

University of Nebraska - Lincoln

DigitalCommons@University of Nebraska - Lincoln

Mechanical & Materials Engineering Faculty
Publications

Mechanical & Materials Engineering,
Department of

11-2017

OCT-BASED THREE DIMENSIONAL MODELING OF STENT DEPLOYMENT

Pengfei Dong

University of Nebraska-Lincoln

David Prabhu

Case Western Reserve University

David L. Wilson

Case Western Reserve University


Hiram G. Bezerra

Cleveland Medical Center Cleveland

Linxia Gu

University of Nebraska-Lincoln, gul@fit.edu

Follow this and additional works at: <https://digitalcommons.unl.edu/mechengfacpub>

 Part of the [Mechanics of Materials Commons](#), [Nanoscience and Nanotechnology Commons](#), [Other Engineering Science and Materials Commons](#), and the [Other Mechanical Engineering Commons](#)

Dong, Pengfei; Prabhu, David; Wilson, David L.; Bezerra, Hiram G.; and Gu, Linxia, "OCT-BASED THREE DIMENSIONAL MODELING OF STENT DEPLOYMENT" (2017). *Mechanical & Materials Engineering Faculty Publications*. 276.

<https://digitalcommons.unl.edu/mechengfacpub/276>

This Article is brought to you for free and open access by the Mechanical & Materials Engineering, Department of at DigitalCommons@University of Nebraska - Lincoln. It has been accepted for inclusion in Mechanical & Materials Engineering Faculty Publications by an authorized administrator of DigitalCommons@University of Nebraska - Lincoln.



HHS Public Access

Author manuscript

Int Mech Eng Congress Expo. Author manuscript; available in PMC 2018 March 28.

Published in final edited form as:

Int Mech Eng Congress Expo. 2017 November ; 3: . doi:10.1115/IMECE2017-72146.

OCT-BASED THREE DIMENSIONAL MODELING OF STENT DEPLOYMENT

Pengfei Dong,

Department of Mechanical & Materials Engineering, University of Nebraska-Lincoln, Lincoln, NE 68588, USA

David Prabhu,

Department of Biomedical Engineering, Case Western Reserve University, Cleveland, OH 44106, USA

David L. Wilson,

Department of Biomedical Engineering, Case Western Reserve University, Cleveland, OH 44106, USA

Hiram G. Bezerra, and

Department of Medicine-Cardiovascular Medicine UH Cleveland Medical Center Cleveland, OH 44106, USA

Linxia Gu

Department of Mechanical & Materials Engineering, University of Nebraska-Lincoln, Lincoln, NE 68588, USA

Abstract

Stent deployment has been widely used to treat narrowed coronary artery. Its acute outcome in terms of stent under expansion and malapposition depends on the extent and shape of calcifications. However, no clear understanding as to how to quantify or categorize the impact of calcification. We have conducted ex vivo stenting characterized by the optical coherence tomography (OCT). The goal of this work is to capture the ex vivo stent deployment and quantify the effect of calcium morphology on the stenting. A three dimensional model of calcified plaque was reconstructed from ex vivo OCT images. The crimping, balloon expansion and recoil process of the Express stent were characterized. Three cross-sections with different calcium percentages were chosen to evaluate the effect of the calcium in terms of stress/strain, lumen gains and malapposition. Results will be used to the pre-surgical planning.

INTRODUCTION

Percutaneous intervention, such as stenting, has been widely used for the treatment of artery stenosis [1]. The plaque, accumulated in the vessel, is composed of lipids, calcium, collagen, and inflammatory infiltrates, etc. [2]. Calcifications are of great concern when planning and implementing stenting due to abnormal stiffness [3, 4]. For example, the calcification was associated with under expansion or incomplete expansion of the stent[5], even the rupture of fibrous cap [6, 7], Calcifications altered the stress distribution in the artery which was correlated with the hyperplasia of the neointimal[5, 8]. The extent and shape of

calcifications could affect the decisions on surgical techniques [9], however its quantitative characterization is lacking.

