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Original Article

Haemodynamics Study of Tapered Stents Intervention to Tapered Arteries

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Abstract
Purpose—In-stent restenosis (ISR) is related to local haemodynamics in the arteries after stent intervention. However, the haemodynamics of stents implanted into tapered vessels is rarely studied and remains unclear. This study aimed to study the haemodynamic performance of a stent in a tapered artery to reveal the haemodynamic differences between tapered and cylindrical stents after stent implantation and guide the stent selection for the treatment of coronary artery stenosis.
Methods—Cylindrical and tapered stents were implanted into the tapered arteries. A model of a cylindrical stent implanted into a cylindrical artery was established as the contrast model. Using the finite element method, the flow velocity and wall shear stress distribution of the three models were compared.
Results—At t_1, t_2, t_3 and t_4, the flow rate of the tapered artery with tapered stents (TT) after the implantation increased by 8.59, 3.80, 12.81 and 3.66%, respectively. In addition, the wall shear stress in the tapered arteries of TT was 23.48, 36.67, 13.00 and 8.06% higher than that of the tapered arteries with cylindrical stents (TC).
Conclusions—The implantation of a tapered stent in the tapered artery can effectively improve intravascular haemodynamics. The tapered stent allows the tapered artery to obtain better haemodynamics and reduces the probability of ISR.

Keywords—Tapered stent, Cylindrical stent, Tapered arteries, Haemodynamics, Numerical simulation.

INTRODUCTION

Stent implantation has become an important method in treating coronary artery stenosis. However, in-stent restenosis (ISR) after stent implantation is a major obstacles in long-term treatment.[21] ISR is not only related to the stent structural mechanics but also to the local haemodynamics in the arteries after stent intervention.[11,14,33] Complex intravascular environments may cause local blood flow disorder, which not only decreases blood flow and blood kinetic energy but also affects the normal physiological activities of parietal cells and increases the possibility of vascular inflammation.[26] Clinical tests show that atherosclerotic plaque is concentrated in areas with low wall shear stress (WSS).[32] The interaction of blood cells and other macromolecules and endothelial cells in the blood is caused by a low WSS. The functions and structure of the endothelial cells are disturbed, thereby promoting the formation and development of atherosclerotic plaque and ISR.

Extensive research on haemodynamic analysis after stent implantation has been conducted,[2,3,6,8,10,24,34] so the present study concentrated on cylindrical and bifurcation vessels. Beier *et al.*[2] established stent models with different parameters, including strut spacing, stent size and luminal protrusion, to study their haemodynamic effects in cylindrical vessels. Using an ideal cylindrical vessel, Chen *et al.*[6] evaluated the mechanical effects of undersizing and oversizing of stents on the endothelial WSS and vessel wall stress to determine the possible biomechanical mechanism of ISR and thrombosis. Chiastra *et al.*[8] performed a comprehensive study on the haemodynamics of two realistic stented coronary bifurcation models to demonstrate the feasibility and investigate the haemodynamics of patient-specific coronary bifurcation geometries. Beier *et al.*[3] established a bifurcation vascular model, analysed the computational fluid dynamics of the vessel after stent implantation and discussed the effect of vascular bifurcation angle on blood flow. Qiao *et al.*[24] investigated the effects of endovascular stents with different links on the treat-

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ment of the stenotic vertebral artery and determined the relationship between the shape of the link and ISR. However, tapered vessels, such as the left coronary and carotid arteries, are rarely involved in current haemodynamic research.[12,19,20,27–30,35] Although most of the current clinical stents are cylindrical stents,[1,13,18,23,25] tapered stents are also used in clinical settings and have achieved good results in the latest literature[31,37] with the development of stent design and production. Given that few reports are available regarding the haemodynamics of tapered stents that are implanted into tapered vessels, this study will focus on this subject.

