Effect of stent designs on the paravalvular regurgitation of transcatheter aortic valve implantation

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Abstract

Objective Transcatheter aortic valve impantation(TAVI) rapidly developed in recent decade, however, paravalvular aortic regurgitation (AR) , as a complication, significantly influences the morbidity and mortality after TAVI. In this study, it was evaluated that effect of stent design on the paravalvular regurgitation of transcatheter aortic valve implantation based on numerical simulations. **Methods** Three self-expanding transcatheter aortic valve stent designs model were developed base on the commercial products. Three stents had the same inflow end but different outflow end. Stent1 had more struts on the outflow end which is similar first generation stent. Stent 2 had a sparser outflow end. Stent 3 had most sparse struts on the outflow end. They were radial compressed and implanted into the representative calcified human aortic root models. Then the effect of different stent design on the aortic root stresses, stent deformations and the gaps between the stent and aortic root was analyzed in order to understand the relationship to paravalvular regurgitation. **Results** The same inflow end and the different degree of sparse outflow end was found in the three stent, which induced the different stent deformation, a different stress on the calcified plaques and aortic root, and a different gap between the stent and aortic root. Both an excessively dense or sparse outflow end design resulted in a lager stent deformation, a higher stress calcified plaques and aortic root, and a lager gap, which led to more serious paravalvular regurgitation. Stent 2 had a moderate sparse outflow end obtained the smallest deformation, the lowest stress, and the smallest gaps, indicate this design will lead to a low risk of paravalvular regurgitation. **Conclusions** An excessively dense or a sparse outflow end would result in a larger stent deformation indexes, a higher stress calcified plaques and aortic root, and a lager gap, and led to serious paravalvular regurgitation. This study provided the guidance for design of transcatheter aortic valve. And it would help predict the clinical outcome after implanted.

Keywords: Transcatheter aortic valve implantation; Finite element model; Stent design; Paravalvular regurgitation

1 Introduction

Transcatheter aortic valve implantation (TAVI) have been first used in human in 2002[1], and developed rapidly in the last decade. It has been broadly used to treat aortic valve stenosis of impossible surgery and high-risk patients [2-3]. However, paravalvular aortic regurgitation (AR) significantly influences the morbidity and mortality after TAVI. Clinical follow-up indicated moderate or severe AR post-TAVI was about 6% to 21% [4]. It is considerably higher than that surgical valve replacement. 1-year mortality in patients with moderate or severe AR was 60.0%, compared with 19.6% in patients with none/mild AR [5]. Median survival time in patients with at least moderate AR was 1.7 years, compared with 3.4 years in patients with mild/trivial/no AR [6]. Recently study indicated that mild AR was also associated with an increased hazard ratio for mortality [7]. So it is very important to investigate the influencing factor and method to reduce the incidence of the paravalvular regurgitation.

Numerical simulation had been used to analyze TAVI, especially in patient-specific simulations of transcatheter aortic valve implantation [8]. Stent apposition and deformation, stress on valve leaflets, stent, and calcified plaque were studied to evaluate the ability of anchoring by finite element analysis [9-11]. It was indicated that lager calcified spot stress will lead to risk of stroke [11]. Aortic rupture location had been investigated and got the same outcome in clinic [12]. It was also simulated the influence of the asymmetric coaptation, anchoring position and angle, calcification position, pattern and size to paravalvular regurgitation and clinical outcome in previous studies [9][11][13-14]. Recently, a workflow had been developed to simulate the potential leakage prior to the implantation to help decide the best implant type, size and position [15].

