OUTER BOUNDARY AMBIGUITY EFFECTS ON INTRA-PLAQUE STRESS DISTRIBUTION IN ATHEROSCLEROTIC PLAQUES

M.R. Ahmadian*

* LEMA- Laboratoire d'Etude Mécanique des Assemblages, Université de Versailles et Saint Quentin-en-Yvelines, 45 Avenue des Etats Unis, 78035 Versailles, France

Reza.Ahmadian@meca.uvsq.fr

Abstract: Biomechanical analysis can be used as a diagnostic technique for predicting the likelihood of atherosclerotic plaque rupture through investigation of mechanical stress/strain patterns. In many cases, the progression of plaque is believed to result in sudden death due to the plaque rupture or plaque erosion. There are some mechanical factors such as stress concentration and rupture site. The tissue properties and the morphology of plaques are major determinants of coronary-related clinical syndromes. These characteristics even can be used in processing of the arterial images and then used as a criterion in surgery decisions. Inadequate data on plaque proprieties and materials is one of the limitations in plaque pathology studies. Using more accurate imaging techniques or processing of different images can be helpful to obtain more accurate data on lesion composition. Optical Coherence Tomography (OCT) is one of the capable diagnostic imaging modalities acquiring in vivo images with high resolution. The ultimate goal is to study of plaque failure mechanics [14, 15, 16, 17]. Toward this end, in the present study the effect of ambiguous segmentation at the outer plaque boundary is examined by using Finite Element Modeling (FEM) based on a cross section of a histological image. This sensitivity analysis of stress patterns to variations in the outer boundary location is evaluated because outer plaque boundaries can be ambiguous in OCT. The results indicate that outer boundary ambiguity has minimal effect on intra-plaque stress distributions. In fact in biomechanical processing of OCT images, ambiguity in outer boundary has the minimal effect on the results.

Introduction

Atherosclerotic plaque rupture has been suggested to be responsible for the majority of myocardial infarction deaths [1, 6, 7]. Biomechanical analysis has suggested that rupture is associated with stress concentrations, which are affected by plaque area, thickness and compositions (lipid, fibrous and calcific contents). In fact the characteristics of the plaque including plaque geometry and content provide significant information regarding the vulnerability of the plaques [4, 9, 10, 11, 12]. The researches showed that there exists a high correlation between the locations of plaque rupture in histology of plaques and locations of high stress concentrations investigated by computer simulations of those plaques [4,]. Recently, new techniques have been proposed for the identification of vulnerable plaques which may help in understanding the pathological and physiological mechanisms implicated in the rupture of atherosclerotic coronary lesions. Histology based models have developed to process the correlated IVUS images [14, 15, 16]. In many reported cases rupture occurred in plaques with small growth [5, 6, 7]. Plaque rupture does not just depend on plaque growth; the plaque morphology has crucial role in this event [7, 14, 16, 17]. The stress concentration caused by blood pressure may contribute to the plaque rupture [8].

Optical Coherence Tomography (OCT) imaging provides high resolution in vivo cross-sectional images of blood vessels with more realistic morphology. OCT is a catheter-based technique utilizing back reflected infrared light to obtain in-vivo micron-scale tomography imaging [2]. This method is attractive since it may differentiate lipid-based and water-based constituents even in heavily calcific tissues. Some researchers have done the first finite element models based on this new method [3, 13]. Because of attenuation of OCT beams the accurate modeling of adventitial border is impossible. The objective of this study is to determine the mechanical effects of plaque morphology and contents to obtain a pattern for plaque rupture and correct prediction of plaque rupture by clinical images.

Materials and methods

To determine the effect of ambiguous segmentation in modeling of the outer plaque boundary, the border location was varied while the other borders remained constant. The finite element models were modified to show these new plaque boundaries. Material properties, boundary conditions and arterial pressure remained the same.

The effect on the estimated stress patterns from finite element modeling was then examined. Three candidate locations were used: the original outer boundary from pathological suggestions, a shrunken boundary (1/6 reduction in plaque area), and an expanded boundary (1/6 increase in plaque area). The diseased artery segmented by cardiologist and pathologist to identify the boundaries of lipid-rich, calcific and fibrous tissue regions. In Figure 1, picture A shows histological image of one atherosclerotic artery. In picture B the corresponding OCT image is shown which represents the ability of OCT imaging modality to produce structural and compositional data that are comparable to histology.