Our previous work has shown that a larger arc of calcium led to stent malapposition and under expansion[10]. Our ongoing ex vivo stenting experiment could characterize the lesion composition and detailed morphology by OCT [11]. The goal of this work is to capture the ex vivo stent deployment and quantify the effect of calcium morphology on the performance of stenting. A patient-specific artery model with calcified plaque was reconstructed based on OCT images. The influence of the calcium on the stenting outcome was evaluated in term of stress/strain, lumen gains and malapposition. This work could provide insights for pre-clinical planning for complicated lesions.

MATERIALS AND METHODS

A three dimensional model of plaque with detailed calcium distributions was reconstructed based on OCT images with the commercial software Mimics (Materialize, NV). The OCT images in this work generated by OCT machine (Cleveland Clinic), with the pixel's size of 8.2 μ m, and the distance between adjacent images is 200 μ m. The grey color in the images represents the plaque and the light color represents the calcium in the plaque (Figure 1a). In Mimics, the size of the lumen diameter and the distribution of the calcium can be observed and measured. As seen in the images, the lesion lumen of the vessel is eccentric with a diameter range from 0.5mm to 1.6mm.

Model reconstruction

The reconstruction of the tissue model actually is kind of reverse engineering problem, for which the model was constructed based on the measure of the object, rather than the designed parameters. The model development process was illustrated in figure 1 (part of the model). First, according to the difference of the calcium and the soft plaque in OCT images, transform the OCT images into .bmp images, which contains calcium and soft plaque, represent by different colors, then imported into Mimics. In Mimics, extract the contour line of each image, which represents the profile of the plaque (the red line in figure 1b). The model contains all the contour lines called polyline model. Connect adjacent contour lines to generate the surfaces of the plaque to create the geometry model of the plaque. Ultimately, mesh the surfaces of the geometry model to generated the surface element and volume element model. The mesh convergence was performed and 258799 tetrahedron elements with element size of 0.1mm were adopted for the plaque including calcium.

The artery was constructed by offsetting the meshed outer surface of the plaque with a thickness of 0.5 mm [12]. The Express stent, with the nominal diameter of 3 mm, length of 16mm, thickness of 0.13 mm, and strut width of 0.2 mm, was deployed inside the lumen.

Material property

The material property of the Express stent, which made of 316 L stainless steel, described by a perfect linear elastic-plastic material with the Young's modulus as 190 GPa, Poisson's ratio as 0.3, yield strength as 207MPa. All lesion tissues were considered as hyperelastic

isotropic materials based on our previous work [10]. Their constitutive model was a third order polynomial strain energy density function U with coefficients

$$U=C_{10}\cdot(I_1-3)+C_{01}\cdot(I_2-3)+C_{11}\cdot(I_1-3)\cdot(I_2-3)+C_{20}\cdot(I_1-3)^2+C_{02}\cdot(I_2-3)^2+C_{03}\cdot(I_1-3)^3+C_{03}\cdot(I_2-3)^3$$

(1)

Where I_1 and I_2 are the first and second invariants of the Cauchy-Green tensor:

$$I_1=\lambda_1^2+\lambda_2^2+\lambda_3^2 \quad (2)$$

$$I_2=1/\lambda_1^2+1/\lambda_2^2+1/\lambda_3^2 \quad (3)$$

The material coefficients C_{ij} were listed in table 1. For the soft plaque, the plastic behavior was considered with a perfect plastic model. the yield stress of soft plaque is of 0.07MPa.

According to the previous experiments results, the plaque and calcium have different material properties. In this work, the calcium was segmented from plaque by assigning different material properties. In Mimics, the grey color of the plaque and the light color of the calcium has a different value, the grey value at local region can be calculated automatically, which provide a method to segment the calcium at the element stage. it's convenient to assign the material based on the average value of each element, by which the calcium and plaque are segmented (Figure 1e).

Boundary conditions

Consider the physiological environment in the body and the stenting process, a symmetric constrains were applied to both ends of the artery. The pre-balloon expansion was implemented using displacement control. The stent was crimped from the diameter of 3 mm to 1 mm, then it was expanded till 2.5 mm. The expansion diameter was 10% larger than the nominal diameter of the vessel. The contact between the stent and the tissue is a general contact consider the self-contact of the stent itself with a frictionless method[5].

