Finite Element Study on Influence of Stent Deployment upon Mechanical Response of Coronary Artery

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Abstract: A stent is a small medical device that is used to open the stenosed artery for securing blood flow. Since the stent has higher rigidity than the blood vessel, the stent deployment may induce stress concentration and damage on the vessel wall and may cause restenosis or thrombosis. In order to reduce the risk, it is important to understand the mechanical response occurring in the artery by the stent placement. In the present study, we performed the axisymmetric finite element analysis, in which the stent was modeled as rigid struts while the three-layered coronary artery was modeled according to the mechanical properties reported by Holzapfel et al., and then, the influences of the strut cross-sectional shape, the strut width, and the distance between struts on the deformation and the stress in the artery were investigated. The results revealed that the large stress was generated in the intima in the vicinity of the intima-media interface by the movement of the strut. It was found that the deformation and the maximum stress were more influenced by the distance between the struts than the cross-section shape and the strut width. The findings will be utilized to optimize the strut shape as well as the strut arrangement on designing the stent.

Keywords: Stent, Coronary artery, Finite element analysis, Deformation of an artery, Physical properties

1. Introduction

In recent years, patients with coronary artery diseases have been increasing due to food culture changes. As a treatment method for coronary artery diseases, balloon-expandable vascular stents have been used to widen narrowed blood vessels and secure blood flow. The stent is required to have mechanical properties such as radial stiffness holding the narrowed part in its expanded state [1] and bending flexibility capable to follow a curved blood vessel [2]. However, since the stent has higher rigidity than the blood vessel, the risk has been pointed out that the stent placement may induce mechanical stimulus, namely stress to the blood vessel and cause restenosis [3-5]. The stent may also have the risk to cause stagnant flow near the vessel wall. In order to reduce the risks, it is important to clarify the influences of the stent deployment upon the mechanical responses of the coronary artery [6].

This study aims to clarify the mechanical influences of the stent placement upon the coronary artery to contribute to the optimization of the stent design. Since the coronary artery consists of three layers, it is important to take into account the mechanical properties of the respective layers. Holzapfel et al. [7] performed tensile tests on individual layers of coronary artery samples and showed the stress-stretch relations. The mechanical properties of the layers were approximated by the James-Green-Simpson function which is adaptable to nonlinear elastic finite element analyses. In this study, a single-strut model and a multi-strut model having stenosis were developed. The cross-sectional shape of the stent strut was modeled as a circular rigid body or a rectangular rigid body, while the coronary artery with the stenosis was modeled as an axisymmetric long tube with a nominal inner diameter of 3 mm with a stenosed area. Using these models, axisymmetric finite element analyses were performed, in that, the stent struts were moved to expand the inner diameter of the coronary artery. Then, the stress and the stretch in the artery, deformation of the artery wall, and the reaction force induced by the stent placement were investigated. Although the stenosis is not necessarily formed in an axisymmetric, the axisymmetric finite element modeling using fine mesh is effective for the detailed investigation of the effects of the stent strut shape and the strut arrangement on the mechanical response of the coronary artery.

2. Analysis

2.1 Mechanical properties of coronary artery

Human arteries consist of three layers, intima, media, and adventitia. The stent is inserted and expanded in the artery, so that the outer surface of the stent contacts with the inner surface of the intima, as shown in Fig. 1. Each layer has different mechanical properties, due to different constituents [7, 8]. Among the Cauchy stress $\sigma$ - stretch $\lambda$ relations provided by Holzapfel, et al. [7], we selected the results of three specimens, IV, V, and VII. The Cauchy stress-stretch relations of those specimens were shown in Fig. 2. The rigidity of the intima is larger than those of media and adventitia. It is also obvious that the rigidity of the artery strongly depends on the specimen. The Cauchy stress-

Fig. 1 Coronary artery having three layers: Expanded stent contacts with intima in the artery
stretch relations were approximated by the exponential function as,

$$\sigma = \alpha \left\{ e^{\beta (\lambda - 1)} - 1 \right\}$$  \hspace{1cm} (1)

where $\alpha$ and $\beta$ are constants. The values of constants are summarized in Table 1.