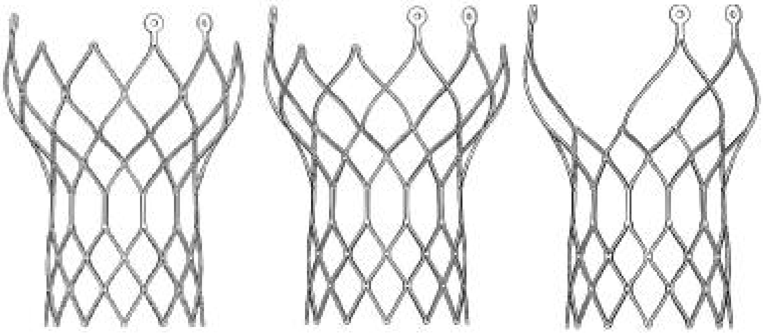
There are little studies was reported that the effect of the stent designs on the paravalvular regurgitation based on numerical simulation. Therefore, it would be analyzed the deformation of stent, the stress of aortic wall and calcified plaque, the gap of stent and aortic wall after TAVI. And evaluate the effect of stent designs on paravalvular regurgitation of different calcification patterns in this study.

2 Methods

1.1 The three stent design models

Three self expanded stent designs was established, and all the stent designs come from KingstronBio (Changshu) Co, Ltd, China. Self expanded stents was widely used as transcatheter aortic valve stents, such as CoreValve and Portico transcatheter aortic valve. The diameter of the outflow was in generally bigger than the inflow diameter for self expanded stent. The smaller inflow end anchored on the aortic valve root, and the bigger outflow end archored on the aorta ascends. The three stents had the same inflow end construction, but with different degree of sparseness for outflow end design, as shown in Fig.1. The outside diameter of the inflow end is 26mm for all the stents. Stent1 had more struts on the outflow end which is similar first generation stent. Stent 2 had a sparser outflow end. Stent 3 had most sparse struts on the outflow end.

The stents were structured by Solidworks(Dassault Systemes, France), divided into hexahedral element from adopting Hyoermesh 12.0(Altair Engineering USA), and imported into ABAQUS 6.13(SIMULIA, USA). This study adopted a linear-elastic, isotropic material model to simplify the superelasticity of the Nitinol stent materials [14]. TheYoung modulus, poisson ratio and density of Nitinol were set 50000Mpa, 0.3 and 6450 kg/m3 [16]. Because of the negligible effect of sealing skirt and leaflet compared to Nitinol alloy [17], the skirt and leaflet were not included in this investigation.



Stent 1　　　　Stent 2　　　　Stent 3

Figure 1 Three stent designs with different sparse outflow design

1.2 Aortic root model

The healthy aortic root model was shown in Fig. 2, include the left ventricular outflow tract (LVOT), aortic sinus, aortic heart valve and ascending aorta [17-18]. Aortic sinus includes right coronary sinus, left coronary sinus, and non-coronary sinus. The thickness was set 2.5mm for all the LVOT, aortic sinus, aortic anulus and aorta ascends, meshed by C3D10M tetrahedral element. The diameter of the aortic annulus was set as 24mm. Leaflet thickness was set as 0.3mm [19], and meshed by S4R shell element. All the materials were set linear-elastic, isotropic material. Young modulus, Poisson ratio and density of Nitinol were set to 2Mpa, 0.45 and 2000 kg/m3, respectively.

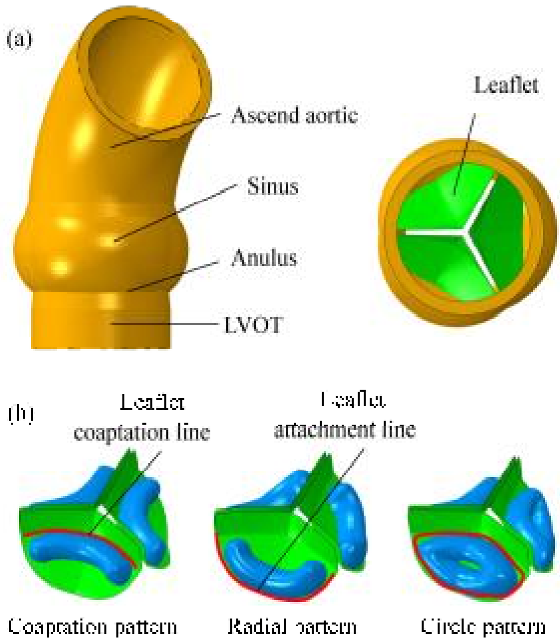


Figure.2 The model of (a) the health aortic root; (b) the three calcification patterns

