The Effect of Plaque and Artery Parameters on Stent Expansion during the Implantation Process

Chao-Ming Hsu[1], Ah-Der Lin [2], Hui-Lung Chien[3], Yung-Yu Chen[3], Jao-Hwa Kuang[3,*]

[1] Department of Mechanical Engineering, National Kaohsiung University of Applied Science, Kaohsiung, Taiwan, R.O.C.
[2] Department of Mechanical Engineering, Cheng-Shiu University, Kaohsiung, Taiwan, R.O.C.
[3] Department of Mechanical and Electro-Mechanical Engineering, National Sun Yat-Sen University, Kaohsiung, Taiwan, R.O.C.

Abstract: The simulation results of stent expansion motion with considering the plague and artery stretch effect is presented. The 3D elastic-plastic finite element model was employed to simulate the artery stent implantation process. The axial symmetrical components of artery, plaque, metal stent and balloon are included in the proposed model. The curve fitted nonlinear elastic Ogden strain energy function has been used to describe the stress-stretch relationships of artery and plaque. Based on the ultimate strength of plaque, the stent implantation is divided into two stages. In the first expansion stage, the plaque is assumed to be distributed continuously in circumference during the stent's expansion. After the maximum stress in the plaque reaching the ultimate strength, i.e. into the second stage, the plaque is considered to be failed and cracked into two pieces. The simulated results present the relationship between the stent expansion and the pressure in balloon. The effects of plaque and artery parameters on the stent deformation are also studied in this work. Numerical results indicate that the proposed model is feasible to investigate the artery stent implantation process.
[Chao-Ming Hsu, Ah-Der Lin, Hui-Lung Chien, Yung-Yu Chen, Jao-Hwa Kuang. **The Effect of Plaque and Artery Parameters on Stent Expansion during the Implantation Process.** *Life Sci J* 2013;10(3):1717-1720]. (ISSN:1097-8135). http://www.lifesciencesite.com. 258

Keywords: Sent, Atery-plaque model, Ogden strain energy function

1. Introduction

Coronary artery atherosclerosis is featured by the atherosclerotic plaque accumulation at the inner wall of the coronary artery. The symptom can induce artery stenosis, reduce blood flow and finally lead to myocardial infraction. Among the treatments of coronary artery atherosclerosis, percutaneous transluminal coronary angioplasty with stent implantation is preferred in view of shorter hospital stays. The idea of stent implantation for supporting artery wall was initially described by Dotter and Judkins in 1964 [1]. In 1985, the method of stent expanded by inflating balloon was proposed by Palmaz et al [2]. In the stent implantation operation, a stent mounted on a balloon catheter is delivered to the stenosis site, and then the balloon is inflated to expand the stent. The expansion of the stent will restore the blocked artery and produce normal blood flow. Several clinical experiments of stent implantation in human body were subsequently proceeded [3, 4], and the routine clinical treatment of stent implantation began in the 1990s [5]. In the biomedical engineering field, some of the stent studies used the finite element analysis (FEA) to investigate the mechanic behavior of the stent [5-9]. As to the stent implantation, an optimal stent design is concerned with less stent foreshortening, radial recoil, and dogboning, etc. A qualified stent is also expected to have a uniform expansion in the operation. In the implantation operation, the stent takes compression from balloon and resistance from plaque and artery wall. However, according to the studies [5-9], the effects of plaque and artery parameters were not fully studied. It is obvious that a feasible numerical model should take account of plaque and artery parameters in the simulation for the stent expansion process. Different material behavior models for plaque and artery wall were introduced in the pioneering studies [10-14]. Roger et al. [11] assumed a linear elastic material behavior model for plaque and artery wall. Auricchio et al. [12] considered that the material behavior of plaque and artery wall was nonlinear elastic. In the nonlinear elastic model, the strain energy functions were proposed for the stent studies, such as Mooney-Revlin strain energy function. A special viscoplastic material behavior model was presented by Liang et al. [14] for simulating plaque and assessing the injury of artery wall. Plaque, squashed by the stent surface and strut edges, goes failed and split into pieces during the stent expansion process. Most models of the pioneering works did not consider the influences of the plaque crash in the stent expansion process.

In this study, a FEA model is proposed for simulating the stent expansion process. In the model, the parameters for artery wall and plaque are included [15]. Particularly, a two-phase artery-plaque model is proposed for evaluating plaque failure and split in the stent implantation. Nonlinear elastic Ogden strain energy function is used to describe the stress-stretch relation of artery and plaque. The simulation will reveal the relationship between the stent expansion and the pressure in balloon. The effects of plaque and artery parameters on the stent deformation are also studied in this work.

