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Target Lesion Calcium Arc Influence the Performance of Stenting

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1 Background

Percutaneous coronary intervention (PCI) is the most common revascularization procedure, in which, fibrocalcific plaques are found in 17–35% of patients undergoing PCI [1]. Numbers will rise with population aging and prolonged statin treatment. Calcifications often lead to stent under expansion and strut malapposition, with increased risk of thrombosis and in-stent restenosis [2]. Presence of calcium strongly inhibits stent performance, a well-documented metric for outcome [3]. The goal of this work is to develop the finite element models for inspecting the influence of the calcium arc extent on the stenting outcomes, such as the stress and strain distribution within the plaque, and the lumen gain following stenting. Finite element method is an effective tool to reveal the mechanism of the stent expansion and its interaction with target lesion, provide guidance for optimal clinical outcomes.

2 Methods

2.1 Geometry

The deployment of a Express stent (Boston Scientific Corp., MA) in a straight artery with an eccentric plaque is considered in this work (Figure 1a) [4]. The artery has an inner diameter of 3mm, thickness of 0.75 mm and length of 26 mm. An asymmetric plaque has a length of 13 mm, and thickness ration of 2:1 leading to a minimal lumen diameter of 1.5 mm, i.e., a 50% diameter stenosis. Three representative calcium arcs with various circumferential angles were adopted from literature [5], i.e., 60°, 180° and 270° (Figure 1b). The stent has a nominal diameter of 3mm, thickness 0.13 mm and length 16 mm.

2.2 Material

The stent is made of 316LN stainless steel, which was described as a perfect linear elastic-plastic material model with the Young's modulus $E=190$ GPa, Poisson's ration $\nu=0.3$, and yield stress $\sigma_Y=207$ MPa. The target lesion, including artery, plaque and calcium are all modeled as hyperelastic material using a third-order polynomial strain energy density function U as:

$$U = \sum_{i,j=1}^3 C_{ij} (I_1 - 3)^i (I_2 - 3)^j$$

where the I_1 and I_2 are the first and second invariants of the Cauchy-Green tensor, defined as

$$I_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2, I_2 = \lambda_1^{-2} + \lambda_2^{-2} + \lambda_3^{-2}$$

The material coefficients C_{ij} are adopted from literature [6]. Briefly, for the artery, $C_{10}=0.014881$ MPa, $C_{20}=0.014920$ MPa and $C_{30}=0.000939$ MPa. For plaque, $C_{10}=0.04$ MPa, $C_{02}=0.003$ MPa and $C_{03}=0.02976$ MPa, and its yield stress was set at 0.07 MPa. For calcium, $C_{10}=-0.49596$ MPa, $C_{01}=0.50661$ MPa, $C_{11}=1.19353$ MPa, $C_{20}=3.6378$ MPa and $C_{30}=4.73725$ MPa.

2.3 Finite element meshing and boundary conditions

The 8-node hexahedral element is used. Per our mesh convergence study [4], the element size for stent, artery and plaque are chosen as 0.02 mm, 0.14 mm, 0.12 mm respectively. Symmetric boundary constraints are applied to both ends of the artery. The plaque is tied to the artery to avoid relative movement. The stent-lesion contact is modeled using a general contact algorithm with a friction coefficient of 0.05 [7]. The stent crimping, expansion and recoil are modeled by displacement constraints.

3 Results

3.1 Stent Loading

Stent induced resistance force on the lesion during its expansion and recoil are obtained from our models (Figure 2). It is clear that the equilibrium force on the stent increased from 1.5 N to 2.5 N and 3.6 N as the calcium arc altered from 60° to 180° and 270°. However, following the balloon withdrawal and stent recoil, the final load on the stent is the smallest for the largest calcium arc of 270°.

3.2 Stress and strain distribution in the plaque

The distributions of von Mises stress and maximum principal strain in the plaque are illustrated in Figure 3. As the calcium arc increases, the stent induced von Mises stress in the plaque, especially in its softer portion, are elevated. As the calcium arc increases from 60° to 180° and 270°, the corresponding peak principal strain are 1.144, 1.396 and 2.126 respectively. The stress or strain concentrations are located near the ends of calcium arc. It is also clear that the larger the calcium arc is, the irregular the lumen shape becomes. Specifically, a relative round lumen is observed for a calcium arc of 60°. The irregular “D” shape is obvious at the calcium arc of 270°. The diameter lumen gains for all three cases of calcium arc at 60°, 180° and 270° are 1.528 mm, 1.244 mm and 0.668 mm, respectively.

3.3 Stent malapposition

Figure 4 has depicted the stent malapposition for various calcium arcs. No malapposition was found for the calcium arc of 60°. The maximum malapposition is measured as 0.084mm and 0.637mm for the calcium arc of 180° and 270° respectively.

4 Interpretation

The role of calcium arc on the stenting performance was investigated through finite element method. Results demonstrated that a larger calcium arc required much more force to expand the stent till its targeted diameter. Abnormal stent load was associated with the arterial injury and remodeling. A larger calcium arc also resulted in a smaller equilibrium force after stent recoil, indicating a potential poor stent outcome. It is as expected that a larger calcium arc induced higher stress and strains in the plaque. This might lead to clinically observed calcium fractures. Aggregated stent malapposition was observed also for large calcium arc. The dramatic under expansion of stent in the calcium arc of 270° indicated that an appropriate calcium scoring technique is needed prior stenting. The geometries of the artery and plaque were simplified for this comparative study. More realistic models considering patient specific geometry and plaque compositions could be developed for predicting the plaque behaviors in details. Despite these simplifications, the present work demonstrated the importance of calcium arc on the stenting performance, which may have significant clinical implications for in-stent restenosis and /or thrombosis.

Acknowledgments

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Figure 1.

(a) Stent-artery interaction model, (b) mid cross-section view of plaque with calcium arc at 60°, 180° and 270° (left to right).

Figure 2.
Stent loading

Figure 3.

Distributions of Von Mises stress and maximum principle strain in the plaque with calcium arc at (a) 60°, (b) 180°, and (c) 270°

Figure 4.
Malapposition of stent strut for calcium arc at (a) 60°, (b) 180°, and (c) 270°