According to correlation analysis, we established three calcification pattern: coaptation pattern, radial pattern, and circle pattern (Fig. 2b).Calcification plaque was arc shaped and located along the coaptation line for coaptation pattern; calcification plaque was along the attachment line for the radial pattern, and circle pattern was the combined pattern of the two, which represented the severe calcification. The maximum thickness of calcification plaque is 4.5mm, and the volume of the three plaques was 1085mm^3, 1083mm^3 and 1696mm^3, respectively. The material of the calcification plaque were set linear-elastic, isotropic material. Young modulus, Poisson ratio and density were set 12.6MPa,0.3 and 2000kg/m3, respectively[13].C3D10M tetrahedral element was adopted for calcification plaque.

1.3 Boundary and loading conditions

The deployment process was shown in Fig.3.A rigid cylinder shell was adopted to control the stent crimp and release. Firstly crimp the stent into the cylinder shell. Constrain the inflow end to move along the longitudinal center line during the crimp process. The compressive pressure was loaded on the leaflet surface to make the leaflet open, withdrawn the shell to release the stent and the pressure on the leaflet simultaneously. No friction was set between the stent and shell. The stent would contact with leaflet, aortic wall, and calcification plaque until the stent was fully deployed. Frictional coefficient was set 0.2 among the stent and leaflet, aortic wall, and calcification plaque. The distance of the stent bottom under the aortic anulus was set 4.5mm. No friction was set between the stent and shell.

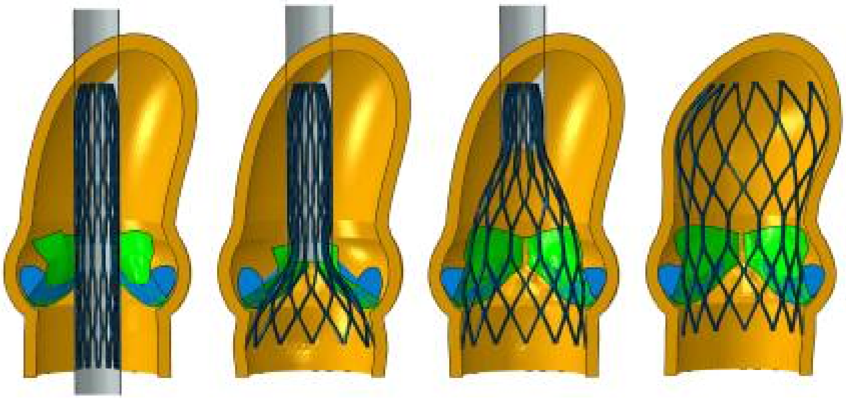


Fig.3 Steps of the valve stent deployment

The stent deformation, Von Mises stress and the maximum principle stress of aortic wall and calcification plaque, gaps between the stent and aortic wall was analyzed. Six planes was set on the position near the leaflet. The coordinate of the stent on the plane was extracted, and geometrical center and distance from the centre to the strut were calculated using the MATLAB R2014b (MathWorks, USA). The maximum and minimum distances were defined as r_{max} and r_{min}. The ratio of the maximum and minimum distance, $r_{max}/r_{min,}$ was defined as stent defomation index e. Stent defomation index indicated the comformity of the stent deformation. Fig. 4 showed the position of the 6 planes and r_{max} and r_{min} of the plane 1.