RESULTS

The representative cross-section profiles with the ratio of calcium 54.70%, 37.31%, 7.78% respectively were chosen to show the effect of calcium on the stenting outcomes (Figure 2). The performance of stenting was investigated in term of using lesion stress and strain, lumen gain and malapposition of stent struts.

Stress and strain

The stress and strain distribution in these three cross-sections were shown in Figure 3. It can be seen the calcium always showed a higher stress compared with the soft plaque, it may due to the higher stiffness of the calcium. Stress concentration appeared at the ends of the calcium along the circumferential direction. In the soft plaque, the strain at the location near the ends of the calcium is higher than other positions.

Lumen gains

The changes of lumen area before and after the stent deployment was shown in table 2. The lumen gains of the lesion vessel, represented by the ratio of the lumen area after stenting to that before stenting, is usually related with the ratio of calcium in the plaque, in the cross-section a, even the initial lumen area is larger than b and c, while the lumen gains is lower due to the severe calcium. In this model, the thickness and the arc angle combined together contributed to the volume ratio of the cross section, also we need to notice that the lumen gains not only related to the ratio of the calcium in the certain cross section, also related to the morphology of the calcium.

Malapposition

The malapposition of the stent strut were investigated in term of the maximum/minimum, the average and percentage of malapposition struts in the cross-section (Table 3). Consider the measurement error, the malapposition less than 0.01 mm were ignored in this work, as shown in figure 3a, there are 20 struts in each cross-section and there are three struts malapposed in each cross-section. At the cross-section c, the maximum is 0.189 mm, which is due to the sharp corner of the lumen, the malappositions in cross-section a may be induced by the large angle of the calcium arc.

DISCUSSION

The presence of the calcium will affect the outcomes of the stenting and the treatment of the severe calcium is still a challenge for clinicians, not even the long-term outcomes[13, 14]. Consider the complex morphology of the plaque and calcium, a three dimensional configurations of the plaque and the calcium were reconstructed from OCT images through segmentation based on the gray levels. The role of calcifications on the acute outcomes of stenting was demonstrated through three cross-section profiles with the volume ratio of calcium 54.70%, 37.31%, 7.78% respectively. Results have shown that the peak stress and strain occurred at the interface between the calcium and plaque. Lumen gain is positively correlated with the volume ratio of the calcium. However, the malapposition do not exhibit any obvious relationship with the volume ratio of the specific cross section.

It showed stress concentration at the ends of the calcium along the circumferential directions. The soft plaque tissue showed a higher strain than calcium, especially near the ends of the calcium, which indicated a higher stretch at that position. This phenomenon may attribute to the material mismatch. This aligned with the observations in literature. Specifically, Zhao et.al. has demonstrated that [10] the arterial stress with calcified lesion is less than that with soft plaque and the lumen gain is adversely associated with the extent of

calcifications. The calcification was considered as a protection for artery in terms of stresses [5]. The fracture of calcifications, ignored in the previous and current work, might altered these observations.

The malapposition of the strut will change the hemodynamic environment of the artery and induce the pathological change of the vessel, resulting in adverse impact in the artery. Our results have shown that the malapposition do not exhibit any obvious relationship with the volume ratio of the specific cross section. It is the combinational effect of the angle of the calcium arc[15], and the morphology of the calcium, including the thickness and the length. We observed that the irregular shape of the lumen, such as the sharp corner, plays important role on the malapposition. As a local non-fully contact of the strut and artery wall, malapposition of stent strut relies more on the profile of the lumen. The model in this work didn't consider the axial movement at the ends of the artery. Isotropic material models adopted for the artery and plaque tissue, which may come up with some differences from the realistic situations. Despite these simplifications, the present work demonstrated the importance of calcifications on acute outcomes of stenting, which may have significant clinical implications for pre-clinical planning and long-term stenting outcomes.

