Graduate School of Creative Science and Engineering
Waseda University

博 士 論 文 概 要
Doctoral Thesis Synopsis

論 文 題 目
Thesis Theme

Study on Expansion Performance of Calcified Coronary Arteries by Finite Element Modeling and Analysis of a Balloon with Blades
ブレード付バルーンの 有限要素モデル化と解析による 冠動脈石灰化病変の拡張性能に関する研究

申 請 者
(Applicant Name)

Xiaodong	ZHU
朱	暁冬

Department of Modern Mechanical Engineering,
Research on Mechanical Engineering in Medical Field

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Coronary artery disease has been recognized as the first cause of death in the world among the common causes of death in non-communicable diseases, which induced the largest number of deaths in 2017 and a high increase of 22.3 % from 2007 to 2017. Coronary artery calcification is a risk factor associated with major adverse cardiovascular events and increases luminal stenosis and cause of coronary artery thrombosis. Although drug-eluting stents have substantially reduced the rate of in-stent restenosis and have improved clinical outcomes compared with those of bare-metal stents, coronary artery calcification is still a problematic lesion, increasing the possibility of procedural failure and the risk of complications after conventional balloon angioplasty. Furthermore, it is associated with stent underexpansion, a higher rate of restenosis, and stent thrombosis compared with simpler lesions. Therefore, plaque modification, utilizing cutting balloon, scoring balloon, or rotational atherectomy devices for calcified artery lesions prior to stent implantation is a key procedure in percutaneous coronary intervention.

Cutting balloon angioplasty has been a useful alternative treatment for calcified artery lesions before stent implantation. The cutting-balloon catheter has three or four microsurgical metal blades mounted longitudinally on the outer surface of the balloon, which can create incisions in the calcification during expansion to improve the coronary artery compliance to gain larger lumen expansion to facilitate the subsequent stent implantation. However, cutting balloon angioplasty in calcified lesions is associated with increased incidences of arterial dissection and perforation. A multicenter randomized clinical trial showed that the incidence of coronary artery perforation was associated with the cutting balloon, although the rate of target vessel revascularization was reduced in comparison with conventional balloons.

For cutting balloon expansion, like conventional balloon angioplasty, a balloon-to-artery ratio of 1:1 is used. However, there is little knowledge of how the balloon-to-artery ratio for the cutting balloon influences both effective incision of the calcification and potential perforation

The author hypothesizes that there exists an adequate balloon-to-artery ratio specific to the cutting balloon in terms of effectively inducing stress concentration at the calcification for fracturing calcification while reducing the stress concentration at the borders of the coronary artery adjacent to the calcification for preventing perforation. The number of blades facing a calcified lesion may also be crucial for expanding calcifications while avoiding dissection and vessel injuries.

The author aims to investigate the influences of balloon-to-artery ratios of the cutting balloon on the stress concentrations and distribution in the calcification model and at the borders of the coronary artery adjacent to the calcification using finite element analysis in order to obtain a criterion for the balloon-to-artery ratio for the cutting balloon. The author also focuses on a calcified artery with a 180° calcification model with two conditions where either one or two blades face the 180° calcification model to gain mechanistic insights into calcification incisions using cutting balloons and to provide suggestions for improving the clinical outcomes of cutting balloon angioplasty.

This thesis is composed of five chapters. Descriptions of each chapter are presented following.

Chapter 1 introduces the current therapies for coronary artery calcification and highlights the complications in

the cutting balloon angioplasty. The author summarizes the related studies in the field of numerical researches of balloon expansion. Moreover, the author shows the necessity of investigation of the cutting balloon expansion in calcified lesions and describes the purpose of this study.

Chapter 2 introduces the novel modeling of a three-folded balloon. The initial diameter and Young's modulus of the balloon model are obtained based on the manufacturer's compliance chart data indicating the relationship of the diameter and pressure. An innovative numerical process of crimping and compressing is employed to generate a realistic three-folded balloon model according to the manufacturing process. The numerical expansion of the folded balloon model is in agreement with the compliance chart data. In addition, the folded balloon model is successfully used to expand a coronary stent model and the phenomenon of dogbone shape is reproduced. Finally, the balloon expansion of the stent model in a stenotic artery model is carried out to confirm the reliability of the balloon model in comparison with a radial displacement-driven cylinder expansion. The simulations of expansion are carried out in Abaqus/Explicit solver with adequate analysis time step and loading rate to ensure a quasi-static analysis while the kinetic energy remains almost below 5% of the internal energy for each model. The contact condition between each model is defined utilizing the general contact algorithm with a static friction coefficient of 0.2. The peak value of the von Mises stress occurred in the stent model for the balloon expansion was similar to that for the cylinder expansion at the final process. On the other hand, the peak value of the maximum principal stress in the plaque model for the cylinder expansion was 144 % higher than that for the balloon expansion of that for the balloon expansion. The folded balloon model shows a good response to the realistic expansion and the method of validated modeling promotes further modeling of the balloon.