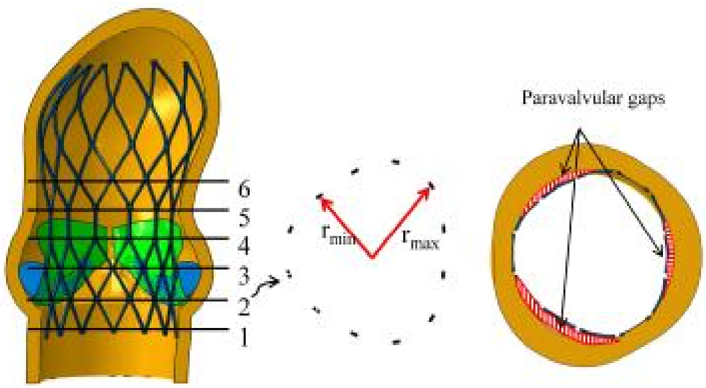


Fig.4 Measure of deployed valve stent distortion and paravalvular gaps (R: right coronary sinus, L: left coronary sinus, N: non-coronary sinus)

Paravalvular regurgitation would happen when there was a bad contact between the stent and aortic root. The degree of the contact was calculated by the gaps area of the stent and aortic root [9]. It was found that gaps located under the right coronary sinus, left coronary sinus, and non-coronary sinus, therefore, the three gaps were calculated individually and then got the total gap. Fig. 4 showed the gaps in plane 2.

3 Results

3.1 Deformation of stent

As Fig.5 shown, the stent deformation index for all stents and calcification pattern, increased from the inflow end to the outflow end. It arrived on the peak value at plane 3 or plane 4, and then decreased. However, there are many distinguish on each planes for different stents and calcification patterns. Stent 2 had the minimum stent deformation index at plane 2 for all the calcification patterns.

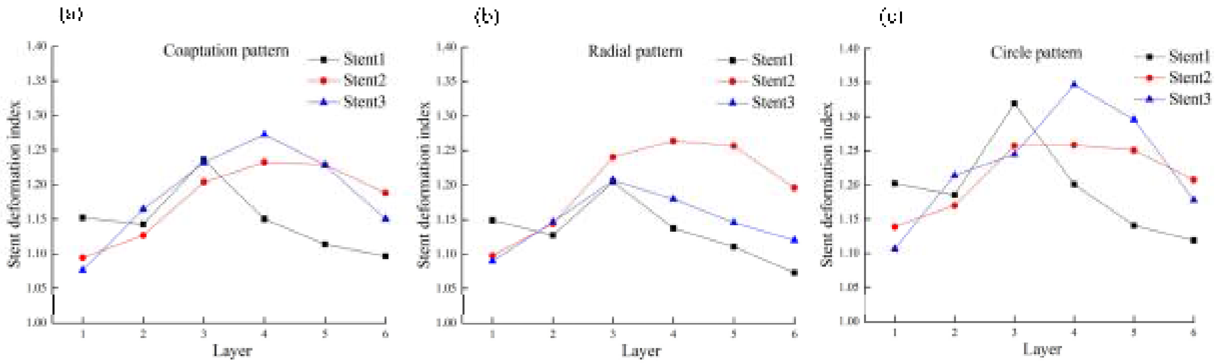


Fig. 5 Stent deformation index of (a)Coaptation pattern; (b)Radial pattern;(c)Circle pattern

3.2 Stress for calcification and aortic wall

Table 1 provided the peak value of von mises stress and maximum principle stress of aortic wall and calcification plaque. Stent 2 had the lowest peak value of the von mises stress and the maximum principal stress for all three calcification patterns. Stent 3 had the highest stress for all the patterns.

Table 1 Max stress of aortic wall and calcification plaque

Pattern and stent	Aortic wall		Calcification plaque	
	Max. von mises	Max. principle sress	Max. von mises	Max. principle stress
Coaptation pattern				
1#	2.3	0.9	7.2	2.8
2#	1.0	0.7	6.9	2.6
3#	2.1	2.4	8.6	10.5
Radial pattern				
1#	1.8	2.0	10.5	9.3
2#	1.5	1.8	9.9	8.6
3#	1.7	2.0	10.7	9.2
Circle pattern				
1#	1.7	0.8	7.9	5.1
2#	1.1	0.8	5.7	4.3
3#	2.0	2.3	11.4	11.4

Table 2 described the location of the maximum stress. The aortic wall maximum stress of all stents happened at leaflet commissure, which located on the plane 3-4. For the radial and circle pattern, the calcification plaque maximum stress of all stents happened on the plane 3. However, for the coaptation pattern, the maximum stress of stent1 and 2 located on the plane 3-4.

