Characterization of Morphological Features and Critical Mechanical Condition along Carotid Plaques using in vivo MRI and Finite Element Simulation

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Introduction: The rupture of atherosclerotic carotid plaque is one of the main causes of ischemic cerebrovascular events such as stroke. Growing evidence shows that plaque rupture is associated with plaque morphological features, such as soft components in the plaque. From a mechanical point of view, rupture possibly occurs when the extra loading exceeds the material strength of fibrous cap. Therefore, it has been suggested that both the morphological features and the mechanical condition within the plaque structure should be considered for plaque vulnerability assessment [1]. Previous studies have shown that the vulnerability has an asymmetric distribution along the plaque. The site proximal to the maximum stenosis of the plaque is more likely to rupture and has a heavier burden of inflammation [2,3,4]. However, the quantitative morphological and mechanical features along the plaque are rarely explored.

Objective: We aim to quantify the morphological and mechanical features along the plaque to identify high risk factors for rupture.

Methods: (1) ***MRI data acquisition and volume computation*****:** 54 asymptomatic (mean age: 70.4) and 46 acutely symptomatic patients (mean age: 72.4) underwent multi-contrast MR-imaging of the carotid arteries in a 1.5 Tesla MRI system (Signa HDx GE Healthcare, Waukesha, WI) with a 4-channel phased-array neck coil [5]. The acutely symptomatic patients were imaged within 72 hours of onset of symptoms. Axial T1, T2-weighted, proton density-weighted (PD) and STIR images was acquired (Fig.1A). Plaque components such as lipid-rich necrotic core (LRNC), hemorrhage (PH) and calcium (Ca) were manually segmented using previously published criteria (Fig.1B) [5]. The component volume between two slices was approximated by a circular truncated cone using 2D contours. The plaque was then divided into sites proximal and distal to the site of maximum stenosis for comparsion. The percent volume of each component was defined as the volume of the component at the proximal or distal site over the component total volume in the plaque. **(2)** ***Finite element simulation*****:** A pre-shrinkage method was applied to the 2D contours derived from in vivo MR images to get the computational start state under zero pressure [6]. The material property of the plaque components was considered hyper-elastic using results from previous studies [7,8]. The blood pressure of each patient was acquired as the loading condition for patient-specific mechanical simulation. Maximum principle stress (Stress-P_1) of each slice was computed in a commercial finite element solver (ADINA8.5, ADINA, Inc.).

Results: The proximal site has a larger percentage plaque volume than the distal site (median: 71.83% vs. 28.17%, p<0.0001), and a larger percentage volume of LRNC (64.53% vs. 35.47%, p<0.0001), PH (68.41% vs. 31.59%, p=0.006) and Ca (75.08% vs. 24.92%, p=0.003), respectively. Fibrous cap rupture/ulceration was observed in 40 patients (10 asymptomatic and 30 acutely symptomatic), with 19 located proximally, 14 at the site of maximum stenosis, only six at the distal site and one at both sites. 50.5% of P-CStress was located proximal to the maximum stenosis, 32.4% at the point of maximum stenosis and 17.1% at distal sites.

Conclusion: The results obtained provide interpretation from morphology and mechanics for the clinical observation that plaque rupture occurs proximal to the maximum carotid stenosis in both symptomatic and asymptomatic patients. Larger volume of LRNC, PH, Ca and most ruptures are located at the proximal site, which is subjected to high mechanical loading. It is very likely that an underlying soft component induces high mechanical stress, which in turn causes tissue damage and promotes inflammation, and such inflammation will further contribute to plaque progression and weakening of the fibrous cap. Thus for a more accurate plaque vulnerability assessment, plaque morphology and biomechanical stress conditions should be considered in an integrated way.

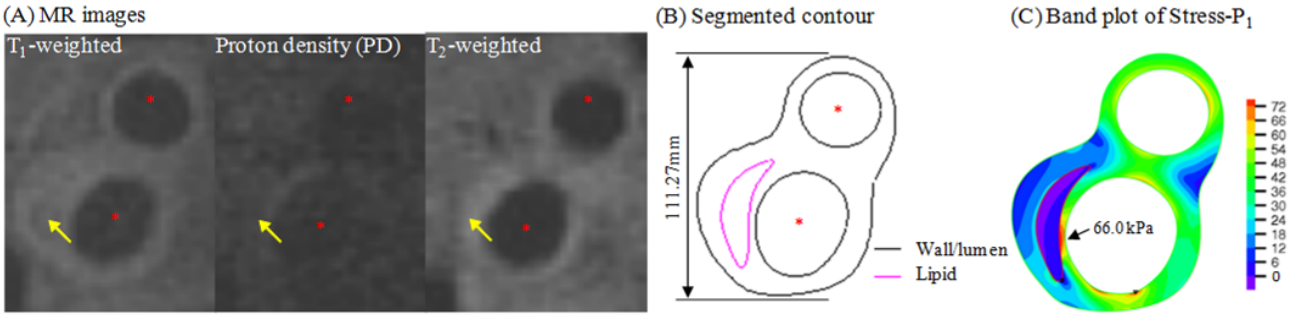

Figure. 1 (A): High-resolution, multi-contrast MRI showing different atherosclerotic components. Red stars indicate lumen, yellow arrow indicates LRNC; (B): segmented contour used for simulation; and (C): Band plot of Stress-P_1 showing critical stress at the vulnerable site (unit: kPa).

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