MATERIALS AND METHODS

Geometry

Cylindrical and tapered stents were implanted into tapered arteries. The artery was tapered to 0.78°, and the length of the artery model was 20 mm. Another cylindrical stent was implanted into the cylindrical artery to serve as the contrast model. The cylindrical stent used was a sinusoidal unit wave stent with a length of 9 mm, eight cell rings and two L-shaped links. The geometric parameters were consistent with the cylindrical stent. The dilation of the vessel after stent implantation caused the original model to expand with the central diameter as the base. The initial diameter of the artery's middle part was 3.5 mm, and the expansion ratio of the stent model was 1.20, resulting in a final middle diameter of 4.2 mm. The simplified tapered artery with tapered stent implantation was assigned as TT (Fig. 1), whereas the cylindrical and tapered arteries with cylindrical stent implantation were assigned as CC and TC, respectively.

Numerical Approaches

The blood set by an incompressible Newtonian fluid model[7] had a density of 1060 kg/m^3 and dynamic viscosity of 0.004 Pa s. No-slip boundary conditions were applied to all internal surfaces. The geometries were rigid because stent deployment and calcification of the arterial wall stiffened the vessel; for work involving the analysis of near-wall quantities (e.g. WSS), slight differences exist between rigid-wall and compliant fluid–structure simulations.[7] To ensure the accuracy of calculations, a five-layer tetrahedral mesh was used to divide and refine the stent placement. The remaining parts were then divided by tetrahedron meshes with three gradually encrypted layers.

The numerical simulations were based on the 3D incompressible Navier–Stokes equations:

$$\rho(\vec{u}\cdot\nabla)\vec{u} + \nabla p - \mu\Delta\vec{u} = 0$$

$$\nabla\cdot\vec{u} = 0$$

where $\vec{u}$ is the fluid velocity vector; ρ and μ are the density and viscosity of the blood, respectively; and p is pressure.

For pulsatile flow simulation, a time-dependent flow pressure waveform (Fig. 2) was set at the inlet. The blood pressure at the outlet was set to a constant value of 50 Pa. Blood flow was analysed at four moments: t_1, t_2, t_3 and t_4, which represent the starting time of the contraction period (0.1 s), the time when pressure peaks (0.25 s), the contraction period near the end of the moment (0.4 s) and the beginning of the diastolic period (0.5 s), respectively.

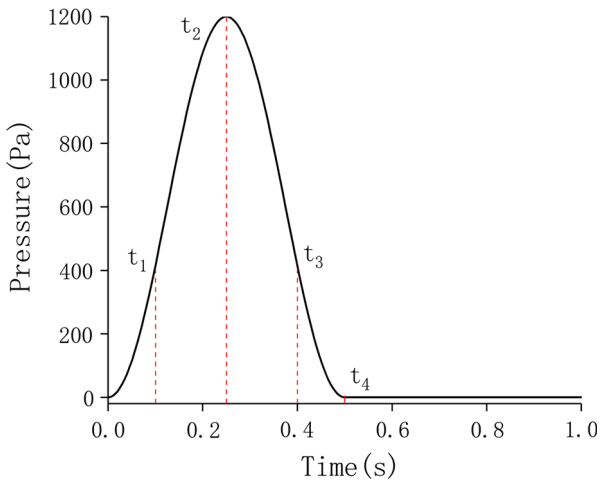

FIGURE 2. Pressure-time relationship of blood flow inlet in a heartbeat cycle.

FIGURE 1. Finite element models of stenting tapered artery using tapered stent.