CONCLUSION

In this work, the artery model with calcified plaque was constructed to evaluate the influence of the calcium on the outcomes of stenting. Lesion stress/strain, lumen gains and malapposition were investigated at different cross sections of the model. The results showed the morphology of the calcium plays an important role in the stress distribution and lumen gains after stenting. The eccentric lumen shape and the calcium induce the malapposition of the stent strut. The results in this work may help researchers and doctors deeply understand the complex response of the vessel to the stenting. This work will provide a fundamental understanding of the interaction between the reconstructed heterogeneous lesion and stent, to provide guidance for choosing the surgical techniques in the presence of calcification

Acknowledgments

The authors gratefully acknowledge the support by the National Science Foundation CAREER award (CBET-1254095)

References

1. Zahedmanesh, H., Cahill, PA., Lally, C. Vascular stent design optimisation using numerical modelling techniques. InTech; City: 2012.
2. Naghavi M, Libby P, Falk E, Casscells SW, Litovsky S, Rumberger J, Badimon JJ, Stefanadis C, Moreno P, Pasterkamp G. From vulnerable plaque to vulnerable patient. *Circulation*. 2003; 108(14): 1664–1672. [PubMed: 14530185]
3. Holzapfel GA, Sommer G, Regitnig P. Anisotropic mechanical properties of tissue components in human atherosclerotic plaques. *Transactions of the ASME-K-Journal of Biomechanical Engineering*. 2004; 126(5):657–665.
4. Teng Z, Zhang Y, Huang Y, Feng J, Yuan J, Lu Q, Sutcliffe MP, Brown AJ, Jing Z, Gillard JH. Material properties of components in human carotid atherosclerotic plaques: a uniaxial extension study. *Acta biomaterialia*. 2014; 10(12):5055–5063. [PubMed: 25200842]

5. Pericevic I, Lally C, Toner D, Kelly DJ. The influence of plaque composition on underlying arterial wall stress during stent expansion: the case for lesion-specific stents. *Medical engineering & physics*. 2009; 31(4):428–433. [PubMed: 19129001]
6. Byrne RA, Joner M, Kastrati A. Stent thrombosis and restenosis: what have we learned and where are we going? The Andreas Grüntzig Lecture ESC 2014. *European heart journal*. 2015; 36(47): 3320–3331. [PubMed: 26417060]
7. Madhavan MV, Tarigopula M, Mintz GS, Maehara A, Stone GW, Généreux P. Coronary artery calcification: pathogenesis and prognostic implications. *Journal of the American College of Cardiology*. 2014; 63(17):1703–1714. [PubMed: 24530667]
8. Shimada Y, Kataoka T, Courtney BK, Morino Y, Bonneau HN, Yock PG, Grube E, Honda Y, Fitzgerald PJ. Influence of plaque calcium on neointimal hyperplasia following bare metal and drug-eluting stent implantation. *Catheterization and cardiovascular interventions*. 2006; 67(6):866–869. [PubMed: 16649232]
9. Gil R, Di Mario C, Prati F, von Birgelen C, Ruygrok P, Roelandt JR, Serruys PW, Van Swijndregt W, Ligthart J. Influence of plaque composition on mechanisms of percutaneous transluminal coronary balloon angioplasty assessed by ultrasound imaging. *American heart journal*. 1996; 131(3):591–597. [PubMed: 8604642]
10. Zhao S, Gu L, Froemming SR. Finite element analysis of the implantation of a self-expanding stent: impact of lesion calcification. *Journal of Medical Devices*. 2012; 6(2):021001.
11. Devantier TA, Nørgaard BL, Øvrehus KA, Marwan M, Poulsen MK, Achenbach S, Dey D, Videbech P. Coronary plaque volume and composition assessed by computed tomography angiography in patients with late-onset major depression. *Psychosomatics*. 2014; 55(3):243–251. [PubMed: 24360626]
12. Zahedmanesh H, Kelly DJ, Lally C. Simulation of a balloon expandable stent in a realistic coronary artery—Determination of the optimum modelling strategy. *Journal of Biomechanics*. 2010; 43(11):2126–2132. [PubMed: 20452594]
13. Liu W, Zhang Y, Yu C-M, Ji Q-W, Cai M, Zhao Y-X, Zhou Y-J. Current understanding of coronary artery calcification. *Journal of geriatric cardiology: JGC*. 2015; 12(6):668. [PubMed: 26788045]
14. Abazid RM, Kattea MO, Smettei OA, Beshir Y, Sakr H. Impact of coronary artery calcification on percutaneous coronary intervention and postprocedural complications. *Journal of the Saudi Heart Association*. 2017; 29(1):15–22. [PubMed: 28127214]
15. Alegría-Barrero E, Chan PH, Foin N, Syrseloudis D. Predictors of stent strut malapposition in calcified vessels using frequency-domain optical coherence tomography. *J Invasive Cardiol*. 2013; 25(9):429–434. [PubMed: 23995714]