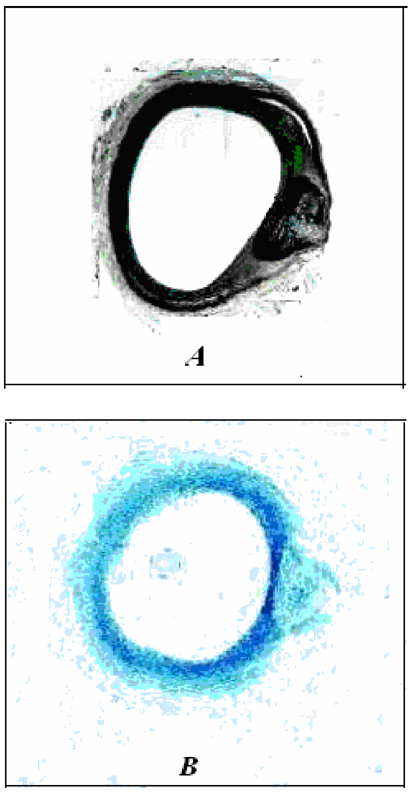

Figure 1: Histological image (A) and its relevant OCT image (B)

Finite Element models of cross section of atherosclerotic arterial wall based on histological image were developed using ANSYS (Version 5.4) software. Richardson et al. have shown that high tensile stresses concentrate at the ends of plaque caps with underlying lipid pools [4]. Finite element analysis can identify areas of stress concentration prone to rupture and thus can be used to assess lesion stability [3, 13]. The 2D Models included the fibrous, lipid and calcific plaque and the entire image domain with the tissue surrounding the vessel represented by an isotropic high elastic material, allowing the arterial wall to expand by pulsation (Figure 2). Table 1 shows the mechanical property of plaque contents in the models. Plane-strain elements were used in meshing, since longitude of the vessel is large enough to neglect its strain (Figure 3-A). The domain of the image considered as boundary conditions and all the nodes were restricted. Finite element analysis performed under physiological loading conditions to obtain the stress distribution.

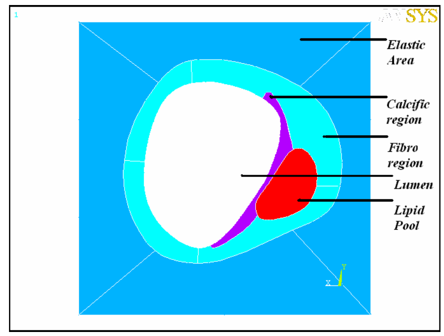

Figure 2: Segmentation in the original Model

To determine the effect of ambiguous segmentation at the outer plaque boundary, a sensitivity analysis was performed. Figure 3-B illustrates the suggested segmentations of the outer boundaries.

Table 1: Artery & Plaque mechanical properties

Region	Young's Module (MPa)	Poisson's Ratio
Calcific region	2.0	0.3
Fibrous region	1.5	0.3
Lipid region	0.02	0.45

Results

The stress distribution result for the applied physiological blood pressure on the models is shown in Figure 5. The elements with the highest stress values are illustrated in Figure 4. The values in Table of results (Table 2) represent the information on these vulnerable elements. Elements 1 and 2 have higher stresses in all three models. In fact the maximum stress values occurred at the junction of the fibrous plaque with calcific plaque. Besides, the regions exhibiting the highest stress in the models are compatible with pathological findings [6, 7]. The calcific tissue region is the stiffest material and is therefore expected to carry the most stress [3]. When plaque thickness is increased, the load is distributed throughout a greater thickness, reducing overall stress magnitudes. The maximum stress in shrunken model is higher than the expanded model (191 *kpa vs.* 185.2 *kpa*).

The maximum stress on the contrary is smaller in expanded model (176.3 *kpa vs.* 185.2 *kpa*).