The stress-stretch relations of Eq. (1) is then converted to the relationship between strain energy density $W$ and stretch $\lambda$ using James-Green-Simpson function [9],

$$W = C_{10} (I_1 - 3) + C_{01} (I_2 - 3) + C_{11} (I_1 - 3)(I_2 - 3) + C_{20} (I_1 - 3)^2 + C_{30} (I_1 - 3)^3$$  \hspace{1cm} (2)

where $W$ is the strain energy density, $I_1$ and $I_2$ are the first and the second invariants of stretch, and $C_{ij}$ are the nonlinear elastic material coefficients.

2.2 Finite element modeling and analysis condition

The finite element analysis was performed using the commercial software MARC (MSC software corp.). The displacement was given to the struts, to open the stenosed artery to the nominal inner diameter. In this study, two types of analysis models, a single-strut model, and a multi-strut model were constructed. In the general case of stenting operation, the stenosed vessel is once opened by the balloon catheter as a pre-treatment and then the stent is inserted. However, the objective of this study is the relative comparison of the influence of stent geometry on the mechanical response of the coronary artery, so that it can be considered as the analysis without pre-treatment is appropriate.

2.2.1 Single-strut model

The single-strut models of the coronary artery shown in Fig. 3 were developed for the detailed investigation of the influence of strut cross-sectional shape on the mechanical response in the coronary artery. Considering symmetry, the length in the axial direction of the artery model was set to 4 mm, while the initial inner diameter of the artery was 3 mm. The wall thickness was 0.88 mm with the thickness ratio of intima, media, and adventitia to be 3:4:4 [7]. In the stenosis model, the trapezoidal stenosis area was added. The minimum inner diameter of the stenosis area was 2.8 mm, which corresponds to the stenosis of about 13%. Although the mechanical properties of the stenosed area of arteries strongly depend on the condition of diseases [10], the comparison between the tensile test results of aortic plaques by Loree et al. [10] and those of respective artery layers by Holzapfel et al. [7] revealed that the tensile properties of the cellular plaques are about similar to those of the intima. Therefore, it was assumed that the properties of the stenosed area were the same as those of the intima in this study. The artery model was discretized using axisymmetric eight-node solid elements.

The stent struts were modeled as rigid bodies. One has a square cross-section with a side length of 100 $\mu$m having the corner fillet with a curvature radius of 5 $\mu$m. The other has a circular cross-section with a diameter of 100 $\mu$m.

In the coronary artery, it is known that there is a thin internal elastic membrane between intima and media, while a thin external elastic membrane exists between media and adventitia. Those membranes are not taken into account in the finite element modeling because they are much thinner than intima, media, and adventitia. Holzapfel et al. [7] anatomically separated the arterial samples into three layers,
2.2.2 Multi-strut model

Figure 4 shows the multi-strut model of the coronary artery, to investigate especially the influence of stent strut arrangement on the mechanical response in the coronary artery. The length and the inner diameter of the coronary artery model were determined as 40 mm and 3 mm, respectively. A half-length of the artery was modeled due to symmetry. The localized stenosed area was modeled to have a length of 12.6 mm and the minimum inner diameter of 1.356 mm, according to the report by Haude et al. [11].

Two different types of cross-sectional shapes of struts were used; one was a circle of 100 μm in diameter and another was rectangular with a height of 100 μm and the width \( w_s \). The struts were arranged with distance \( d_s \). The developed multi-strut models were summarized in Table 2.

The analysis with the multi-strut model was performed only on the specimen VII to intensively investigate the influence of stent strut arrangement on the mechanical response in the coronary artery under the consistent property of the coronary artery.

3. Results and Discussions

3.1 Influence of cross-sectional shape of a strut on mechanical responses of a coronary artery by single-strut model

The change in the reaction force generated by the strut displacement in the single-strut model was shown in Fig. 5.

It was seen that the reaction force of the model with stenosis was much larger than that without stenosis. Besides, there were large differences in the reaction force among the three specimens. The reaction force of the specimen IV was the largest, because of the largest rigidity of intima as shown in Fig. 2. On the other hand, the reaction force by the circle-section strut was almost the same as that by the square-section strut. This fact implies that the cross-sectional shape of strut scarcely influences on the reaction force of the coronary artery.

