Mechanical Assessment of Rupture Risk in Arterial Tissues

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Introduction

The Mechanical properties of soft biological tissues have received a significant amount of attention in recent years. The main motivation behind such studies is that changes in mechanical properties of arteries may be a good indicator of cardiovascular diseases such as atherosclerosis and aneurysms [1], see Figure 1.

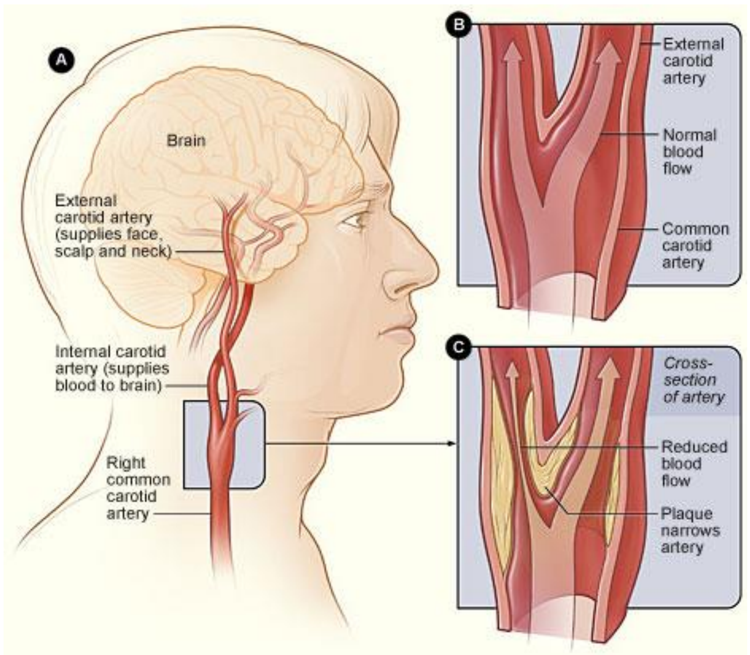

Figure 1: Atherosclerosis in carotid artery bifurcation. [https://www.nhlbi.nih.gov/health/healthtopics/topics/catd]

During atherogenesis, arteries can remodel in parallel with the formation of atherosclerotic plaque. Vessel Remodelling can occur by either outward expansion of the vessel wall or vessel narrowing [2], see Figure 2.

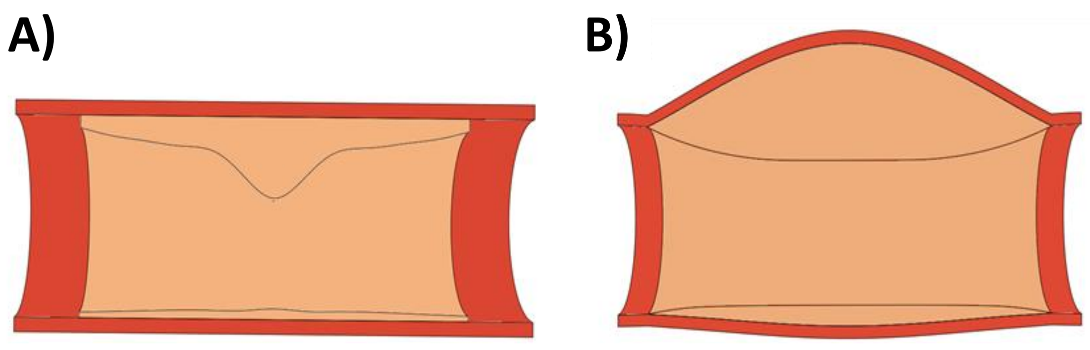

Figure 2: A schematic presentation of A) stenotic vessel and B) outward remodelled vessel.

Arteries are composed of three main layers; namely tunica intima, tunica media and tunica adventitia, see Figure 3. Collagen fibres are the main load bearing constituent of the arterial walls. Therefore, collagen fibre rupture may also be responsible for plaque rupture within damaged arteries [1].