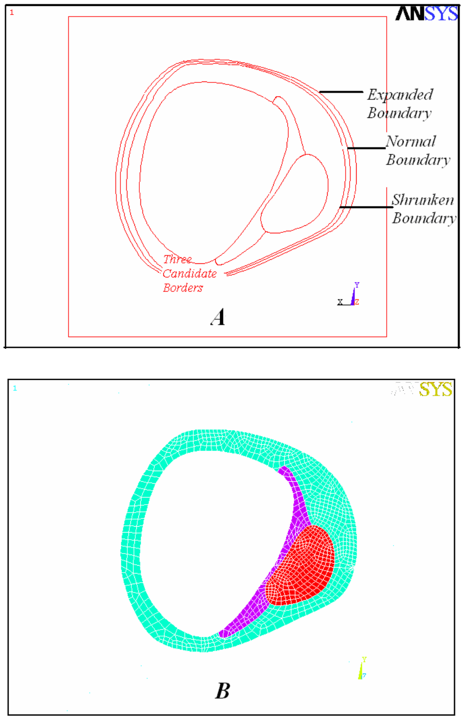

Figure 3: The candidate models (A), and a sample finite element mesh (B)

Variation of the boundary location did not generally affect the overall stress distribution. Increasing the plaque area by 1/6 of plaque area reduces the stress magnitude in the plaque, whereas decreasing it yields increased stress magnitudes.

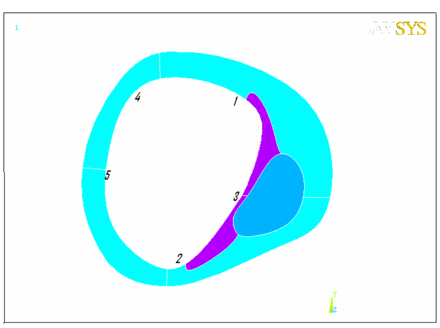

Figure 4: Selected elements in regions of high stress

In spite of the variation in geometry of the models, the stress distribution does not change dramatically in interested regions. Regions of maximum and minimum stress are still in accordance with the first suggested model. Besides, the locations of stress concentrations remain the same in the models. The maximum stress values occur near the inner lumen of the artery and therefore outer boundary variations influence them slightly. Therefore outer boundary ambiguity has minimal effect on intra-plaque stress distributions.

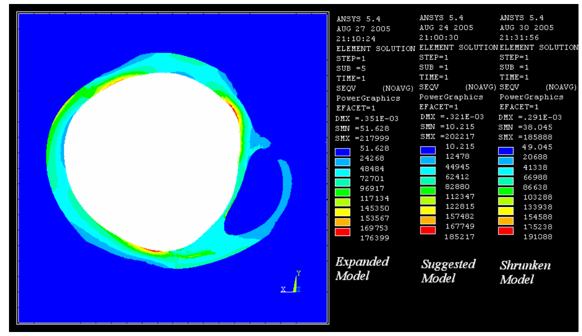

Figure 5: Von Mises Stress plots for Suggested, Expanded and Shrunken Plaque Boundary

Table 2: Maximum Stress values in selected elements in three candidate models (Figure 4 and Figure 5)

Element No.	**Stress Value (pa)**		
	Model Suggested	**Model Expanded**	**Model Shrunken**
1	185217	176399	191100
2	168210	165753	172923
3	92726	82800	101729
4	154215	152436	168422
5	30976	28002	43778

Discussion

The present study used finite element modeling of histological image of a diseased coronary artery. The purpose was to evaluate the effect of outer boundary ambiguity on stress analysis. The finite element modeling was performed based on the histological image, to obtain a pattern of plaque rupture based on the final arterial deformation at the arterial pressure and by comparing with relative clinical image. Dynamic arterial pressure, Heterogeneity of arterial biological tissues and three-dimensional modeling are the limitations in this study which should be included in future studies. The aim of this study was to investigate the effect of morphology on stress analysis. This work can be extended by using more histological images.

Conclusion

Measurement of stress within the plaque and the wall of the coronary artery can provide insight into the processing of the arterial images. In this study the sensitivity of stress patterns to variations in the plaque outer boundary was investigated.

The results demonstrate that models exert minimal influence on intra-plaque stress and suggest that segmentation ambiguities at the outer wall do not significantly change the quality of biomechanical analysis results.

Stress analysis can be applied as a technique to Image Processing. Clearly, reliable predictions of stress and strain in loaded plaques in vivo would provide in sight in to the potential for subsequent plaque failure.

Acknowledgments

The author wishes to acknowledge Dr. M. Tafazzoli Shadpour, Dean of the Biomedical Engineering Department in Tehran Polytechnic and also Dr. D. Akhlagh Moayed (Cardiologist and Interventionist) in Cardiac Catheterization Laboratory in N.I.O.C Hospital in Tehran for pathological analysis in this study.

