Arterial luminal curvature and fibrous cap thickness affects critical stresses within atherosclerotic plaques: an in vivo MRI-based finite element method simulation study

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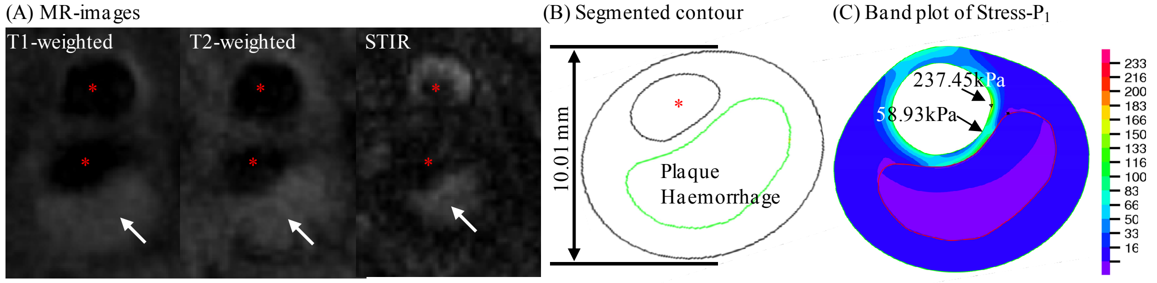
Introduction: Atherosclerotic plaques may rupture without warning and cause acute thromboembolic events such as ischaemic strokes. It has been hypothesized that critical stress conditions at the vulnerable sites (i.e. where plaque rupture is likely to occur), may be closely related to plaque rupture. In mechanical terms, fibrous cap (FC) rupture occurs when the external loading exceeds its material strength [1]. High-resolution magnetic resonance (MR) imaging is capable of identifying high-risk plaques morphologically and biomechanically by utilizing finite element analysis [2, 3]. Atherosclerotic tissue is however, a structure made up of multiple components. Its complexity, which is increased by the presence of an irregular arterial lumen and non-linear material properties, renders the identification of the vulnerable site difficult. Although considerable research has been done to discover a negative correlation between FC thickness and critical stress conditions [3,4] the relationship of arterial luminal curvature and its irregularity with plaque vulnerability remains unexplored [5].

Aim: To assess the affect of arterial luminal irregularity on the critical stress condition within symptomatic atherosclerotic plaques.

Methods: ***(1) MRI acquisition*** Twenty-one patients underwent high-resolution black-blood MR imaging of their symptomatic carotid artery. Axial T_1, T_2-weighted, proton density-weighted and STIR images covering the entire carotid plaque were acquired (Fig.1A). Manual segmentation of plaque components was performed using previously published criteria, to identify FC, lipid pool, calcification and plaque haemorrhage [2] (Fig.1B). ***(2) Finite element simulation*** As the in vivo MR-images were obtained under pressurized condition, the segmented contours were shrunk to get a computational baseline non-pressurized shape [3]. Maximum principle stress (Stress-P_1) was generated using finite element method and solved in ADINA8.5 (ADINA, Inc.) (Fig.1C). The plaque components were assumed to be hyper-elastic as described by modified Mooney-Rivlin strain energy density function. The material parameters from earlier studies were used [1,6]. The blood pressure for each patient, measured before MR imaging, was used as the loading condition to perform the patient-specific simulation. ***(3) Lumen irregularity quantification*** Lumen contour was interpolated with 200 equidistant points using cubic spline function. The local curvature was computed using the radius of the circle, determined by the three adjacent points. ***(4) Result analysis*** All slices showing atherosclerotic plaque components were used in this study (In total 93 MR image slices were used). Values of Stress-P_1 at the thinnest FC site and at the site with maximum curvature (i.e. luminal irregularity) over the FC were extracted for the analysis. Stress-P_1 for the normal arterial wall segments was excluded.

Results: Maximum stress concentration was present at the site of minimum FC thickness or at the location with maximum lumen curvature (maximum luminal irregularity). The median critical stress at the site of maximum curvature was significantly greater than that at the site of minimum FC thickness [124kPa (95%CI: 132-207kPa) vs. 115kPa (95%CI: 106-182kPa), $p=0.005$]. This implies that calculating the stress value only at the thinnest FC position would under-estimate the critical stresses within the plaque. It was found that this would have affected 61 out of 93 MR slices if the stress at the thinnest position only was taken. However in 30 slices we would have under-estimated the stress if stress calculation was done only at the site of maximum luminal irregularity. The remaining two slices had minimum FC thickness and maximum luminal curvature at the same site.

Conclusions: Calculation of plaque stresses at the position where the fibrous cap is thinnest significantly under-estimates the critical stress condition and therefore over-estimates the plaque stability. This indicates that stress at the site of maximum luminal curvature, over the fibrous cap, appears to offer better and more realistic representation of the underlying plaque stresses. However we propose that stress calculation at either of these sites be used for a better and refined plaque risk assessment, since failure at either site will results in plaque rupture.


(A) MR-images

(B) Segmented contour

(C) Band plot of Stress-P_1

Figure 1. (A): The multi-contract MR-images showing plaque structure (plaque haemorrhage marked by white arrows) and irregular lumen contour marked by red asterisk; (B): Segmented plaque contour; (C) Band plot of Stress-P_1 showing larger difference of stress values at the thinnest fibrous cap position and the position with maximum lumen curvature.

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