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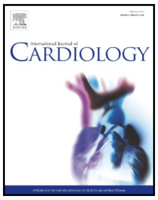

The conical stent in coronary artery improves hemodynamics compared with the traditional cylindrical stent☆

Yi Yu, Yujie Zhou *, Qian Ma, Shuo jia, Sijing Wu, Yan Sun, Xiaoli Liu, Yingxin Zhao, Yuyang Liu, Dongmei Shi

Beijing Anzhen Hospital, Capital Medical University, Beijing Institute of Heart Lung and Blood Vessel Disease, The Key Laboratory of Remodeling-related Cardiovascular Disease, Ministry of Education, Beijing 100029, China

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ABSTRACT

Objectives: This study sought to explore the efficacy of the conical stent implantation in the coronary artery by comparing the effects of cylindrical and conical stents on wall shear stress (WSS) and velocity of flow and fractional flow reserve (FFR).

Background: The traditional cylindrical stent currently used in the percutaneous coronary intervention (PCI) has a consistent diameter, which does not match the physiological change of the coronary artery. On the contrary, as a new patent, the conical stent with tapering lumen is consistent with the physiological change of vascular diameter. However, the effect of the conical stent implantation on the coronary hemodynamics remains unclear.

Methods: The coronary artery, artery stenosis and two stent models were established by Solidworks software. All models were imported into the computational fluid dynamics (CFD) software ANSYS ICEM-CFD to establish the fluid model. After the boundary conditions were set, CFD analysis was proceeded to compare the effects of two stent implantation on the change of WSS, velocity of flow and FFR.

Results: Hemodynamic indexes including FFR, blood flow velocity distribution (BVD) and WSS were improved by either the cylindrical or the conical stent implantation. However, after the conical stent implantation, the change of FFR seemed to be slower and more homogenous; the blood flow velocity was more appropriate without any obvious blood stagnation and direction changes; the WSS after the conical stent implantation was uniform from the proximal to distal side of the stent.

Conclusions: Compared with the cylindrical stent, the conical stent implantation in the coronary artery can make the changes of vascular hemodynamic more closer to the physiological condition, which can reduce the incidence of intra-stent restenosis and thrombosis, thus making it more suitable for PCI therapy.

1. Introduction

Since the first successful case of percutaneous transluminal coronary angioplasty (PTCA) in 1977, the percutaneous coronary intervention (PCI) has experienced four times of technical innovation, from the primitive PTCA, the bare metal stent (BMS), the drug-eluting stent (DES), to the recent bio-absorbable stent (BVS) [1]. Great progress has been made in the material of the stent. In the contradictory, the shape of the stent has not changed much except the size. The traditional cylindrical stent currently used in PCI procedure has a consistent diameter, which does not match the physiological change of the coronary artery. Many studies and clinical experience have confirmed that after the stent implantation, the change of the coronary hemodynamics especially the formation of low wall shear area and low flow velocity area, induces the acute inflammatory responses, delays the endothelium repair and promotes the in-stent restenosis and the thrombosis [2–5]. Therefore, it is of great significance to minimize the hemodynamic change caused by stent implantation as much as possible on the basis that the physical characteristics of the stent can meet the clinical needs.

As a new patent we've applied for, the conical stent with tapering lumen is consistent with the physiological change of vascular diameter. However, the effect of the conical stent implantation on the coronary hemodynamics remains unclear. Frank et al. suggested that the computational fluid dynamics (CFD) analysis software can accurately and efficiently simulate the blood flow within the stent, which is instructive in analyzing the hemodynamic change after the stent implantation [6,7]. This study was designed to compare the coronary hemodynamic change between conical and cylindrical stent implantation using the CFD analysis software, and evaluate the feasibility of the conical stent implanted in the coronary artery.

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* Corresponding author at: Department of Cardiology, Beijing Anzhen Hospital, Capital Medical University, Beijing 100029, China.

E-mail address: azzyj12@163.com (Y. Zhou).

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2. Methods

2.1. The establishment of vessels and stent model

First of all, the model of vascular lumen was established by Solidworks (a solid modeling software). The diameter of the entrance was 4.5 mm, and the diameter of the exit was 2.5 mm. The entrance and the exit section of the model were all cylindrical structure with the length of 10.0 mm. The junction between the entrance and the exit section was a conical vessel with the length of 25.0 mm.

In order to simulate the vascular lumen after coronary stenosis, conical stent and cylindrical stent implantation, three models were established, (1) with a 80%-eccentric stenosis (based on the cross-section area) in the middle of the conical vessel section (Fig. 1A), (2) with a cylindrical stent (diameter: 4.0 mm, length: 15.0 mm) on the conical section of the model which completely solved the eccentric stenosis of the vessel (Fig. 1B), and (3) with a conical stent (diameter of entrance: 4.0 mm, diameter of exit: 2.5 mm, length: 15.0 mm) on the conical section of the model which also completely solved the eccentric stenosis of the vessel (Fig. 1C). The simulative blood density was 1.060 g/cm^3 and the blood viscosity was 0.004. [8].

2.2. The grid partitioning

The three vascular lumen models were imported into ANSYS ICEM-CFD software to divide the grid. Three layers of prismatic grid were used in the near-vascular-endothelium part, and the mixed hexahedral and tetrahedral grids were used in other parts. In order to ensure the calculation precision, the size of the grid was within 0.15 mm. The grid was partitioned as follows: model 1, 992,540 units; model 2, 120,540 units; model 3， 503,986 units.

