

OPTIMIZATION OF PLLA STENT TO ACHIEVE HIGH FLEXIBILITY USING RESPONSE SURFACE METHODOLOGY

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ABSTRACT

Stent flexibility is essential for navigating stent placement through complex cardiovascular anatomy. Flexible stents can minimize the impact of external forces on the arterial wall, which can lead to more stable heart beat. Modern stents often use PLLA material, which have biodegradable properties and are compatible with the arterial healing process. This study investigates the optimization of pure PLLA stent to achieve high flexibility. The analysis was conducted by exploring material properties, including bending moment and thickness, and their effects on stent performance using the Finite Element Method (FEM) and Response Surface Methodology (RSM). Optimization using RSM resulted in the crimped condition of the Pure PLLA stent, with a bending moment of 0.0044 N.mm, a thickness of 87.0002 μm , a curvature index of 0.0261 rad/mm and a von Mises stress of 16.6283 MPa. In the expanded condition of the Pure PLLA stent, with a bending moment of 0.0120 N.mm, a thickness of 75.8579 μm , a curvature index of 0.0895 rad/mm and a von Mises stress of 46.0882 MPa. These results demonstrate the capability of RSM in refining the design and achieving high curvature index as a flexibility.

Keywords: *Stent, PLLA (Poly-L-Lactic Acid), Response Surface Methodology, Flexibility, Curvature Index*

1. INTRODUCTION

Increased stent flexibility is essential for navigating stent placement through complex cardiovascular anatomy, flexibility in stents is useful conform to the dynamic movements of the heart and surrounding tissues, reducing the risk of complications such as stent fracture or malposition (Haji Zeinali et al, 2017; Wissgott et al, 2015). Studies have shown that stents with greater flexibility can better accommodate the natural movements of the arteries and airways during physiological processes, which is critical for maintaining patency and preventing restenosis or obstruction (Saito et al, 2020).

The relationship between stent flexibility and heartbeat dynamics is critical in understanding patient outcomes post-implantation. Flexible stents can minimize the impact of external forces on the arterial wall, which can lead to more stable heart beat. Research indicates that stents that maintain their position and adaptability during cardiac cycles can help prevent arrhythmias, thereby improving overall cardiac function (Sheth et al, 2023). This adaptability is particularly important in patients with complex vascular anatomies, where rigid stents may exacerbate hemodynamic instability.

The stent industry now mainly produces polymer stent, using polymers like PLLA to bind drugs to metals (Nicolas et al, 2023). Previously, a combination of metal and polymer was effective, but CoCr metal is biologically rejected, leading to efforts to reduce metal use. The latest trend is using 100% bioabsorbable polymers (Jeong et al, 2024).

Flexibility is crucial for smooth implantation, allowing stents to navigate curved arteries and expand effectively at the plaque site (Foin et al, 2013; Wu et al, 2007). Stent flexibility is essential for safe installation and plaque support, reducing delivery challenges and tissue tension (Beule, 2008). (Shen et al, 2017) used the Finite Element Method (FEM) to analyze the flexibility of stents. FEM was chosen due to its ability to model material behavior in detail, including the response to deformation and stress distribution across different parts of the stent. FEM allows for the analysis of important variables such as thickness, and pattern of the linkers, which affect the stent's flexibility, and are difficult to evaluate through direct physical experiments. Similarly, (Ibrahim et al, 2023) also used FEM to analyze the stent components, as FEM enables high-precision simulations of various strut and linker design variations, allowing for the analysis of their impact on flexibility without the need for costly and time-consuming experiments. Response Surface Methodology (RSM) is used in stent design optimization because of its ability to analyze the interaction of design factors for optimal results. The application of RSM to stent design with crimped and expanded configurations, produces a more adaptive design and is in accordance with stent performance needs (Pratama, 2017). Flexibility and material properties can be optimized using Response Surface Methodology (RSM) to improve its biomechanical performance (Mahmood, 2024).

This paper investigates the design optimization of pure PLLA stent to achieve high flexibility. By analyzing the effects of material properties on stent performance, this study aims to provide crucial insights into enhancing the flexibility of stents for improved coronary artery implantation. Stent flexibility plays a pivotal role in ensuring safe deployment and effective plaque support once in place, particularly in challenging curved coronary arteries. Utilizing Finite Element Method (FEM) and Response Surface Methodology (RSM), The research aims to optimize stent design by maximizing curvature index and minimizing von mises, enhancing delivery performance and patient-specific adaptability. The findings will contribute to advancing stent for cardiovascular treatments.

2. METHODS

2.1. MATERIALS

In this numerical study, Poly-L-lactic acid (PLLA) were selected as the materials for investigation, with their mechanical properties outlined in Table 1, respectively. The key material characteristics for PLLA include yield stress (MPa), ultimate tensile strength (MPa), Young's modulus (GPa), Poisson's ratio, and density (g/cm³). These material properties are crucial for understanding their performance in drug-eluting stent (DES) simulations.