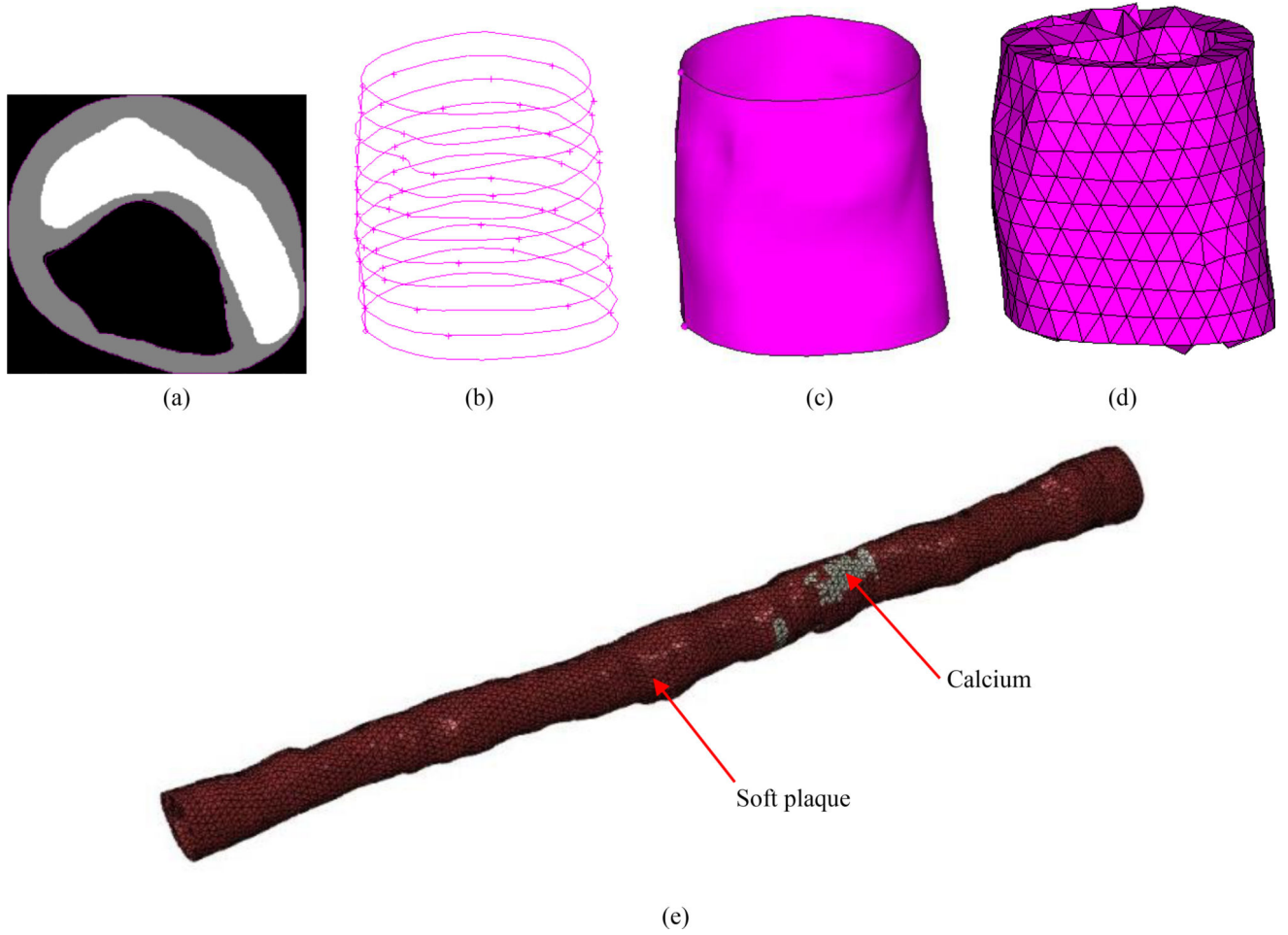


Figure 1. the reconstruction of the plaque model (a) OCT image b) polyline model c) geometry model d) mesh model e) material assignments