Chapter 3 describes the expansion of a cutting balloon with five different diameters in a stenotic calcified artery model. As in conventional balloon angioplasty, a balloon-to-artery ratio of 1:1 is used for the cutting balloon with metallic blades. The author aims to investigate the influence of the balloon-to-artery ratio on the stress concentrations in the calcified model and at the borders of the coronary artery adjacent to the calcification to obtain a criterion of balloon-to-artery ratio for the cutting balloon. The folded cutting balloon model is generated by the method described in Chapter 2 and equipped with three pairs of blades and cast pads on the balloon surface. The cutting balloon model is deployed in a 50% diameter stenotic coronary artery model with a 360-degree concentric, 400-μm-thick, 5-mm-long calcification. Simulations of the expansion of cutting balloons with diameters from 2.0 to 3.0 mm in 0.25-mm increments which corresponded to balloon-to-artery ratios from 0.67:1 to 1:1 were conducted with pressures up to 1.216 MPa (12 atm). The result reveals that the cutting balloon downsized by 0.25 mm and 0.5 mm preserved maximum principal tensile stress concentrations comparable to that of the cutting balloon with a balloon-to-artery of 1:1 while distinctly reducing the stress concentrations at the border of the artery adjacent to the calcification. The data shows that selecting a cutting balloon downsized by 0.25 mm or 0.5 mm should be the first choice for effectively fracturing the calcification while reducing the risks of artery perforation. For the cutting balloon, a balloon-to-artery of 1:1, which is recommended for conventional balloons, seems inappropriate.

Chapter 4 describes the expansion of the cutting balloon in a non-circular calcified artery model. The author

hypothesizes that the balloon-to-artery ratio and the number of blades facing a 180° calcified lesion may be crucial for fracturing the calcification while avoiding vessel injury. Numerical simulations were performed for cutting balloons with five different diameters and two types of blade directions in a 180° calcification model. The calcification expansion ability was distinctly higher when two blades faced the calcification than when one blade did. Moreover, when two blades faced the calcification model, larger maximum principal stresses were generated in the calcification even when using undersized balloons with diameters reduced by 0.25 or 0.5 mm from the reference diameter, when compared with the case where one blade faced the calcification and a balloon of diameter equal to the reference diameter was used. When two blades faced the calcification, smaller stresses were generated in the artery adjacent to the calcification. Furthermore, the maximum stress generated in the artery model adjacent to the calcification under the rated pressure of 12 atm when employing under-sized balloons was smaller than that when only one blade faced the calcification and when lesion-identical balloon diameters were used under nominal pressure of 6 atm. The data suggested that 0.25 mm or 0.5 mm size-down balloons would be effective in not only expanding the calcified lesion but also reducing the risk of dissection.

Chapter 5 summarizes the conclusions and describes the plans for future work.

The significance of the thesis is that the author not only proposes realistic and validated modeling of a three-folded balloon to generate the configurations of the cutting balloons but also reveals the influence of the expansion of the cutting balloons in calcified artery models. These results will contribute to improve the clinical outcomes of cutting balloon angioplasty and help to promote the future development of the cutting balloon.

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氏 名　Xiaodong ZHU　印

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Academic Papers	○ (1) **X. Zhu**, M. Umezu. K. Iwasaki. Finite element analysis of cutting balloon expansion in a calcified artery model of circular angle 180°: Effects of balloon-to-diameter ratio and number of blades facing calcification on potential calcification fracturing and perforation reduction. PLoS ONE.16(5): e0251404.2021.5 ○ (2) **X. Zhu**, M. Umezu. K. Iwasaki. Finite element analysis of the cutting balloon with an adequate balloon-to-artery ratio for fracturing calcification while preventing perforation. Circulation Reports.3(1): 1-8.2021.1 (3) A. Takahashi, **X. Zhu**, Y. Aoyama, M. Umezu, K. Iwasaki, Three-dimensional strain measurements of tubular elastic model using tomographic particle image velocimetry, Cardiovasc Eng Technol. s13239-018-0350-5, 1-10, 2018.3
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