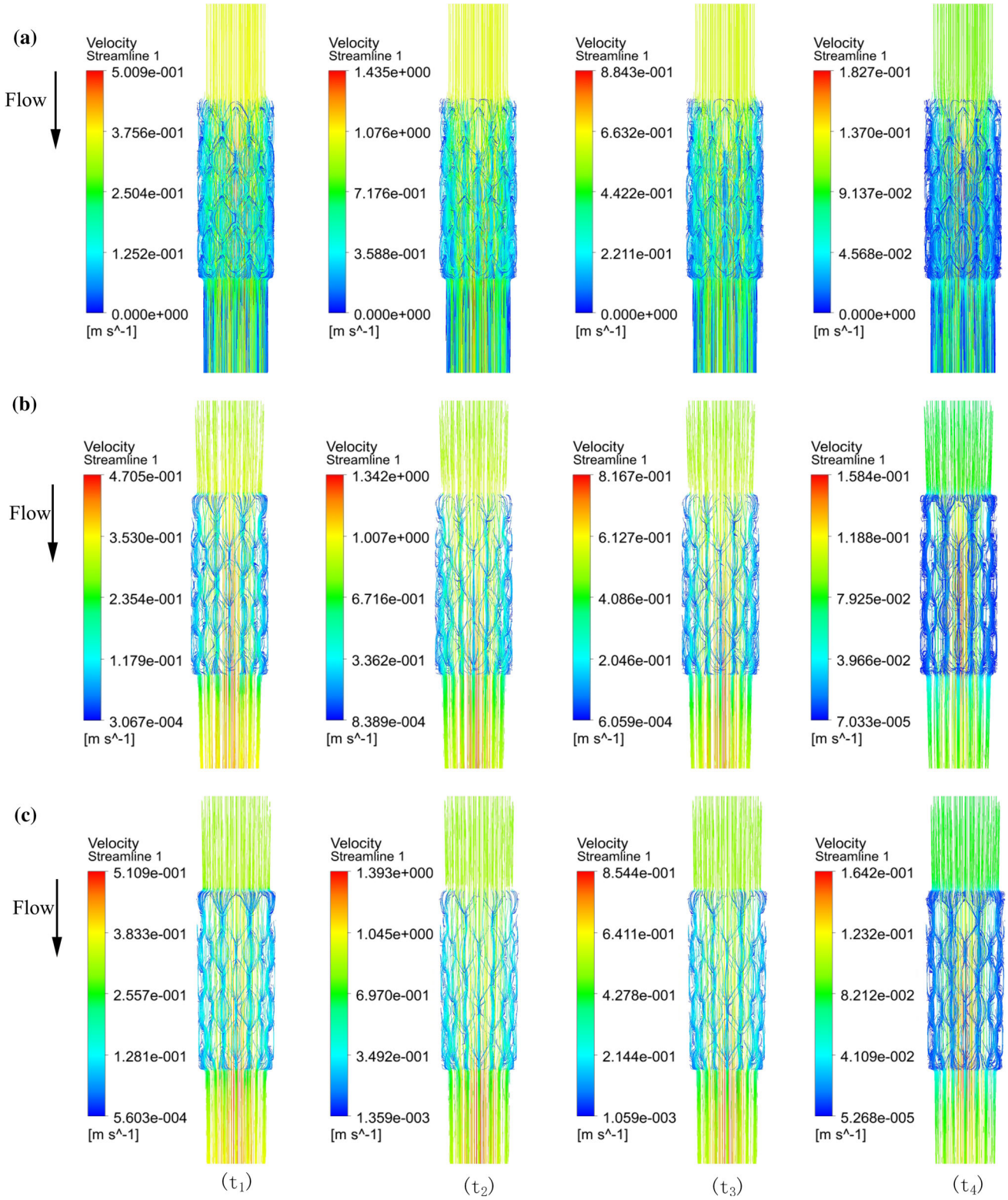

FIGURE 3. Velocity streamline distribution in (a) cylindrical artery implanted with cylindrical stent, (b) tapered artery implanted with cylindrical stent and (c) tapered artery implanted with tapered stent (c) at t_1, t_2, t_3 and t_4.

