculated with: $J = (4\sqrt{2} W_p) / (\pi D^2 h_s) (1 + \cos \phi)^{3/2} / \sin \phi$, with D , the diameter of the tip and h_s the tip penetration depth. The micro toughness values will be compared to the macro toughness values to determine the possible hierarchical relationship.

CONCLUSION: Toughness is a simple mechanical parameter that can be measured at the micro and macro scale. Since it is directly linked with the notion of fracture and its formulation can accommodate for non-linear material, it appears as a potential natural parameter to characterize the rupture of vascular tissue for integration into numerical models.

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