Table 2 Position of the max. Von mises stress point.

Stent and pattern	Calcification plaque	Aortic wall
coaptation pattern		
1#	plane 3-4	plane 3-4
2#	plane 3-4	plane 3-4
3#	plane 3	plane 3-4
Radial pattern		
1#	plane 3	plane 3-4
2#	plane 3	plane 3-4
3#	plane 3	plane 3-4
Circle pattern		
1#	plane 3	plane 3-4
2#	plane 3	plane 3-4
3#	plane 3	plane 3-4

Fig.6 was the stress distribution diagram of stent 1 for different calcification patterns. It showed the location of the maximum stress for aortic wall and calcification plaques.

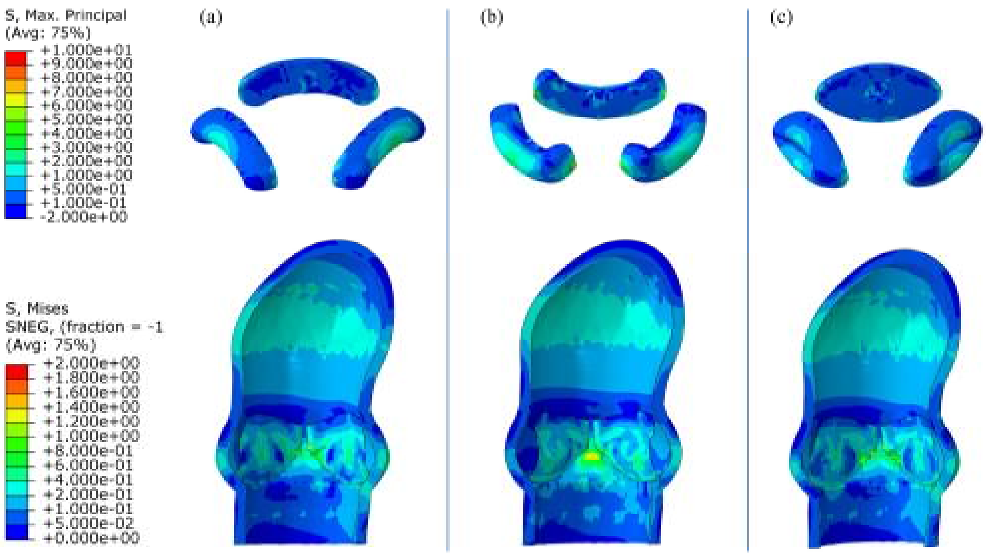


Fig. 6 Calcification plaque and aortic wall stress distribution diagram of (a)Coaptation pattern; (b)Radial pattern;(c)Circle pattern

3.3 Paravalvular Gaps

Fig. 7 showed the paravalvular gaps of all the stents and calcification patterns on plane 2. Stent 1 had the maximum total paravalvular gaps for all three calcification patterns. Stent 2 and 3 had the similar total paravalvular gaps. The total gap for radial pattern was larger than other two patterns. The coaptation pattern had the smallest total gaps. The gap near the right coronary sinus is larger than which near left and no coronanry sinus. The gap near right coronary sinus of stent 1 was significantly larger than other two stents for all three calcification patterns.