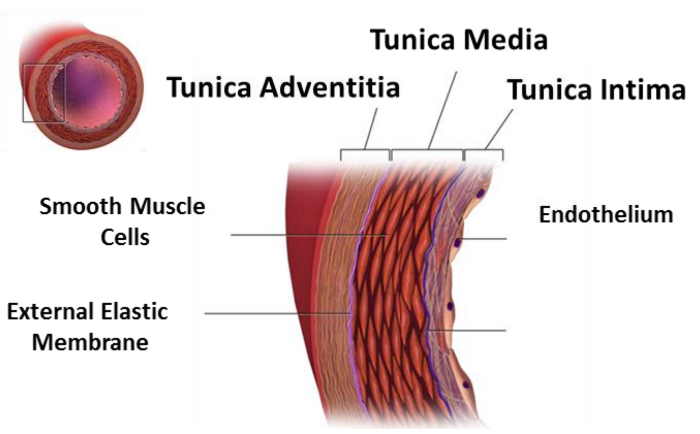

Figure 3: Architecture of the arterial wall.[www.boundless.com/]

In this research three factors are investigated to explore the risk of rupture in arterial tissues, see Figure 4.

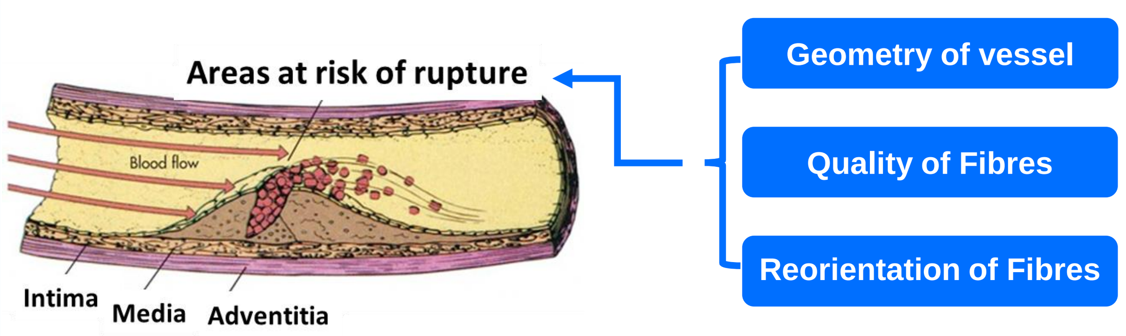

Figure 4: Parameters associated with plaque rupture in arterial tissue [http://thoracickey.com].

Materials and Methods

Geometrical Assessment of Arteries

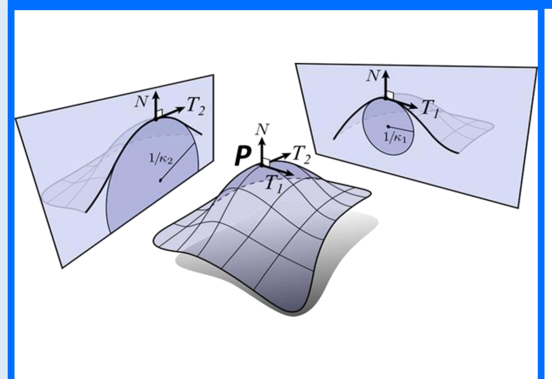

Figure 5: Principal curvatures of a surface at point *p*. [http://brickisland.net/]

The maximum principal curvature of the lumen and vessel is used for assessing the risk of rupture in arterial walls.

Figure 5 presents the principal curvatures of a surface at point *p* in $\mathbf{X_1}$ and $\mathbf{X_2}$ directions where **N** and **X** are normal and tangent vectors of the surface respectively.

The difference in curvature between the two surfaces is then weighted by the aggregate thickness of the plaque and vessel wall, see Figure 6.

This weighted curvature difference (WCD) is used as a metric for assessing the risk of rupture in arterial walls.