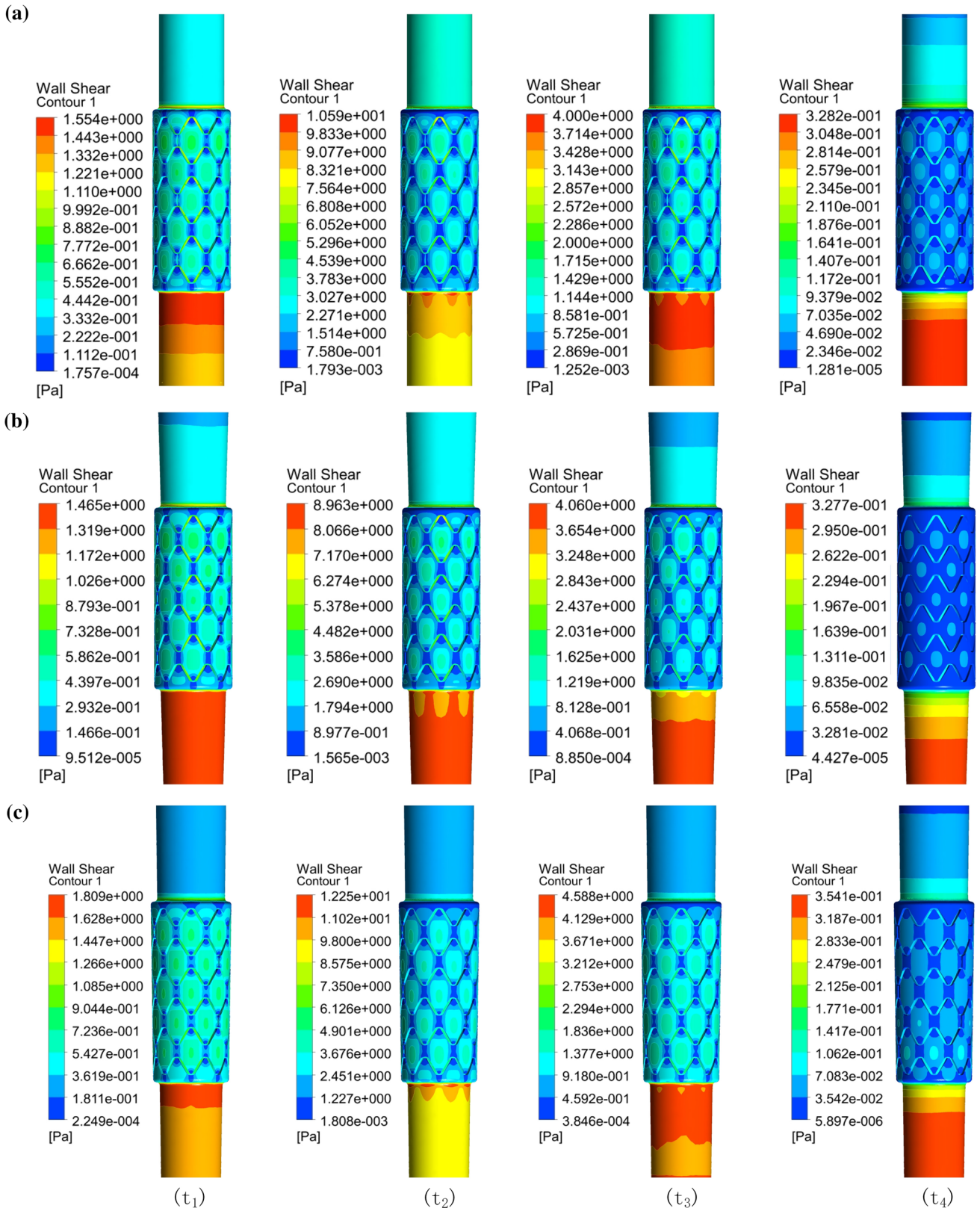

FIGURE 4. WSS distributions in (a) cylindrical artery implanted with cylindrical stent, (b) tapered artery implanted with cylindrical stent and (c) tapered artery implanted with tapered stent (c) at t_1, t_2, t_3 and t_4.

RESULTS

Figure 3 shows the flow streamline distribution in models CC, TC and TT at the four moments. The velocity of the blood reached the maximum value near t_2 and the minimum value near t_4. In addition, flow velocity was low near the stent, and the shape of the stent was clearly visible in all models. In model CC, blood velocity decreased from the proximal end to the distal end, and the velocity near the blood inlet was greater than that of the other regions. During a pulse, the minimum value of the blood velocity was 0 m/s, in model CC. It means that there are stagnation areas of blood flow in the fluid field. By contrast, the velocity in models TC and TT increased along the direction of flow, the velocity of blood flow near the outlet was remarkably higher than that near the inlet, blood flow resumed circulation and stagnation areas were not present.