TABLE 1. Material properties of Poly-L-lactic acid (Pauck & Reddy, 2015)

Mechanical Properties, Unit	Material Poly-L-lactic acid
Yield Stress (σ_y), MPa	45
Ultimate Tensile Strength, MPa	65
Modulus Young (E), GPa	1,8
Poisson's Ratio (ν)	0,35
Density (ρ), g/cm ³	1,25

2.2. STENT DESIGN

The geometrical configuration of the Bioabsorbable Polymers Stent (Pure PLLA Stent) was designed with a stent length of 4.2 mm, with a diameter of 1 mm in the crimped condition and 3.1 mm when expanded. The stent being investigated comprises 3 links and 4 rings, featuring struts oriented in opposite directions ($S > <$). In the crimped pure PLLA stent design has a thickness between 80-100 μm PLLA. The expanded pure PLLA stent design is characterized by a thickness of 80-100 μm PLLA. The designs for both the crimped and expanded pure PLLA stents, are depicted in Figure 1 to Figure 2.

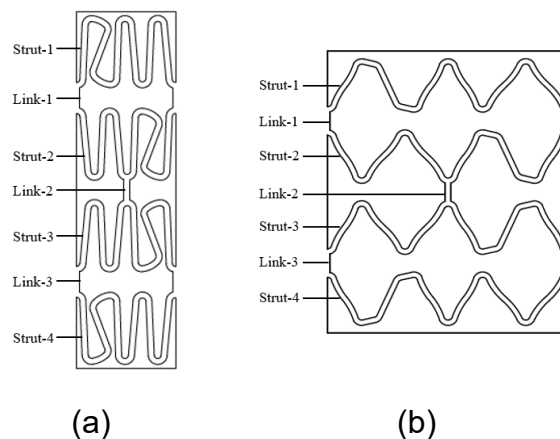


Figure 1. Mirror Direction Strut and Link in 2D View (a) Crimped stent (b) Expanded stent

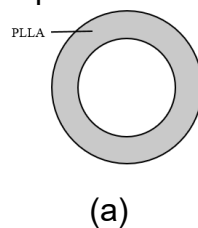


Figure 2. Stent Material of Pure PLLA stent

2.3. CURVATURE INDEX

In this context, the flexibility of the stent was determined by the relationship between the formed angles and the length of the stent. The larger the angle, the greater the flexibility of the stent. Flexibility of the stent is expressed through a curvature index, denoted as X (rad/mm), which is calculated as the ratio of the angle to the stent's length. Let the length of the stent be represented by L (mm), the bending moment by

M (N.mm), and the change in angle by $\Delta\theta$ (rad). Therefore, the curvature index can be determined using equation (1)

$$X = \frac{\Delta\theta}{L} \quad (1)$$

The simulation to determine the curvature index under crimped conditions was conducted using ABAQUS 6.14. The stent model consisted of 83376 elements of Quadratic Tetrahedral C3D10 type. In this simulation, the balloon catheter, which is typically located underneath the crimped stent and expanded stent was not considered. Bending moments were applied to both ends of the stent in the x and y directions (Mxx and Myy). As a result of these bending moments, a rotation angle was generated. Before simulating the flexibility, reference points at both ends of the stent (RP-1 and RP-2) were established. Then, multi-point beam constraints were applied between the reference points (RP) and the edge of the strut. Figure 3 illustrates the reference points and their corresponding multi-point constraints. Meanwhile, Figure 4 provides a detailed illustration of how the bending moments are applied along both the x and y axis of the stent model.

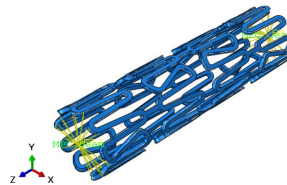


Figure 3. Multi-Point Constraints (MPC) applied at Pure PLLA Stent

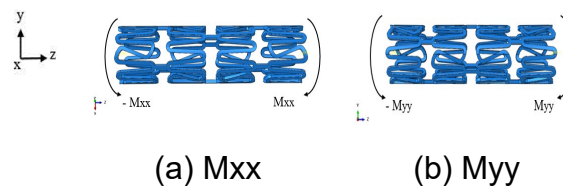


Figure 4. The Model is Subjected to Bending Moments: (a) Mxx; (b) Myy.

2.4. RESPONSE SURFACE METHODOLOGY

Response Surface Methodology (RSM) was used to model the relationship between the design variables (moment, M, and thickness, T) and the performance outcomes, which include the curvature index and von Mises stress. Initially, a first-order RSM model was developed using linear terms to approximate the relationship between the input variables and outputs. This model provided an initial approximation of the system's behavior. If the P-value curvature for the response curvature Index and von mises is smaller than α of 0.05, it leads to the rejection of H_0 . Thus, it is necessary to conduct a 2nd order analysis. To improve the accuracy, a second-order RSM model was then constructed, incorporating quadratic terms and interaction effects between the variables. The second-order model better captured the nonlinearities of the system and provided a more accurate prediction of the stent's performance. The coefficients for both models were estimated using a set of experimental data obtained from simulations, and the resulting models were used to analyze and optimize the design of the stent. Meanwhile the bending moment and thickness variable used are shown in Table 2.