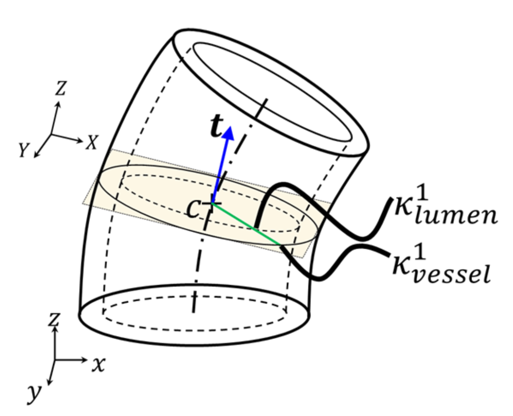

Figure 6: Curvature difference between the lumen (κ^1_{lumen}) and vessel (κ^1_{vessel}) is determined for radial lines from the lumen centre (green line)

Quality of Collagen Fibres

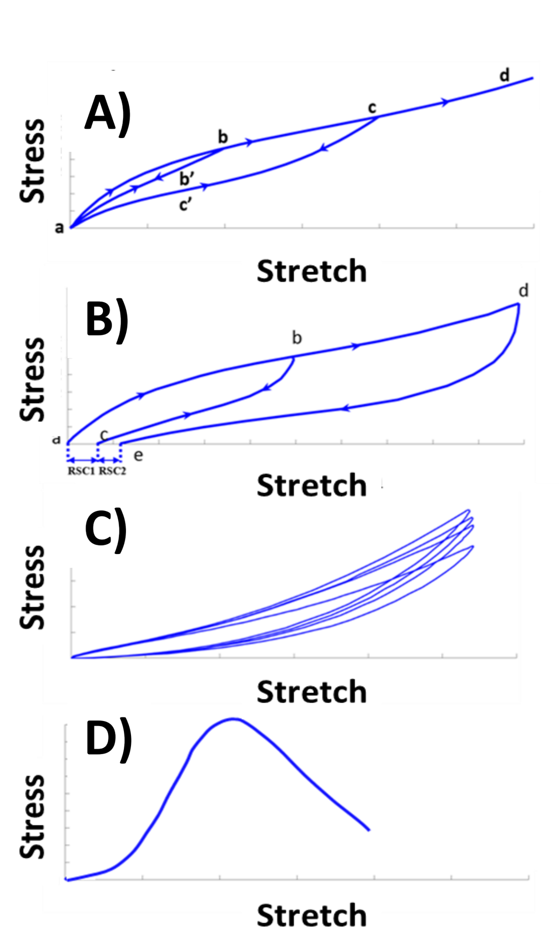

Figure 7: A) Mullins effect, B) permanent set, C) hysteresis and D) fibre rupture

A continuum damage mechanics (CDM) approach has been employed to simulate relevant damage phenomena in arteries (UMAT).

The evolution of two internal variables is used to capture the response of tissue to supraphysiological loadings including, see Figure 7 :

- Stress softening under cyclic loading (Mullins effect)
- permanent deformation under high cyclic loading (permanent set)
- Continuous degradation of the artery (Hysteresis)
- Rupture of fibres as a result of excessively high loading

Orientation of Collagen Fibres

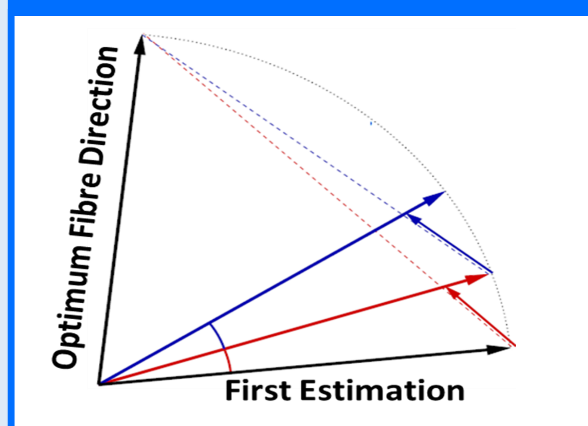

Figure 8: A presentation of one step of reorientation toward the optimum fibre direction.

