Study on Mechanical Properties of Curved Vascular Stent after Crimping

Chen Pan¹², Yafeng Han¹* and Jiping Lu¹
¹ School of Mechanical Engineering, Beijing Institute of Technology, Beijing 100089, PR China
² Institute of Engineering Medicine, Beijing Institute of Technology, Beijing 100089, PR China
Email: hanyafeng@bit.edu.cn

Abstract. It is a great challenge to improve the mechanical properties of vascular stent, especially in curved vessels. Vascular stent should have ideal mechanical properties, such as high elasticity, high strength and biocompatibility. At present, most of the literatures focus on the mechanical properties of the stent after expansion, ignoring that of the stent before the stent is implanted into the human body. After the stent is crimped, it has a great impact on the stress fatigue of the stent. Excessive compression will lead to the weakening strength, which cannot support the blood vessel. Therefore, in this paper, an improved algorithm was proposed to crimp and straighten a curved stent to a smaller diameter to generate the required boundary conditions by finite element analysis (FEA). This method is helpful to study the mechanical properties of the stent after being crimped and treat lesions in highly curved locations.

1. Introduction
Atherosclerosis is a kind of cardiovascular disease, which can trigger the formation of plaque and thickening of arterial wall, causing vascular blockage. As one of the effective methods to treat atherosclerosis, vascular stent has been widely used in clinical operation. In general, vascular stent is a kind of small tubular structure, which is used to restore the blocked cardiovascular system by expanding in the blood vessel. The vascular stent supports the vascular wall, expands the vascular cavity and prevent the arterial wall from rebounding [1-2]. Generally speaking, vascular stent should have ideal function and mechanical properties [3]: (1) high elasticity; (2) high strength and anti-fatigue; (3) good biocompatibility. At present, the clinical application of vascular stent, after decades of development, has had the corresponding treatment function and mechanical properties, the technology is gradually becoming mature, and the arterial occlusion after interventional therapy has been significantly reduced.

However, a large number of existing studies have shown that the widely used stent often leads to large deformation of blood vessels, high wall stress, tissue damage and other problems [4-5]. Due to the influence of the structure and material properties, vascular stent has a very obvious axial “straightening” trend during the expansion process, which will lead to a significant reduction in the curvature of the implanted stent [6-8], destroy the inner wall of the vessel, induce intimal hyperplasia, and cause secondary blockage or restenosis in the stent, especially for curved vessels. It is necessary for stent to be able to adapt to the geometric shape of vessel curvature. Studies have also shown that in the more curved vessels, the stent has higher stress on the vessel wall and greater damage [5]. Therefore, the curvature of the curved blood vessels generally decreases significantly after stent
implantation. Gyöngyösi et al [6] found that before and after stent implantation, the bending angle of the aorta was 67° down to 58°. The curvature of blood vessels decreased significantly. Through finite element simulation, Wu et al [8] found that there were high stress gradient and stress concentration at both ends of the stent. Studies have shown that the bending degree of human blood vessels is 30° to 150° [9].

At present, most of the scholars focus on the mechanical properties of vascular stent after expansion, ignoring crimpability of stent. The crucial factor of crimpability affects mechanical failure of the stent during crimping, especially for self-expandable nitinol vascular stents [10-11], which will trigger serious complications such as metal fracture leading to device failure thereby rendering the stenting procedure unsuccessful. Kumar et al [12] proposed an algorithm to achieve the crimpability of curved stents by the finite element simulation, their study provided a theoretical basis for evaluating the mechanical properties of stents in curved vessels. However, in this paper, an improved algorithm was proposed to crimp and straighten a curved stent to a smaller diameter to generate the required boundary conditions by finite element analysis (FEA). This method could achieve crimp and straighten a curved stent, and effectively evaluate the mechanical properties of stent after being crimped.

2. Material and Method

2.1. Material and Geometrical Model of Vascular Stent

At present, there is 316L stainless steel [13], shape memory alloy [14], biodegradable materials [15] and so on. Ni-Ti alloy is widely used as vascular stent material because of its super elasticity, shape memory, biocompatibility, corrosion resistance, fatigue resistance and strength [16-17]. Crimping Ni-Ti stent has been studied extensively [18-20], but most of the studies have been done on straight stents with a straight rigid cylinder mimicking the crimper. In this finite element analysis, the thermal mechanical super elastic-plastic constitutive model is adopted, and the material properties of Ni-Ti SMA are realized by the built-in UMAT subroutine of ABAQUS2016. The curved stent with a suspended arc angle of 60° and honeycomb shape was built in Solidworks2019.

2.2. Method

In the process of finite element analysis, it is a challenge to realize the crimpability of curved vascular stent. Kumar et al [12] proposed an algorithm for crimping the curved stent. The simulation analysis of radial crimpability of curved stent was successfully carried out. Because Praveen Kumar team only confirmed that the algorithm can crimp curved stent in the curved vessel, it did not realize crimp and straighten the curved stent. In actual surgery, the stent with straight cylinder is delivered to the blocked vessel. Therefore, based on Praveen Kumar algorithm, here improves Praveen Kumar algorithm. Figure 1 (a) is the geometric change of cylinder before and after the deformation according to the algorithm proposed by Praveen Kumar. Figure 1 (b) is the geometric change by the improved algorithm simulation. In figure 1, it can be clearly compared that the improved algorithm can make a curved tubular thin and straight, which is more in line with the actual situation.