2.3. The calculation of CFD

The partitioned grid was imported into the ANSYS Fluent software to calculate. In the coronary artery, blood can been treated as incompressible Newtonian fluid with a density of 1060 kg/m^3 and a kinematic viscosity coefficient of 0.0040 kg/(m·s). The boundary conditions were set as follows: (1) the pressure of entrance was according to entrance pressure of the coronary artery calculated during the measurement of FFR after using adenosine and was set to 60 mm Hg, (2) the pressure of exit was based on the algorithm of the artificial circuit exit, (3) the blood vessel wall was set so that no slip occurs [9].

2.4. Calculation and analysis

In order to ensure the accuracy, we used Semi Implicit Method for Pressure-Linked Equations (SIMPLE) algorithm in the solver and Second-order Up-wind Finite Volume Method to calculate the space discrete scheme. The exit velocity pressure and calculating residual were monitored during the calculation. When the flow of exit turned stable and the residual fell to 10^{-4}, the calculation was considered as convergent. It was necessary to save the FFR value of each unit during the process of the calculation while FFR value was considered as the ratio of unit pressure and entrance pressure. After calculation, results were saved for further analysis.

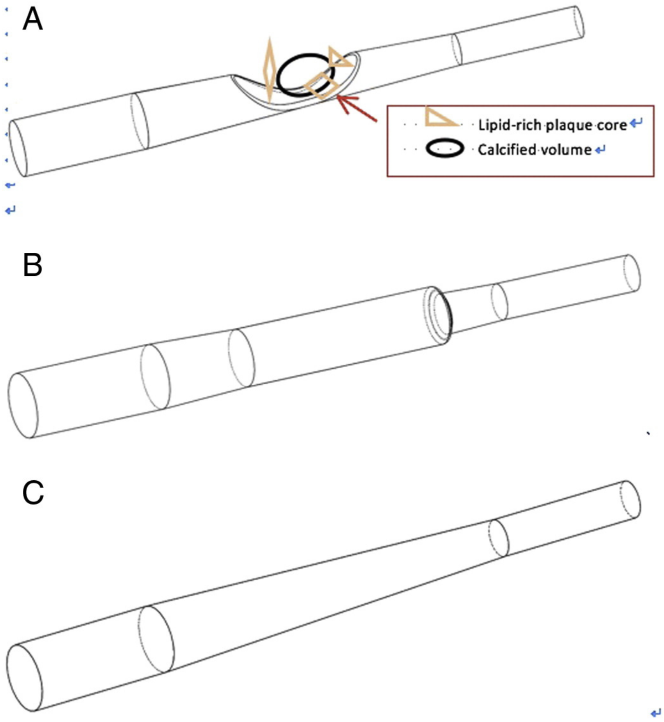

Fig. 1. The model of the vessel and stents. (A) Coronary vessel with a 80%-eccentric stenosis. (B) A cylindrical stent (diameter: 4.0 mm, length: 15.0 mm) on the conical section of the model. (C) A conical stent (diameter: 4.0 mm, length: 15.0 mm) on the conical section of the model.

3. Results

In order to simulate the effects of the conical stent on coronary hemodynamics, the model of stenosis, the conical stent and the cylindrical stent implantations were established.

The FFR is an index to evaluate the coronary blood flow by measuring the pressure, which is defined as the ratio of the distal pressure of the stenosis to the proximal pressure [10]. FFR is an important index to evaluate the stenosis and ischemia as well as the recovery of the blood flow after the stent implantation [11].

The blood flow velocity is closely related to atherosclerosis. Low velocity can cause lipid deposition and atherosclerosis. However, high velocity promotes the rupture and fall-off of the plaque [12,13]. Meanwhile, the form of the blood flow is determined by the distribution of the blood flow velocity. Vortexes is easily formed if the velocity distribution is uneven, which is prone to promoting the formation and rupture of the plague [14].

The wall shear stress (WSS) is defined as the pressure of the vascular wall and the endothelial cells produced by the blood flow. The change of WSS is closely involved in the formation and rupture of the atherosclerotic plaque [15,16]. The low WSS tends to cause the formation of the atherosclerotic plaque, while the high WSS tends to rupture it. [17].

The three indexes are important in reflecting the dynamic change of hemodynamics, so we compared the change of the FFR, blood flow velocity and the WSS after the conical or cylindrical stent implantation.

3.1. Fractional flow reserve

Before stent implantation, FFR on the stenosis was significantly lower than normal blood vessels (Fig. 2A). In contrast, FFR was significantly improved after either the cylindrical stent or conical stent implantation which suggested that both stents were effective in treating stenosis (Fig. 2B and C). However the changes of FFR seemed to be slower and more homogenous in the conical stent implantation. That is to say, compared with the cylindrical stent, the conical stent decreased the gradient of endovascular blood pressure more evenly, which was closer to the physiological changes of the blood vessels.

3.2. The blood flow velocity distribution

The change of BVD after stent implantation was shown in Fig. 2. Before stent implantation, blood flow velocity on the stenosis was significantly faster, while the speed was not uniform, and the flow was disturbed (Fig. 3A), which was easy to cause plaque rupture and acute cardiovascular events. In contrast, the blood flow velocity was significantly decreased and became evener after implanting both two stents (Fig. 3B and Fig. 3C). However, the blood flow velocity after the cylindrical stent implantation was too slow, especially on the edge of the stent, which was prone to promoting lipid deposition and atherosclerosis. Meanwhile, the blood flow was suddenly stagnated at the distal narrow site of the cylindrical stent, which was easier to induce the formation of plaque progression and micro thrombosis. On the contrary, the conical stent was complied with the physiological structure. The blood flow velocity after conical stent implantation was faster without any obvious blood stagnation and direction changes.

3.3. Wall shear stress

Before the stent implantation, WSS on the stenosis site was significantly higher than normal blood vessels with evenly distribution