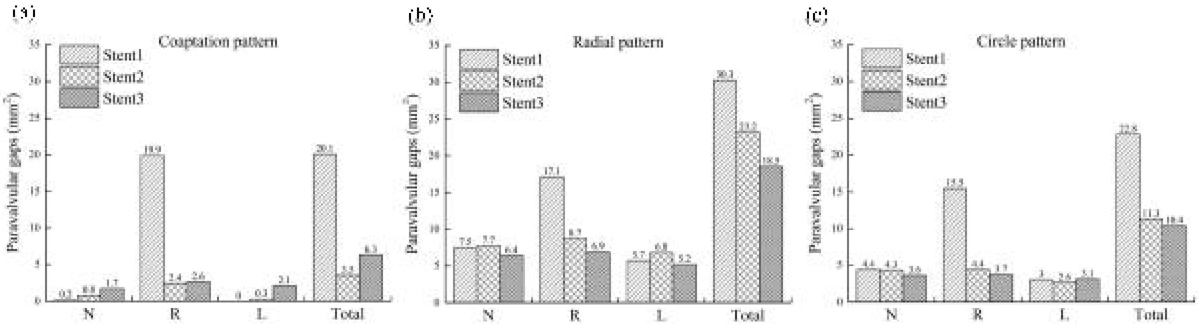


Fig. 7 Paravalvular gaps of (a)Coaptation pattern; (b)Radial pattern;(c)Circle pattern

4 Discussion

Transcatheter aortic valve impantation(TAVI) rapidly developed in recent decade. Paravalvular aortic regurgitation (AR) as a complication significantly influences the morbidity and mortality after TAVI [5-7]. In this study, it was evaluated that effect of stent design on the paravalvular regurgitation of transcatheter aortic valve implantation based on numerical simulations. Three self-expanding transcatheter aortic valve stent designs model were developed base on the commercial products. Three stents had the same inflow end but different outflow end. They were radial compressed and implanted into the representative calcified human aortic root models. The effect of different stent design on the aortic root stresses, stent deformations and the gaps between the stent and aortic root was analyzed and discussed in follow to reveal the relationship to paravalvular regurgitation.

4.1 Deformation of stent

Stent deformation was commonly found after TAVI. It commonly appeared triangle and ellipse [20]. Noncircular stent would lead to a higher stress on the leaflet [21-22].

In this study, stent 1 had the maximum stent deformation index for all three calcification patterns at plane 1. Three stents had the same design except for the outflow end, therefore, the different degree of sparseness caused the influence to deformation index.

The stent anchored on plane 2 which was the plane of aortic annulus. The deformation of stent on this plane was simultaneously affected by stent design and calcification plaque. Stent 1 had a higher deformation index than stent 2 for coaptation and circle patterns on this plane. It indicated that the deformation of stent 1 was more inhomogeneous compared to stent 2. The sparseness caused a critical influence relative to the calcification. However, the stent 3 had the maximum index for the two calcification patterns. It may be the reason that the stent 3's excessively sparse outflow end made the support force obviously decrease, resulting in a serious inhomogeneous deformation. This indicated calcification may be has the primary effect to the deformation. All the three stents had the similar deformation for the circle pattern. For the circle pattern, the calcification plaque along the coaptation line and the attachment line commonly effect the stent deformation. The degree of sparse for the outflow had a little influence for circle pattern.

Stent 1 still had a higher index than stent 2 on plane 3 for coaptation and radial patterns. This still indicated that deformation of stent 1 was more inhomogeneous than stent2. The degree of the sparseness still caused a critical influence relative to the calcification. Calcification plaque mainly located near the plane 3 for coaptation pattern, therefore, calcification plaque made an important effect to stent 3 and result in a higher deformation index. Calcification plaque was far away from this plane, so there is a lower deformation index of stent 2 and 3 for circle patterns. There was a similar index for all the three stents for radial pattern, which indicated the calcification made a primary effect to radial pattern.

The plane 4, 5 and 6 were far away from the calcification plaque, the deformation index was determined by degree of the sparseness of stent outflow end. Less sparseness outflow end made the bend aortic easily straighten, therefore, got a more concentricity deformation. However, if the outflow end was too sparse, there was no strut at the maximum deformation spot. And result in a lower deformation index, such as stent 3 on plane 6. These planes had a little effect to the paravalvular regurgitation.