2. Finite element method

In this study, the stent expansion process is simulated by a commercial FEA package, ABAQUS. The FEA model includes balloon, stent, plaque, and artery. The element for the proposed model is a 1/16 symmetrical three-dimensional one with 1/8 circumferential and 1/2 axial symmetry, as shown in Figure 1. The mesh model for balloon, stent, plaque, and artery has 10349 eight-noded hexahedron elements. The dimensions and material properties for the proposed FEA model are listed in Table 1.

2.1. Stent and balloon

The Palmaz type stent is used in this study. The stent has a slot length of 1.512 *mm* and a slot angle of 7.5 degrees, respectively. The studies [9, 10, 14] used a balloon of the cylindrical shape. To simulate the balloon inflation under the active pressure, these studies assumed virtual balloon Young's moduli whose values are much less than the real value. In this study, observed from the stent implantation process, the balloon is simulated as 16 folds about the axis in the FEA model. The Young's modulus of semi-compliant material [11] takes 690 *MPa* in this study. To confirm the feasibility of the assumed folded balloon model, the simulation of inflating the balloon is carried out. The simulation results have a good agreement with the measured data of a Cordis AQUA-T3 balloon [16], as shown in Figure 2.

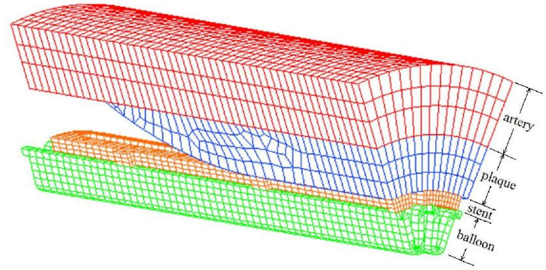


Figure 1. Finite element model for stent implantation

Table 1. Dimensions and mechanical properties of different parts in finite element model

item	artery wall	plaque	stent	balloon
outer diameter (mm)	3.5	2.5	1.7	nil
thickness (mm)	0.5	0.4	0.1	0.05
length (mm)	4.284	3.36	4.284	4.284
material model	nonlinear (Ogden)	nonlinear (Ogden)	elastoplastic	linear elastic
Young's modulus (GPa)	nil	nil	196	0.69
yielding strength (GPa)	nil	nil	205	nil
Poisson's ratio	nil	nil	0.3	0.3

2.2. Two-phase artery-plaque model

During the stent expansion, the plaque distribution takes one of the two phases, continuous and split. At the initial stage of the stent expansion, the plaque distribution is continuous around circumference. Later, owing to the compression of stent, the plaque distribution is discontinuous with gaps around circumference. In this study, the proposed model is named as a two-phase artery-plaque (TPAP) model. The plaque phase transition, from a continuous phase to a discontinuous phase, is decided by the plaque maximum stress which reaches the plaque ultimate strength of 0.65 *MPa* [14]. In FEA simulation, the plaque elements initially distribute in a cylindrical shape (the continuous phase). Following is the balloon expansion which expands the stent and pushes the plaque. When the maximum von Mises stress of plaque reaches 0.65 *MPa*, the plaque elements on the axial symmetric plane become inactive (the second phase). Figure 3 shows the transverse section of TPAP model.

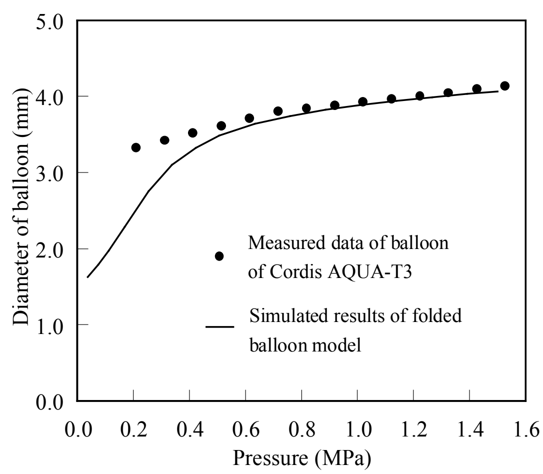


Figure 2. Comparison of the folded balloon model and the measured data of Cordis AQUA-T3 balloon [16]

