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Short Communication

Stent expansion in curved vessel and their interactions: A finite element analysis

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Abstract

Coronary restenosis after angioplasty has been reduced by stenting procedure, but in-stent restenosis (ISR) has not been eliminated yet, especially in tortuous vessels. In this paper, we proposed a finite element method (FEM) to study the expansion of a stent in a curved vessel (the CV model) and their interactions. A model of the same stent in a straight vessel (the SV model) was also studied and mechanical parameters of both models were researched and compared, including final lumen area, tissue prolapse between stent struts and stress distribution. Results show that in the CV model, the vessel was straightened by stenting and a hinge effect can be observed at extremes of the stent. The maximum tissue prolapse of the CV model was more severe (0.079 mm) than the SV model (0.048 mm); and the minimum lumen area of the CV was decreased (6.10 mm^2), compared to that of the SV model (6.28 mm^2). Tissue stresses of the highest level were concentrated in the inner curvature of the CV model. The simulations offered some explanations for the clinical results of ISR in curved vessels and gave design suggestions of the stent and balloon for tortuous vessels. This FEM provides a tool to study mechanisms of stents in curved vessels and can improve new stent designs especially for tortuous vessels.

Keywords: Curved vessel; Coronary stent; Finite element methods; In-stent restenosis; Mechanical properties

1. Introduction

In-stent restenosis (ISR) still remains an obsession to cardiologists (Mitra and Agrawal, 2006) even though drug-eluting stents are shown to improve stenting treatment (Tanabe et al., 2003). Stent–vessel interactions are considered as a controlling factor of ISR (Zhou et al., 2003), especially in tortuous vessels (Colombo et al., 2002). For the interactions of stents in curved vessels, a few in vivo (Abhyankar et al., 1997; Zhu et al., 2003) and in vitro (Kalmar et al., 2002; Rieu et al., 2003) studies have been done. However, these works just described clinical results or measured conformability of stents, and mechanics of stent deformation in curved vessels have not been discussed. Finite element methods (FEMs) are considered to be an efficient way of testing and improving stent designs to minimize ISR from biomechanical aspects (Prendergast et al., 2003; Brand and Ryvkin, 2005; Holzapfel et al., 2005; Lally et al., 2005; Wang et al., 2006) or fluid dynamics (Natarajan and Mokhtarzadeh-Dehghan, 2000; Wentzel et al., 2000; Chen et al., 2005; LaDisa et al., 2005; Johnston et al., 2006); however, stenting in curved vessels has seldom been modeled yet. This work proposed a FEM to describe the expansion of a stent in a curved vessel (the CV model) and their interactions. For comparison, the same stent was expanded in a straight vessel (the SV model). With the simulations, we expect to offer some explanations for ISR in curved vessels through biomechanical view and try to explain the results in terms of the model physics.

2. Materials and methods

2.1. Geometry models and material properties

The geometrical models were generated using Pro/Engineer (Parametric Technology Corporation) and were transformed into FEM code ANSYS (ANSYS, Inc.) for analysis. Both SV and CV models have four