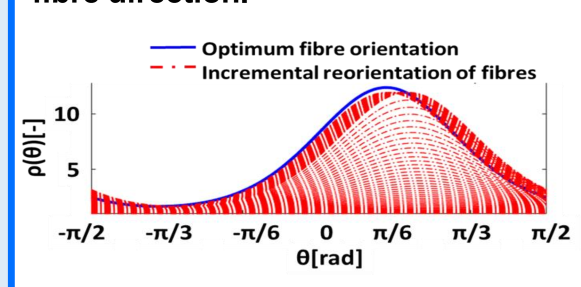

Figure 9: Incremental reorientation of collagen fibres from an isotropic distribution to an anisotropic distribution.

Collagen fibre directions evolve *in vivo* to optimize the load bearing capacity of the tissue [3-5]. In this research, reorientation of collagen fibres is explored using the distribution function, $\rho(\theta)$, presented in [1], where both fibre directions and dispersion are subjected to remodelling rules.

Reorientation of collagen fibres toward the preferred distribution is then modelled incrementally using a first order rate equation, see Figure 8 and 9.

Results

Geometrical Assessment of Arteries

The results of the stress and curvature analysis of an idealized stenotic and real vessel are shown in Figure 10(A) and (B), respectively. The left graph depicts the von Mises stress distribution on the lumen of the vessels. The graph in the centre presents the von Mises stress distribution on the unwrapped luminal surfaces. The distribution of WCD(Ω) is shown in the graph in the right. The location of the highest von Mises stress coincides with the highest value of WCD which is an indicator of high risk of rupture.