2.3. Material properties

In the simulation, the stent material is 316L stainless steel and its material is elastoplastic The balloon material behavior is assumed to be linear elastic. The material properties are cited from literatures [11, 12] and listed in Table 1. In the simulation, the nonlinear elastic Ogden model is introduced to describe the stress-stretch relationship for the coronary artery and plaque. Based on the strain energy function of the stretches and the constraints of incompressibility for a biological material, Ogden proposed the strain energy function as [17]

$$U = \sum_{n=1}^{N} \frac{\mu_n}{\alpha_n} \left(\lambda_1^{\alpha_n} + \lambda_2^{\alpha_n} + \lambda_3^{\alpha_n} - 3 \right) \qquad (1)$$

where U denotes the strain energy function for the nonlinear elastic Ogden model. N is the item number. λ_1, λ_2, and λ_3 represent the principal stretches. α_n and μ_n are material constants used in the Ogden model. In the simulation, the material constants are found by the curve-fitting method substituting the artery and plaque measured data into the Ogden model. These constants, μ_1, μ_2, α_1, and α_2, are listed in Table 2 [15]. The fitted curves of the Ogden models for the coronary artery and plaque are shown in Figure 4 [15]. The maximum inflation pressure of balloon is 1.5 *MPa*. When constructing the proposed FE model, all materials are assumed homogeneous and isotropic. The contact elements between balloon, stent, plaque and artery are frictionless in the FEA analysis.

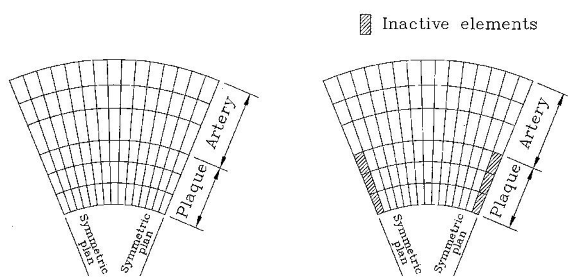


Figure 3. Transverse section of the proposed two-phase artery-plaque (TPAP) model

Table 2. Curve-fitted Ogden model parameters for coronary artery and plaque [15]

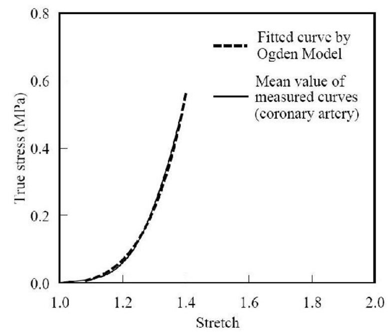
	μ_1 (MPa)	μ_2 (MPa)	α_1	α_2
artery	1.755×10^{-2}	-11.39	10.79	1.661×10^{-2}
plaque	1.437×10^{-3}	4.366×10^{-9}	45.03	32.48

3. Results and discussion

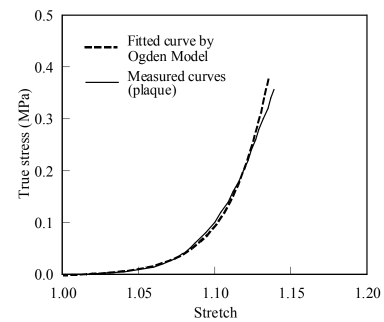
To express the size variation in the radial direction for the stent, the radial expansion ratio of stent is defined by equation (2),

$$\text{Radial expansion ratio} = \frac{D - D_0}{D_0} \times 100\% \qquad (2)$$

where D_0 and D are the inner diameter of stent with and without balloon pressure, respectively.



(a) Coronary artery



(b) Plaque

Figure 4. Ogden model for the coronary artery and plague [15]

Using the proposed TPAP model, the variation of radial expansion ratio under pressure is shown in Figure 5. It is observed that the stent expansion has three stages, which are marked by the curve segments, SU, UV, and VW. In the first stage (segment SU), the plaque distribution has a shape of an all-circumferential cylinder and keeps intact. The intact and tough plaque can withstand a high compression from the stent expansion. In this stage, the stent extends slowly and has a tendency of slowdown in the segment TU. At the point U, when the deployed pressure is about 1.0 *MPa*, the maximum value of stress for plaque reaches the ultimate strength 0.65 *MPa*. It is observed that the plaque distribution turns into the second phase. This alteration presents that the plaque is failed and split. From the point U on, the plaque distribution is circumferentially discontinuous on the inner surface of the artery wall. The plaque loses its ability to resist the stent expansion. At the second stage (segment UV), the plaque is so weak that the stent extends suddenly, marked by a jumping up. As shown in Figure 5, the stent expansion ratio increases rapidly from 20.3% to 131.5% accompanying with a very small pressure increment of 0.049 *MPa*. At the third stage, represented by segment VW, the circumferential stretch of the arterial wall increases and limits the expansion of the stent. At the final stage, the recoil of the stent is found when the pressure is released.

To discuss the characteristics of the TPAP model, the following three models are presented and applied in the stent expansion simulation.

I. Model A: The plaque distribution is always continuous around circumference during the whole stent expansion process. In this model, the plaque distribution is continuous.

II. Model B: The plaque distribution is always discontinuous with gaps around circumference during the whole stent expansion process.