The distribution of stress in axial direction after the expansion to the inner diameter of 3.5 mm is shown in Fig. 6. The axial stress was selected to see the influence of stenosis on stress distribution. It was found that not only the inner diameter but also the outer diameter of the coronary artery became larger with the strut displacement. In the expanded region, the wall thickness was reduced to about 88% of the initial one in the model without stenosis. The obvious stress concentrations were observed in the intima region just on the stent strut and in the intima region in the vicinity of the intima-media boundary. The axial stress in the intima on the strut was compressive, while that close to the intima-media boundary was tensile because of the bending in the axial direction induced by expansion. There is no notable difference between the stress distributions with the square-section strut and the circle-section strut. On the other hand, the area of stress concentration spreads wider with stenosis. The comparison of the stress distribution of specimens IV, V, and VII with stenosis revealed that the magnitude of stress generated by the stent deployment was strongly influenced by the mechanical
properties of three layers. The rigidity of the intima especially had a strong influence on the magnitude of stress, that is, the harder intima induced larger stress. It also should be noted by the results shown in Fig. 6 that the stent is not embedded in the intima and protruded into the coronary artery. Such protrusion is considered inappropriate because it interferes with the blood flow and causes restenosis and thrombosis. Therefore, the optimization of the cross-sectional shape of the stent is required to avoid protrusion.

As to be shown in Fig. 6, the axial stress in the intima becomes larger than that in the media. This fact implies that the axial strain in the intima in the vicinity of the intima-media boundary is also different from that in the media. The occurrence of the strain difference may damage the artery and induce the change of mechanical stimulus, which causes problems such as intimal hyperplasia [12]. The difference in axial strains between the intima and the media in the vicinity of the intima-media boundary induced by the stent strut displacement is then investigated and is shown in Fig. 7. It was found that the strain difference of specimen IV was almost the same with that of specimen V. That is because the strain difference is affected mainly by the difference of stress-stretch relations between intima and media, not by the rigidity of each layer. It was also noteworthy to see that the strain difference of the model without stenosis was larger than that with stenosis. This tendency may be raised by the protruded stenosis that is possible to change the deformation pattern in the vicinity of the intima-media interface. It is then suggested that the shape of stenosis is one important factor affecting the stress and strain conditions in the artery by stent deployment.

3.2 Influence of strut arrangement on mechanical responses of a coronary artery by multi-strut model

3.2.1 Deformation of a coronary artery by stenting

Figure 8 shows the deformed shapes of the coronary artery and the maximum principal stress distributions when the stent strut was expanded to 3 mm in diameter in the multi-strut model. Although the stenosed area was opened after
stenting in all the models, the degree of inward bulging of the artery between struts strongly depends on the distance between struts.

The minimum inner diameters after stenting are summarized in Fig. 9. A comparison between the results of the circle strut models and the rectangular strut models revealed that the inner diameter of the former is smaller than the latter. This fact implies that the rectangular strut is better to open the artery than the circle strut. The inner diameter increases with larger strut width, however, the increasing rate is not so high. Meanwhile, inner diameter remarkably increases with decreasing the distance between struts, that is, an increase in the number of struts in the fixed length. Although the covering area ratio, which is the ratio of the area of artery contacting with the stent strut to the total stenting area, of Model R043W1 is almost the same with that of Model R130W3, the inner diameter of the former is much larger than the latter. From these facts, we can conclude that decreasing the distance between struts is more effective to secure the blood flow than widen the strut.