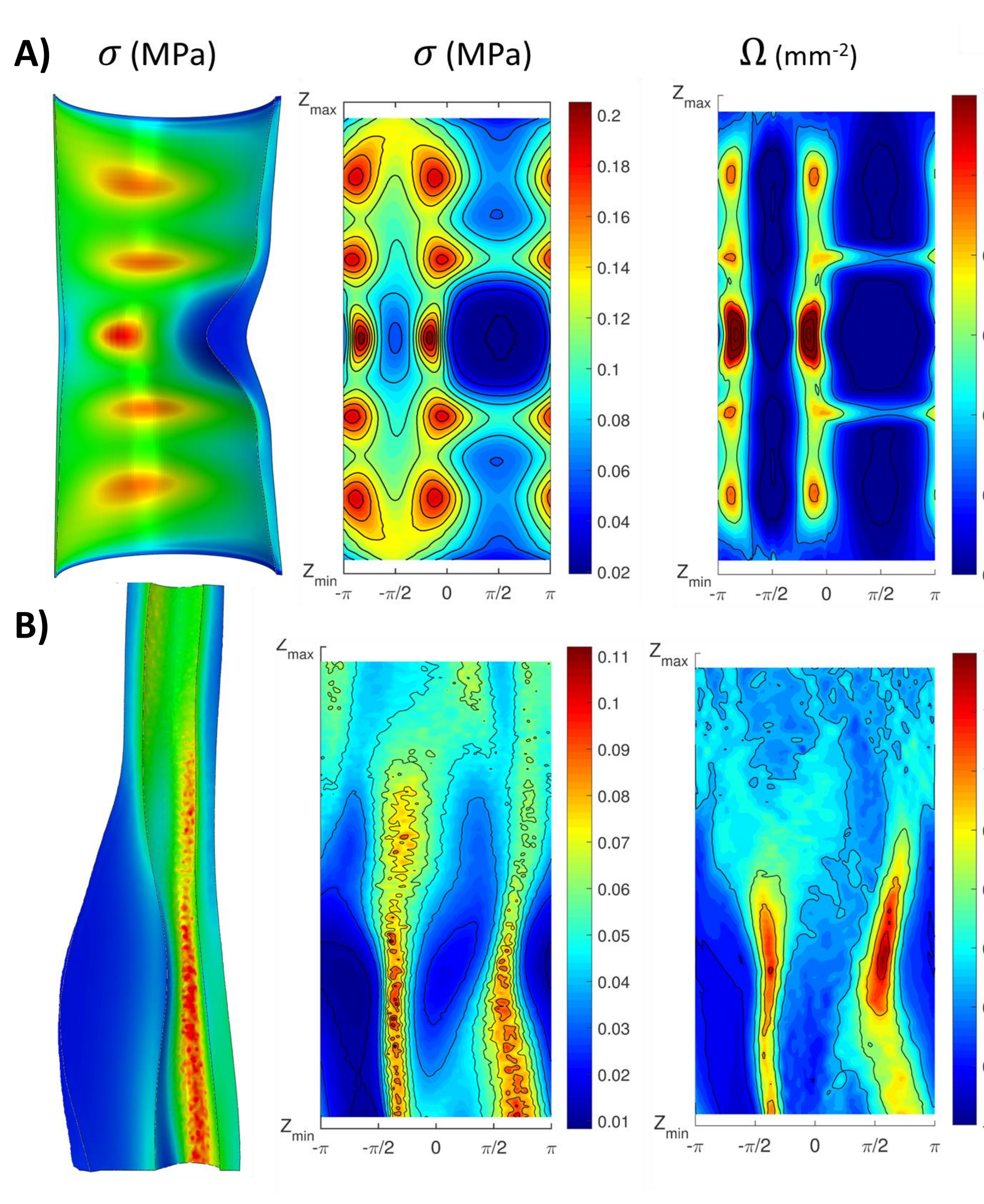

Figure 10: The stress and WCD distributions on A) an idealized vessel and B) real vessel geometry.

Quality of Collagen Fibres

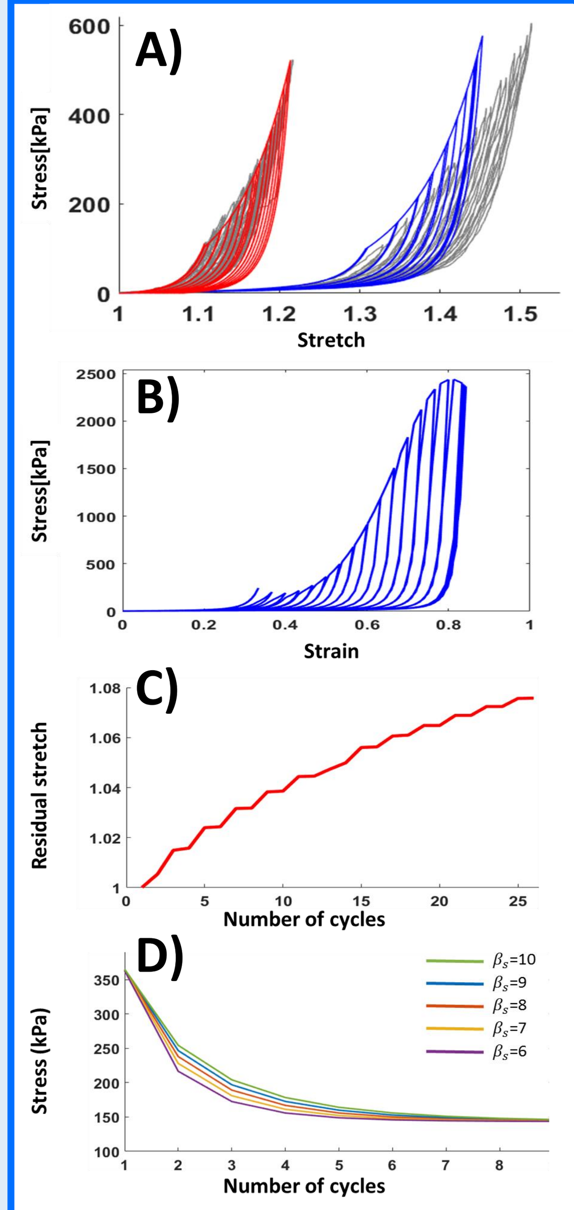

Figure 11: Arterial damage phenomena

Results of the implemented CDM model is shown in Figure 11.

The model was defined by fitting to stress strain curves obtained from axial and circumferential specimens of human carotid artery under cyclic loading, see Figure-11(A) [6].

The softening of the tissue in response to supra-physiological loading is evident in Figure 11(B), whilst the rupture of fibre is also clearly evident in this figure.

Permanent residual stretch of the tissue as a result of cyclic loading is shown in Figure 11(C).

