Finite Element Modelling of Diseased Carotid Bifurcations; Identification of a Potential Clinical Indicator of Plaque Vulnerability

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Introduction
Atherosclerotic plaques frequently develop at the carotid bifurcation and plaque disruption at this location is a leading cause of ischemic strokes. Over 50% of these stokes occur in asymptomatic patients and thus better indicators of the disease need to be developed 1.

Finite element studies of arterial wall segments have provided key information on the biomechanics of arteries such as prediction of atherosclerotic plaque vulnerability 2. In this study, patient specific finite element models of the carotid bifurcation are used to investigate the usefulness of geometrical variables and von Mises stress in the diagnosis of vulnerable plaques.

Materials and methods
Twelve patient specific models of diseased carotid bifurcations were created from in vivo computerised tomographic angiography as described in Creane et al 3.

The plaque material model was generated by fitting to uniaxial tensile tests on carotid plaque 4. The healthy wall material model was taken from the literature 5. The plaque and healthy wall were both modelled as isotropic hyperelastic materials with their strain energy density functions defined by:

\[ W = c_{10}(I_1-3) + c_{01}(I_2-3) + c_{20}(I_1-3)^2 + c_{11}(I_1-3)(I_2-3) + c_{02}(I_2-3)^2 \]

where \( I_1 \) and \( I_2 \) are the first and second strain invariants and \( c_{10}, c_{01}, c_{20}, c_{11}, \) and \( c_{02} \) are material constants. The models were solved using the finite element package ABAQUS® (Simulia, Providence, RI, USA).

The 3D gaussian curvature of the plaque inner and outer surfaces was calculated using Matlab® (Mathworks, Natick, M.A USA). The difference between the inner and outer plaque surface curvature, defined as \( K_{3\delta} \), was determined for each of the models and this measure was then plotted onto each plaque surface.

Results and discussion
The von Mises stress distribution of one carotid bifurcation can be seen in fig. 1. The high stress concentrations occur at locations where the plaque thickness reduces sharply. These locations can be characterised as areas where the curvature of the inner wall differs greatly from that of the outer wall, i.e. high \( K_{3\delta} \).

This location is commonly known as the plaque shoulders and has been shown by many investigators to be a potential region of plaque disruption 2,3. As can be seen in fig.1, high values of \( K_{3\delta} \) also occur at this location. We hypothesize that the magnitude of this measure may provide a predictor of plaque rupture/disruption. This is supported by results of a 2D study, where a similar measure of 2D curvature successfully differentiated between symptomatic and asymptomatic patients 3.

Conclusion
The measure \( K_{3\delta} \) can predict regions of high stress in diseased carotid bifurcations and with further development it could provide a powerful clinical indicator of plaque vulnerability.

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References