3.2.2 Maximum stress and stretch

The maximum principal stress distribution shown in Fig. 8 exhibits that the maximum stress appears in the intima just on the strut on the symmetry axis, where the stenosis area is the largest. Based on this fact, the stress evolution was evaluated by the averaged value of three nodes just on the strut along the symmetry axis shown in Fig. 4. The maximum principal stress plotted against the covering area ratio is shown in Fig. 10. A slight increase in the maximum stress was found with increasing the covering area ratio. However, the values of the maximum principal stress were too large for the intima of the artery, because the stress in the intima exponentially increases with the stretch as denoted by Eq. (1). In the tensile test results of Holzapfel et al. [7], the ultimate tensile stress of intima was 394 ± 223 kPa, and the ultimate tensile stretch was 1.6 ± 0.29. Those results of Holzapfel et al. [7] imply that the stress-stretch relation of Eq. (1) is not valid when the stretch becomes very large. Therefore, instead of the maximum principal stress, the nominal diameter of the struts, namely the inner diameter of intima just on the strut, when the maximum stretch reached 1.6 was investigated and plotted in Fig. 11. It was seen that the nominal diameter of the circle struts was a little larger than that of the rectangular struts. However, in all the models, the maximum stretch exceeded the ultimate tensile stretch of 1.6 when the nominal diameter of struts became about 2.19 mm, which is much less than the target diameter of 3 mm. This result implies that the local damage may occur in the stenosed area by the stent expansion, and further research is required on the stent design to reduce the risk of the damage.

3.2.3 Reaction force from artery to strut

The reaction force acting in the radial direction from the coronary artery to the stent strut appears after the expansion. This reaction force is necessary to keep the blood vessel open, on the other hand, the excessive reaction force induces the recoil of the stent, the shrinkage of the artery inner diameter, which may cause restenosis. Figure 12 shows the reaction force working on the strut at the stent expansion of 3 mm in diameter, with the position of strut \( x \) from the symmetry axis shown in Fig. 4. The maximum reaction force was found on Model R130W3 and the second maximum was on Model R130W2, which means the reaction force becomes larger with the larger width of the strut. A comparison between the results of the circle strut

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Fig. 9 Minimum inner diameter of artery models after stent expansion to 3 mm in diameter in multi-strut model of specimen VII

Fig. 10 Maximum principal stress values of models after stent expansion to 3 mm in diameter in multi-strut model of specimen VII

Fig. 11 Nominal diameter of struts at the maximum stretch reaches 1.6 in multi-strut model of specimen VII
and the rectangular strut revealed that the reaction force of the former is a little less than that of the latter. However, the advantage of the circle strut is small. It was found that the most effective way to reduce the reaction force is to decrease the distance between struts nevertheless of the strut shape. The maximum reaction forces acting on the models with the strut distance $d_1 = 0.43$ mm are about 30% less than those of the models with the strut distance $d_1 = 1.3$ mm.

In the practical stenting process, the shortening of the stent happens with the stent expansion and it may induce the reaction force also in the axial direction. However, the degree of the shortening strongly depends on the three-dimensional stent design and the discussion on the reaction force in the axial direction requires further study using a three-dimensional finite element model.

4. Summary

The mechanical response of the coronary artery during stenting was investigated by axisymmetric finite element analysis of single-strut models and multi-strut models.

By the analysis results with single-strut models, the comparison between the models with and without stenosis revealed that the stenosis induced the larger stress when the comparison between the models with and without stenosis was small but it was important concerning the blood flow. The large axial stress appeared in the intima, which was mainly induced by the difference of mechanical responses between intima and media. However, the smaller distances between struts require a larger number of struts in the fixed stent length, which may restrict the expandable diameter of the stent. Therefore, the optimization of the stent design requires to take into account not only the mechanical response of coronary artery investigated in this study but also the function and the reliability of the stent, as the medical devices.

On the other hand, the strut cross-sectional shape, as well as the width of the strut, did not induce remarkable advantages on the mechanical response of the artery. However, the smaller distances between struts require a larger number of struts in the fixed stent length, which may restrict the expandable diameter of the stent. Therefore, the optimization of the stent design requires to take into account not only the mechanical response of coronary artery investigated in this study but also the function and the reliability of the stent, as the medical devices.

**Nomenclature**

- $C_q$ coefficients in James-Green-Simpson strain energy density function [mJ/mm$^3$]
- $d_1$ distance between struts [mm]
- $I_1$ the first invariant of stretch [-]
- $I_2$ the second invariant of stretch [-]
- $x$ position of strut from symmetry axis [mm]
- $W$ strain energy density [mJ/mm$^3$]
- $w_s$ width of rectangular strut [μm]
- $a$, $β$ constants in Cauchy stress - stretch relation [-]
- $σ$ Cauchy stress [kPa]
- $δ$ stretch [-]

**References**