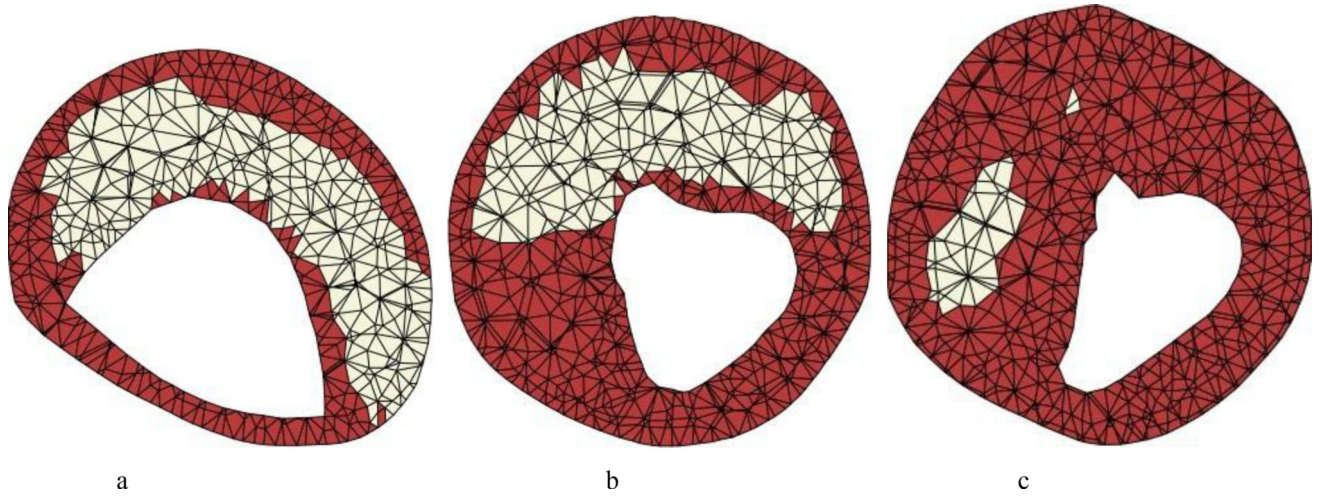


Figure 2.
Cross sections of plaque model

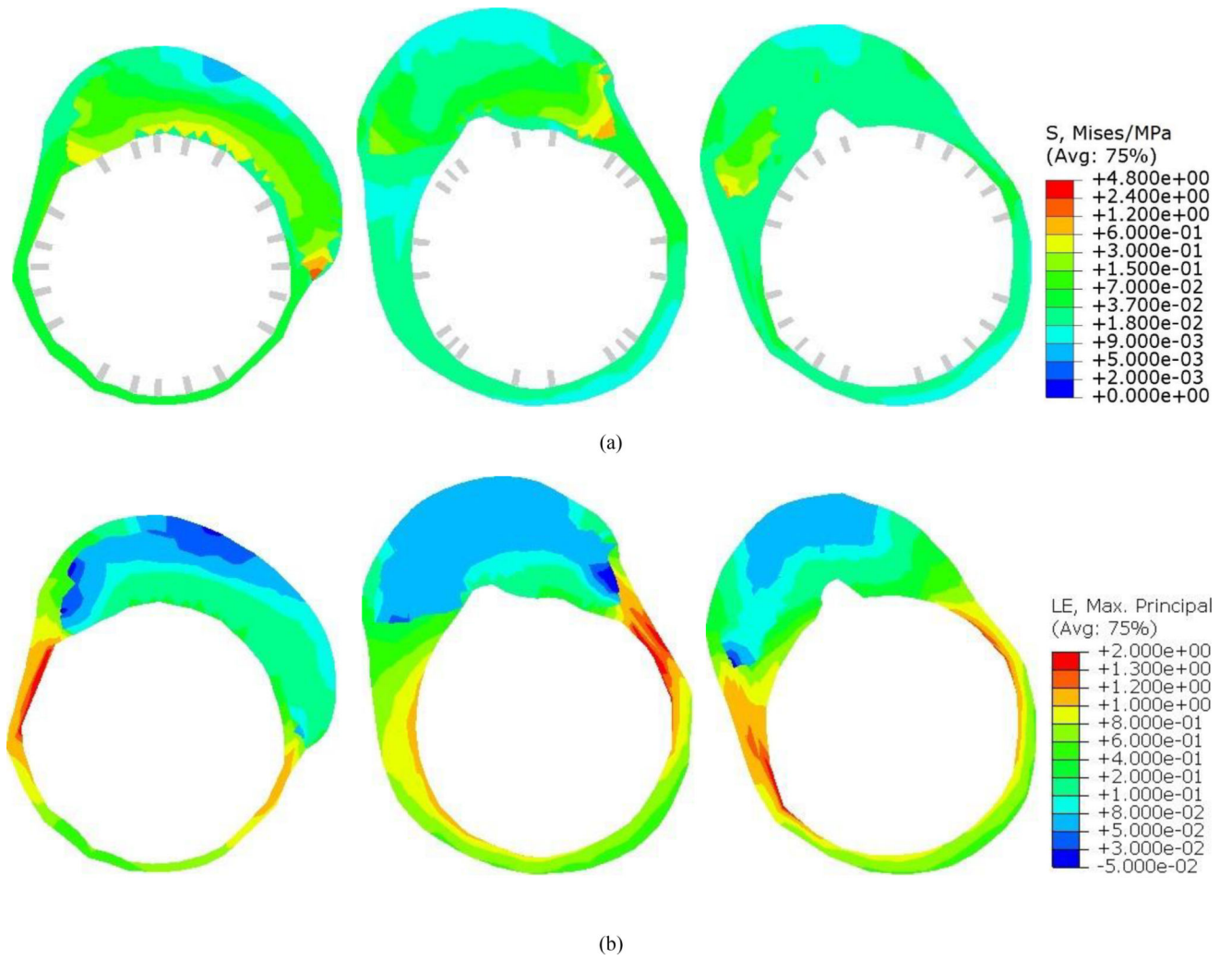


Figure 3. Stress and strain distribution (a) Stress distribution, (b) Strain distribution.

Table 1

Material coefficient

	C10(MPa)	C01(MPa)	C11(MPa)	C20(MPa)	C02(MPa)	C30(MPa)	C03(MPa)
Artery	0.10881	-0.101	-0.1790674	0.0885618	0.062686		
Plaque	0.04				0.003		0.02976
Calcium	-0.49596	0.50661	1.19353	3.6378		4.73725	

Table 2Lumen gains of three cross-sections/mm²

Lumen area	Cross-section a	Cross-section b	Cross-section c
Before stenting	0.797	0.470	0.369
After stenting	2.893	2.453	2.390
Ratio of lumen area	3.630	5.219	6.477

Author Manuscript

Author Manuscript

Author Manuscript

Author Manuscript

Table 3

Malapposition of stent strut /mm

Malapposition	Cross-section a	Cross-section b	Cross-section c
Maximum	0.021	0.070	0.167
Average	0.020	0.047	0.059
Number of malapposed struts	2	4	4

Author Manuscript

Author Manuscript

Author Manuscript

Author Manuscript