Stent 2 had the lowest index for three calcification patterns. Higher deformation index easily lead to lager paravalvular gaps and result in more serious paravalvular regurgitation. There was a smaller difference of the stents for calcification patterns with leaflet calcification, which may indicated that stent 2 possess more excellent performance for less serious calcification patient.

4.2 Stress on calcification and aortic wall

The peak value of stress of calcification plaque and aortic wall located on the plane near plane 3 for all stents and calcification patterns. Location of maximum stent deformation index was close to this plane. This may be the reason of the peak stress.

Stent 2 had the minimum stress of calcification plaque and aortic wall. Rigid outflow end of stent 1 led to a higher deformation index and higher stress for calcification plaque and aortic wall. Stent 3 had the maximum peak value of stress. This may be the reason that the excessively sparse outflow end of stent 3 made the support force obviously decrease, and lead to a higher deformation, eventually result in a higher stress than other two stents.

Higher stress would make the stent easily to anchor on the aortic annulus [9]. And made the stent firmly contact with the aortic wall, then result in a smaller gap between the stent and aortic wall, eventually lead to lower paravalvular regurgitation. However, a higher stress will lead to a risk for aortic fracture and calcification plaque break. A breaken calcification plaque would lead to a risk of stroke. There was less report about stent immigration for self-expand stent, but the incidence was about 1.5-6%% for stroke [23]. It was better when there was a stress lower stress, but a smaller gap between the stent and aortic wall. So stent 2 was the best choice with a lower stroke and lower paravalvular regurgitation.

4.3 Paravalvular Gaps

The gap between stent and aortic wall could be used to predict the paravalvular regurgitation [9-11]. The influence of ascend aortic angle and paravalvular regurgitation had been investigated [24].

In this study, the paravalvular gap of right coronary sinus was the maximum for all the calcification patterns and stents. This may be the reason that the orient of the bent ascend aortic made the location has the lowest interact between the stent and aortic, induced the maximum gaps. Stent 1 had the maximum total gaps. Stent 2 and stent3 had the similar, but lower total gaps. However, stent 3 was a little higher than stent 2.

The location of coronary sinus for stent 1 had the obviously lager gaps than the other two, which led to a total larger gaps than others. This indicated there would be a seriously paravalvular regurgitation after implantation for stent 1. Rigid outflow end of stent 1 caused the stent not be compliance with the bend ascend aortic, result in larger gaps. As discussed in above, the deformation index of stent 2 and 3 on plane 2 was mainly decided by calcification, higher deformation index of stent 3 resulted in a larger gap than stent 2.

There was similar regularity for radial pattern. However, there is a small difference among the three stents. Calcification plaque located on plane 2 caused a critical effect to the gap for radial pattern and circle pattern. Therefore, radial pattern lead to a larger gap than coaptation pattern and circle pattern. The gap of circle pattern was lower than radial pattern, but lager than coaptation pattern. This maybe the calcification plaque on the leaflet decreased the effect of the calcification plaque which located along the attachment line.

Stent 2 had the minimum gap for all location and had the minimum total gaps. Stent 2 also had a smaller gap when the calcification patterns had a little calcification volume, such as coaptation patterns. All investigations indirectly clarified why the new generation transcatheter aortic valve had a more sparseness outflow end than the first generation, such as Corevalve Elout R and Portico.

5 Conclusions

In this study, it illuminated that an excessively dense or a sparse outflow end would result in a larger stent deformation indexes, a higher stress calcified plaques and aortic root, and a lager gap, and led to serious paravalvular regurgitation.

Overall, stent 2 had the most excellent performance compared to other two stents. Stent 2 had morderate sparse outflow end. This made the stent easily be compliance with bend ascend aortic, and had the enough support force. All of these made the stent 2 had the identical deformation, lowest calcification plaque stress and smallest gaps. Especially, stent 2 had a more excellent performance when there was a little calcification, or there was a calcification plaque on the leaflet. This indicated stent 2 was more suitable for lower risk patient.

This study provides guidance for design of transcather aortic valve, and help to predict the clinical outcome.

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