Continuous degradation of the tissue (hysteresis) is shown in Figure 11(D).

Orientation of Collagen Fibres

The distribution of collagen fibres on a human carotid artery is shown in Figure 12. Mean angle of fibres is shown in Figure 12(A). Concentration of fibres (*b*) in each family of collagen fibres is illustrated in Figure 12(B). The rectangles in the images depict the aligned fibres at the apex of carotid bifurcation, whilst the triangles show the regions of near isotropic fibre distribution. The areas with highly aligned fibres, lower angle and higher *b* value are more at risk of rupture.

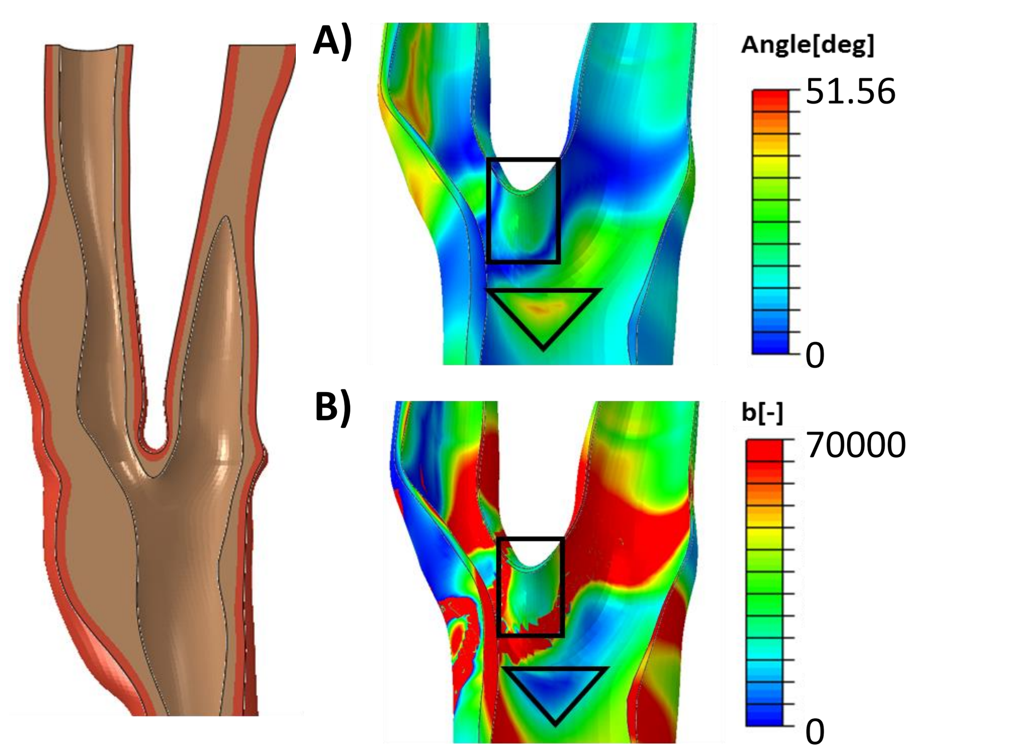

Figure 12: The distribution of fibres in a human carotid artery.
A) The mean angle of collagen fibres.
B) Concentration of collagen fibres.

Discussion

- WCD is a computationally efficient means of assessing the risk of rupture compared to stress analysis where solving the constitutive equations over the whole domain is required. Moreover, using this procedure, there is no need for obtaining the *in vivo* material parameters for the constitutive material models to perform the stress analysis.
- The implemented CDM model can successfully predict the behaviour of tissue under high loading conditions which includes: Mullins effect, permanent set, hysteresis and fibre rupture. Predicting these phenomena may be critical to predicting the risk of failure in the arteries.
- The implemented strain based reorientation algorithm can successfully determine both direction and dispersion of collagen fibres in arteries. The differences between the orientation of fibres in healthy and diseased arteries can be used as a metric for distinguishing the areas at risk of rupture.
- The proposed computational framework can provide objective support for clinical decisions regarding the need for medical intervention.

References

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