Figure 1. Different results based on two algorithms.
2.3. Algorithm

To facilitate the interpretation of the algorithm, the algorithm derivation process is carried out in the form of two-dimensional graphics, as shown in figure 2.

1) On the XY plane, take any point P (x, y, z) on the curved shell, and use trigonometric function to solve the angle between the distance R from the point P to the origin and the X axis α. Point P1 (x1, y1, z1) is obtained by projecting point P onto the XZ plane along the curved surface. Then y1 = 0, z1 = z.

\[
\begin{bmatrix}
  x1 \\
  y1 \\
  z1
\end{bmatrix} =
\begin{bmatrix}
  \cos \alpha & \sin \alpha & 0 \\
  -\sin \alpha & \cos \alpha & 0 \\
  0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
  x \\
  y \\
  1
\end{bmatrix}
\]  

(1)

2) Map all the points on the curved shell onto the XZ plane to form a circle (figure 2A). The point P1 moves radially inward on the circular plane. The introduction of angle β, calculate P1 radial displacement. This step is mainly to realize the radial contraction of the curved shell. And then, calculate P2 (x2, y2, z2).

\[
\begin{align*}
D11 &= R \cdot \cos \beta \\
D21 &= 0 \\
D31 &= R \cdot \sin \beta \\
x2 &= x1 + D11 \\
y2 &= y1 + D21 \\
z2 &= z1 + D31
\end{align*}
\]

(2)

3) Set the coordinates of point P2 along the angle α return the curved shell, and get point P3 (x3, y3, z3). At this time, the whole bending pressing shell has achieved radial contraction, as shown in figure 2C.

\[
\begin{bmatrix}
  D12 \\
  D22 \\
  D32
\end{bmatrix} =
\begin{bmatrix}
  \cos \alpha & -\sin \alpha & 0 \\
  \sin \alpha & \cos \alpha & 0 \\
  0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
  D11 \\
  D21 \\
  D31
\end{bmatrix}
\]

(4)

\[
\begin{align*}
x3 &= x + D12 \\
y3 &= y + D22 \\
z3 &= z + D32
\end{align*}
\]

(5)

4) Apply displacement to curved shell to make it straight. In the process of straightening from bending, the y coordinate of point P4 should be equal to the arc length L of the angle α, and the coordinates of point P4 in X and Z directions are the same as that of point P2.

\[
\begin{align*}
x4 &= x2 \\
y4 &= L \\
z4 &= z2
\end{align*}
\]

(6)

According to the above A-B-C-D process, the subroutine DISP of ABAQUS was written in FORTRAN language, and the displacement boundary condition was applied to crimp and straight the vascular stent.
3. Results and Discussion

Figure 3 shows the FEA result of the stent according to the algorithm. Because material of stent is Ni-Ti alloy with shape memory function, the curved stent on the left of figure 3 is the geometry after expansion in the blood vessels. That is to say, when the stent is processed and fabricated, the stent is already in the expansion state. After being crimped and straightened by the catheter, as shown in the right of figure 3, it is transmitted to the vascular blockage position by the catheter. Finally, the stent will self-expand into the shape shown in the left figure of figure 3.

In the method proposed in this paper, it is necessary to find the centre line of the curved stent first, which is consistent with the idea of Kumar et al [12]. Second, all nodes on the curved stent are mapped into the plane coordinate system XZ to realize the radial contraction. Third, all nodes being contraction are returned to three-dimension space to obtain the curved shape. Finally, the straightening operation of the curved stent is carried out. In this process, it is very important to calculate each bus and the corresponding bus after straightening of stent. According to the algorithm in this paper, the curved stent is crimped and straightened by FEA.

It is not be ignored that catheter causes stress concentration of stent during crimping and straightening. The process of crimping has a great impact on the mechanical properties of vascular stent, and even leads to plastic deformation, which cannot expand normally, seriously affecting the treatment effect. Therefore, the stress of the stent after being straightened was analysed. Figure 4 shows that the high stress of stent is mainly distributed in the upper side. This is because in the process of straightening, the struts of stent at the upper side bear a large torque and shear force, resulting in stress concentration. However, the other struts do not produce large stress. It can be seen that the structure of stent has a great influence on the distribution of stress. In order to reduce the stress and diminish the influence of crimping on the mechanical properties, the design optimization should be carried out for the stent. Consequently, this algorithm in this paper can also be used to detect whether the structure of stent is reasonable,
4. Conclusions

It should be noted that any stent will be physically crimped using standard stent crimping techniques. The stent will then be mounted on the conveying system and deployed in the target location [12]. But there are few reports on crimping and straightening the curved stent. Most of the research work done so far has been the straight stent in a straight artery or in a curved artery. In the actual cardiovascular treatment process, the blood vessel is not a simple straight cylinder, but a complex geometric shape with bending and taper. Consequently, it is of great benefit to research a curved stent in a curved vessel. In this paper, based on the algorithm of Kumar team, a more complex algorithm has been improved. Through this method, the curved stent can be compressed into a straight stent. Additionally, the method can be used to detect whether the structure of stent is reasonable, and can better serve the clinical application.

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