Figures 3a and 3b show that the flow field changed due to the conical characteristics of blood vessels. The blood flow velocity slowed down in a tapered vessel. However, the tapered stent improved flow velocity. The difference between the flow pattern of the tapered vessels after the intervention of the cylindrical and tapered stents is illustrated in Figs. 3b and 3c. The blood flow rate of model TT was slightly higher than that of model TC at all four moments; the flow rate of model TT increased by 8.59, 3.80, 12.81 and 3.66%. Moreover, the minimum flow rate of model TT improved, except at t_4.

Figure 4 displays the WSS distribution of models CC, TC and TT at the four typical moments. The WSS at the centre of the struts decreased in the consecutive struts along direction of flow at all models. The proximal region had a lower WSS than the distal region at both ends of the blood vessel. In Figs. 3a and 3b, the same cylindrical stent was implanted into the cylindrical and tapered vessels. As shown in Figs. 3b and 3c, the WSS in model TC was lower than that in model TT for most of the moments. On the one hand, the peak WSS of model CC was 6.08, 18.15 and 0.15% higher than that of model TC at t_1, t_2 and t_4, respectively. On the other hand, the peak of WSS in model TT was greater than that in models CC and TC at all four moments, with respective increments of 16.41, 15.68, 14.70 and 7.89% and 23.48, 36.67, 13.00 and 8.06%.

DISCUSSION

ISR is a major challenge in the interventional treatment of cardiovascular occlusive diseases. Stent implantation can restore normal blood flow in the stenotic segment of the artery,[5,7,9,15,16,22,36] but it can inevitably lead to some adverse haemodynamic changes in the lumen, which is closely related to ISR.[33] Although research on the haemodynamics of stent implantation has achieved good results,[4,5,9,15,16,22,36] majority of previous studies discussed cylindrical stents. The cylindrical stent is prone to injury at the distal end of the tapered artery, which may lead to ISR.[27] Given that studies on the haemodynamics of tapered stent implantation in tapered arteries are rare, this work investigated tapered stent implantation in cylindrical and tapered arteries. Results showed that flow velocity was low near the stent. In addition, the visible shape of the stent indicated that blood lipid and fibrin were retained in these areas, which could induce plaque formation and ISR.[33] The blood velocity changed after the implantation of the cylindrical stent due to the tapered blood vessel. Moreover, the flow velocity and WSS decreased. Therefore, traditional cylindrical stents are inappropriate for tapered vessels in statics or haemodynamics.

The implantation of tapered stents can effectively improve the haemodynamics of tapered vessels. Compared with the cylindrical stent, the flow velocity in the tapered arteries after implanting the tapered stent increased. In addition, the implantation of the tapered stent provided a higher WSS in the tapered arteries than that of the cylindrical stent; low WSS (WSS $<$ 0.5 Pa) can cause intimal hyperplasia, which may lead to ISR.[17] Therefore, the probability of ISR is reduced by using a tapered stent. Tapered stents demonstrated good therapeutic effects on clinical coronary stenosis, and using tapered stents that are fitted to the patients' characteristics may become a future trend in the treatment of coronary stenosis.

However, this study was conducted in an ideal dilated state and did not consider the intraluminal convexity caused by stent implantation. In addition, the effects of plaque were not considered, and the arteries were assumed to be rigid. In real settings, the blood, arteries, stents and plaque interact with one another, but this study ignored the fluid–structure interaction (FSI) amongst blood, arteries and stents. Future studies should focus on the effects of haemodynamics under the FSI in actual stented tapered arteries.

CONCLUSIONS

Although stent implantation improved the blood flow in the stenotic segment of the vessel, the effects of stent type (i.e. cylindrical and tapered stents) on blood flow varied due to the effect of the vascular taper. The haemodynamic parameters of cylindrical stents in a tapered vessel were difficult to match with those of

cylindrical stents in a cylindrical vessel. However, tapered stent implantation on the tapered arteries could improve the distribution of local haemodynamics. Therefore, compared with cylindrical stents, tapered stents are more suitable for tapered arteries in enhancing haemodynamics and reducing the probability of ISR.

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CONFLICT OF INTEREST

Xiang Shen, Jiabao Jiang, Yongquan Deng, Hongfei Zhu, and Kaikai Lu declare that they have no conflict of interest.

ETHICAL STANDARDS

This article does not contain any studies with human participants or animals performed by any of the authors.

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