III. Model C: The stent is freely expanded without considering the artery wall and plaque effects.

The simulation results of the A, B and C models are shown in Figure 5. As to the model A, the radial expansion ratio variation is the same as that of the TPAP model at the initial stage, segment SU. The segment UX of the model A indicates that the increase of pressure can only produce a small stent expansion. It is attributed that continuous plaque has strong constraints on the stent expansion. However, this result does not fit with the actual outcome in the stent implantation. It is concluded that the plaque split effect should be considered in the simulation models. The difference between the model B model and the TPAP model is featured by the segments TW and T-U-V-W. It is obvious that the radial expansion ratio of the TPAP model has a jumping-up at this stage. For the model B, the ratio of the stent diameter increment to the pressure increment between point T and V is 4.74 *mm/MPa*. However, the ratio at the UV segment of the TPAP model is 34.01 *mm/MPa*. The jumping-up of the TPAP model represents the plaque phase transition, from a continuous phase to a discontinuous phase. In reality, the TPAP model is more feasible than the model B. The curve of the model C is very similar to that of the model B. From the numerical results for the B, C and TRAP models, it is obvious that the strength of stent dominates the final radial expansion ratio.

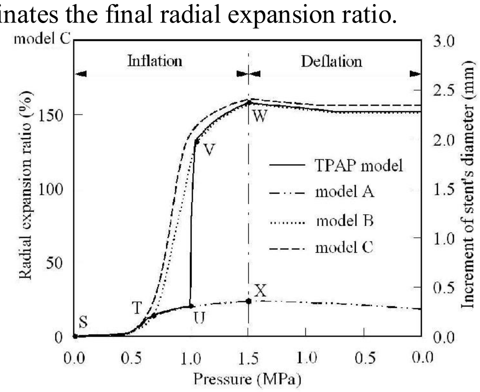


Figure 5. Radial expansion ratio variations for different models

Figure 6 shows the influence of the plaque thickness on the radial expansion ratio for stent. The pressures at the phase transition points are 0.90, 0.95, 1.00, 1.10, and 1.20 *MPa* for the thicknesses of 0.2, 0.3, 0.4, 0.5, and 0.6 *mm*, respectively. At the plaque transition points, all cases have rapid stent expansion. The results show that the pressure of the plaque transition point increases as the plaque thickness increases.

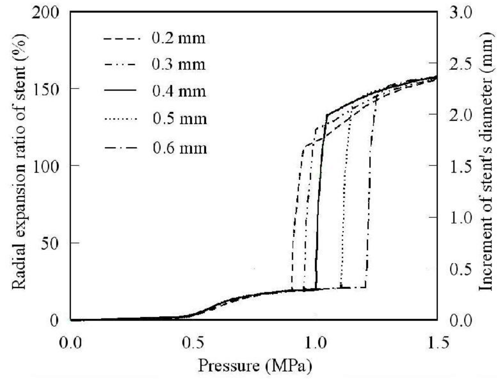


Figure 6. Numerical results of the TPAP model with different plaque thicknesses

4. Conclusion

The finite element simulation was employed to investigate stent expansion during implantation with considering the effects of artery wall and plaque. The Ogden material model was introduced to describe the material behavior for the artery wall and plaque. The material constants were found the curve-fitting method. The two-phase artery-plaque (TPAP) model was proposed to simulate the stent implantation process. The numerical results revealed that a stent expands very slowly in the initial stage. At the phase transition point, representing the plaque split, the stent expansion increases suddenly. At the final stage, the stent expansion ratio slows down and gradually approaches to a stationary value. In this paper, the influence of the plaque thickness on the stent expansion ratio was also investigated.

5. References

1. Gupta P., Tenhundfeld G., Daigle. EO, Schilling PJ, Synthesis and characterization of hard metal coatings by electro-plasma technology, Surface and Coatings Technology, Vol. 200, pp. 1587-1594, 2005.
2. Philipp M. K., Water Plasma Electrolysis, http://Kanarev.innoplaza.net.
3. Weichao G., Dejiu S., Deposition of duplex Al2O3/ aluminum coatings on steel using a combined technique of arc spraying and plasma electrolytic oxidation ", Applied Surface Science, Vol. 252, pp. 2927-2932, 2006.
4. P. Gupta, G. Tenhundfelda, E.O. Daiglea and D. Ryabkov, Electrolytic plasma technology: Science and engineering—An overview, Surface and Coatings Technology, Vol. 201, pp. 8746-8760, 2007.
5. P. Gupta and G. Tenhundfeld, Surface And Mechanical Properties Of Steel Cleaned By Electro-Plasma Technology, Plating and Surface Finishing, Vol. 92, pp. 48-52, 2005.

8/2/2013.