TABLE 2. Stent Bending Moment and Thickness

Stent Type	Moment		Thickness	
	Crimped	Expanded	Crimped	Expanded
Pure PLLA	0.002-0.007 N.mm	0.012-0.013 N.mm	80-100 μ m	80-100 μ m

In the second-order regression model rsm, the use of coded variables standardizes the input factors moments and thicknesses by transforming them into a dimensionless scale, which typically ranges from -1 to $+1$. This transformation simplifies the analysis and ensures comparability across factors with different units or ranges.

$$\hat{y} = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{12} x_1 x_2 + \varepsilon \quad (2)$$

3. RESULTS AND DISCUSSION

Results and discussions are presented concerning the optimization of stent designs using Response Surface Methodology (RSM). The primary objective of this study is to determine the optimal design parameters for stents made from pure PLLA materials, aiming to achieve maximum flexibility, as indicated by the curvature index, while minimizing von Mises stress. The results are analyzed through the RSM, providing insights into the relationships between key design variables, such as bending moment and thickness.

3.1. RSM

The response model produced by RSM is as follows.

a. CI and VM Response Model to Stent Crimped Pure PLLA :

$$\hat{y}_{CI} = 0.02351 + 11.158M - 0.000534T + 21.05M^2 + 0.000003T^2 - 0.06107MT \quad (3)$$

$$\hat{y}_{VM} = 27.8 + 6397M - 0.602T + 5914M^2 + 0.00323T^2 - 30.02MT \quad (4)$$

b. CI and VM Response Model to Stent Expanded Pure PLLA :

$$\hat{y}_{CI} = 0.191 - 1.9M - 0.002200T + 579M^2 + 0.000011T^2 - 0.0663MT \quad (5)$$

$$\hat{y}_{VM} = 90.3 - 2654M - 0.738T + 421475M^2 + 0.00490T^2 - 49.6MT \quad (6)$$

These models provide a quantitative framework for determining further optimization and analysis most effective stent design to achieve maximum flexibility while maintaining von Mises stress within safe limits.

The simulation results obtained through Response Surface Methodology (RSM) provide valuable insights into the performance of the stent design. Curvature Index and von mises illustrates the stent's ability to flex under different conditions, highlighting the optimization achieved in this aspect.

TABLE 3. High Flexibility of RSM

No.	Condition	Moment	Thickness	Curvature Index (rad/mm)	Von Mises Stress (MPa)
1.	Crimped Pure PLLA Stent	0,0044	87,0002	0.0261	16.6283
2.	Expanded Pure PLLA Stent	0,0120	75,8579	0.0895	46.0882

Table 3. above present the Curvature Index (rad/mm) and Von Mises Stress (Mpa) under various conditions. These results were obtained after performing simulations using optimized parameters, which show how the stent design responds to various changing conditions and the impact of the optimized design on the curvature index flexibility and von mises structural integrity. The optimization demonstrate the effectiveness of process in achieving a balanced design that meets the performance criteria within the safe von mises stress limit, for crimped stents below the yield strength of 45 Mpa and for expanded stents beyond the yield strength of 45 Mpa and not beyond the ultimate tensile strength of 65 Mpa.

4. CONCLUSION

The use of Response Surface Methodology (RSM) provides better results in stent design optimization. RSM functions to build a mathematical model that describes the relationship between design variables and stent performance. From the results of the research that has been done, The optimal design parameter values needed to achieve high flexibility in the crimped and expanded conditions of the Pure PLLA stent, while maintaining the maximum stress within safe limits are as follows, Response Surface Method (RSM) produces optimal parameters in the crimped condition of the Pure PLLA stent, with a bending moment of 0.0044 N.mm and a thickness of 87.0002 μm . In the expanded condition of the Pure PLLA stent, the optimal values obtained include a bending moment of 0.0120 N.mm with a thickness of 75.8579 μm .

The curvature index and von Mises stress parameter values that correspond to the bending moment to achieve high flexibility in the stent in crimped and expanded conditions are as follows, Response Surface (RSM) method predicts the response value for the crimped Pure PLLA stent design, namely a curvature index of 0.0261 rad/mm and a von Mises stress of 16.6283 MPa. In the expanded Pure PLLA stent design, the predicted curvature index value is 0.0895 rad/mm and a von Mises stress of 46.0882 MPa.

The results of this study indicate that the Response Surface (RSM) method can be effectively used to determine the optimal design parameters to increase the high flexibility of the stent while maintaining the safe stress limit. These findings can be used as a reference in the development of better stent designs for medical applications, especially in improving the mechanical performance of the stent during installation and expansion.

ACKNOWLEDGMENT

The authors of this article would like to express their deepest gratitude to LPDP (Indonesian Education Fund Management Institute) for the financial support that has been provided so that this research can be carried out.

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