References

[1] AVOLIO A., DEANNA J., TAFAZZOLI S.M. (1998): 'Quantification of Alterations in Structure and Function of Elastin in the Arterial Media', *Hypertension* 32: 170-175

[2] BREZINSKI M. E., FUJIMOTO J. G. (1999): 'Optical Coherence Tomography: High-Resolution Imaging in Nontransparent Tissue', *IEEE Journal of Selected Topics in Quantum Electronics*, Vol. 5, No. 4

[3] ALEXANDRA H. C., RAYMOND C. C., SHISHKOV M., MACNEILL B., IFTIMIA N., GUILLERMO J. T., KAMM R. D., BOUMA B. E., and KAAZEMPUR-MOFRAD M. R. (2004): 'Mechanical Analysis of Atherosclerotic Plaques Based on Optical Coherence Tomography', *Annals of Biomedical Engineering*, Vol. 32, No. 11, pp. 1494–1503

[4] RICHARDSON, P.D., DAVIES M.J., BORN G.V.R. (1989): 'Influence of Plaque Configuration and Stress Distribution on Fissuring of Coronary Atherosclerotic Plaques'. *Lancet* 2, 941–944.

[5] ROSS R., GIOMEST J. A. (1976): 'The Pathogenesis of Atherosclerosis', *The New England Journal of Medicine*, Vol. 295, No. 7, 369-377

[6] STRAY H. C., CANDLER B., DINSMORE R. E., FUSTER V., GLAGOVE S., INSULL W. D., Weissler R. W. (1995): 'A Definition of Advanced Types of Atherosclerotic Lesions and A Histological Classification of Atherosclerosis', *Arteriosclerosis, Thrombosis and Vascular Biology*, 15, 1512-1531

[7] RENTROP P. K. (2000): 'Thrombi in Acute Coronary Syndromes', Circulation, 101- 1619

[8]VERESS A., CORNHILL J. F., Powell K. A., HERDRICK E. E., THOMAS J. D., (1993), 'Finite Element Modeling of Atherosclerotic Plaque', *IEEE*, pp. 791794

[9]FALK E., SHAH P. K., FUSTER V. (1995): 'Coronary Plaque Disruption', Circulation 92, 657–671

[10] LOREE H. M., KAMM, R. D., STRINGFELLOW, R. G., LEE R. T., (1992): 'Effects of Fibrous Cap Thickness on Peak Circumferential Stress in Model Atherosclerotic Vessels', *Circulation Research,* 71, 850–858.

[11] MACISAAC A. I., THOMAS J. D., TOPOL E. J. (1993): 'Toward the Quiescent Coronary Plaque', *Journal of the American College of Cardiology* 22, 1228–1241.

[12] CHENG G. C., LOREE H. M., KAMM R. D., FSHBEIN M. C., Lee R. T. (1993): 'Distribution of Circumferential Stress in Ruptured and Stable Atherosclerotic lesions; A Structural Analysis With Histopathological Correlation', *Circulation* 87(4):1179–1187.

[13] PATAL S. Y., KAAZEMPUR-MOFRAD M. R., ISASI A. G. and KAMM R. D. (2003): 'Diseased Artery Wall Mechanics: Correlation to Histology', Bioengineering Conf., Key Biscayne, Florida, The united states of America, pp. 0499-0500

[14] AHMADIAN M. R., TAFAZZOLI S. M., MOAYED D. A. (2004), The 14th Iranian Heart Congress in Collaboration with British Cardiac Society, Biomechanical Analysis of Atherosclerotic Plaques Based on IVUS & OCT Images, Tehran, Iran

[15] AHMADIAN M. R., TAFAZZOLI S. M., MOAYED D. A., MAJD S. G. (2004): 'Dynamic Stress Analysis of Atherosclerotic Plaques by Using Real Blood Pressure Wave Forms & Clinical Images', The 14th Iranian Heart Congress in Collaboration with British Cardiac Society, , Tehran, Iran

[16] AHMADIAN M. R., TAFAZZOLI S. M., MOAYED D. A. (2004): 'Finite Element Modeling of Atherosclerotic Plaques Based on IVUS', IFMBE Proc. Series, BioMed 2004, Kuala Lumpur, Malaysia

[17] AHMADIAN M. R., TAFAZZOLI S. M. (2004): 'Finite Element Modeling of Atherosclerotic Plaques Based on OCT Image', 11th Iranian Conf. In Biomedical Engineering, Tehran Polytechnic, Tehran, Iran