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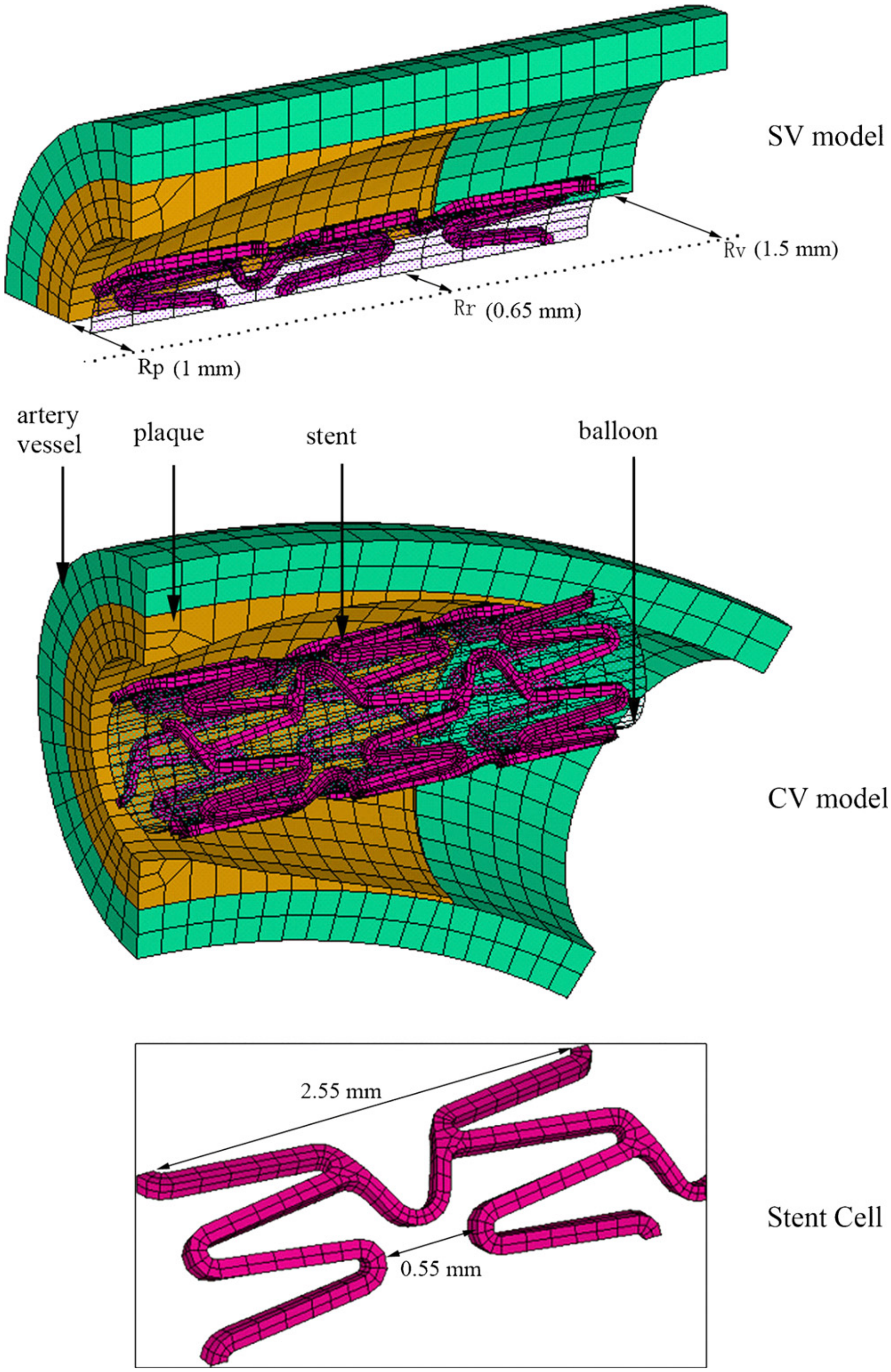

Fig. 1. Finite element models of the SV and CV model. The stent is our patent design, composed of struts with eight rings in circular direction, which are connected by four links in longitudinal direction; and the stent has a length of 9 mm, a thickness of 0.1 mm and an outer diameter of 1.5 mm. The struts will support the vessel and the links provide the stent flexibility for curved vessels. The width of struts and links is 0.1 mm. The sizes of a stent cell are also shown. The balloon was modeled as a rigid body and has a radius $R_r = 0.65$ mm and a length of 10 mm. In the SV model, the vessel has an inner radius $R_v = 1.5$ mm, a thickness of 0.5 mm and a length of 12 mm; the plaque has a length of 8 mm and was constructed through uniform rational B-splines and becomes thinner from middle to extreme parts. With its smallest inner radius $R_p = 1$ mm, the plaque corresponds to the severest stenosis of 56% for the reference vessel lumen area (7.07 mm^2). In the CV model, the lengths of the axes are 8 and 12 mm for the curved plaque and vessel, respectively; the diameters from axes and thicknesses of the vessel and plaque are the same as the SV model. For symmetry reasons, only one-eighth of the SV model was built and one-half of the CV model was modeled (the tissue in the CV model is shown in half).