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Influence of catheter insertion on the hemodynamic environment in coronary arteries

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ABSTRACT

Intravascular stenting is one of the most commonly used treatments to restore the vascular lumen and flow conditions, while perioperative complications such as thrombosis and restenosis are still nagging for patients. As the catheter with crimped stent and folded balloon is directly advanced through coronary artery during surgery, it is destined to cause interference as well as obstructive effect on blood flow. We wonder how the hemodynamic environment would be disturbed and weather these disturbances cause susceptible factors for those complications. Therefore, a realistic three-dimensional model of left coronary artery was reconstructed and blood flow patterns were numerically simulated at seven different stages in the catheter insertion process. The results revealed that the wall shear stress (WSS) and velocity in left anterior descending (LAD) were both significantly increased after catheter inserted into LAD. Besides, the WSS on the catheter, especially at the ending of the catheter, was also at high level. Compared with the condition before catheter inserted, the endothelial cells of LAD was exposed to high-WSS condition and the risk of platelet aggregation in blood flow was increased. These influences may make coronary arteries more vulnerable for perioperative complications.

1. Introduction

Intravascular stents are small tube-like structures expanded into stenotic arteries to restore blood flow perfusion for the downstream tissues that have become clogged by the build-up over time of fat, cholesterol or others substances [1]. After the first percutaneous coronary intervention (PCI) was performed, more than 1.8 million patients received one or more intracoronary stents annually [2]. The deployment of an intravascular stent has become a widely used and minimally invasive treatment for coronary heart disease [3].

With the widespread use of intravascular stents, perioperative complications have emerged, such as vessel spasm, thrombosis and restenosis [2,4–7]. Although rare, these complications are life-threatening complications during and shortly after PCI [8]. Sinha et al. reported that the repeated use of IVUS prior to PCI would result in cardiac arrhythmias and vessel spasm [9]. The antithrombotic and anticoagulant regimens, such as bivalirudin, heparin, glycoprotein IIb/IIIa inhibitors and so on, are essential to avoid thrombogenesis during PCI [10–12], especially for patients with acute coronary syndromes [13]. Even so, Buller et al. observed that unexplained cases of thrombosis primarily that involved PCI equipment despite administration of acetylsalicylic acid, clopidogrel, subcutaneous enoxaparin and abciximab [14]. On the other hand, De Feyter et al. have also reported that acute coronary artery occlusion during surgery often occasionally happened, and its frequency was higher in patients with unstable angina, multi-vessel disease, and complex lesions [15]. Regar et al. reported that restenosis was related to procedure-specific factor, which was affected by implantation technique [16].

The causes for these perioperative complications remain unknown, and some literatures reported the intraoperative factors such as the degree of damaged endothelial cells and depth of the injury, the plaque composition and shape, the type of intravascular stent expansion and local fluid dynamics [17–21]. As an essential and intricate part of intervention operation, the catheter insertion process was hardly considered as another potential factor for perioperative complications.

The catheter insertion process was destined to induce interference or hemodynamics change during surgery. Some published studies reported that the catheter or guidewire in coronary artery could exert obstruction effect on measuring pressure drops for the diagnosis of moderate stenosis, and resulting additional “artifactual” stenosis on the blood flow during operation [22–26]. However, these studies were just conducted with simple 2-D models

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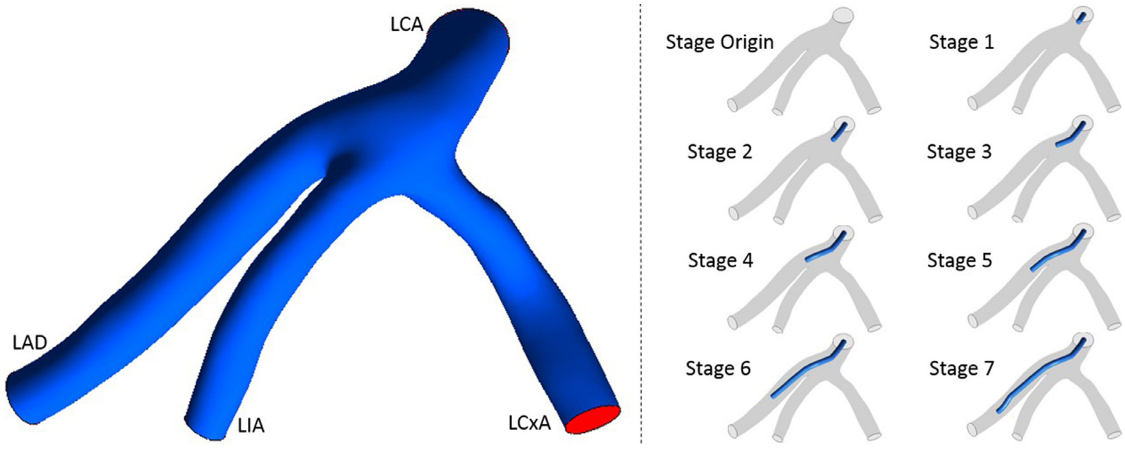

Fig. 1. Coronary artery model and the spatial representation of catheter insertion process. Left: LCA was defined as inlet (diameter 4.39 mm). LAD, LCxA and LIA of this trifurcation were set to be outlets and the diameter were 3.1 mm, 3.13 mm and 2.5 mm respectively. Right: the catheter with crimped stent and folded balloon was simplified to a catheter in semitransparent LCA model.

or 3-D ideal models. The aforesaid interference or hemodynamics change could inevitably appear in realistic coronary arteries with irregular curvature and angulation, and might induce more complicated and serious effects [27]. These effects could directly act on hemodynamic factors such as WSS [28], which has been proved to induce morphological and functional changes in the endothelium and was critically important in regulating the atheroprotective and vessel wall dysfunction [29-31]. In addition, the previous paper reported the shear-induced platelet activation potency and the potential risk of catheter thrombose during clinical performance of these catheters [32]. Therefore, we hypothesized that the insertion process of catheter could disturb the hemodynamic environment in realistic coronary arteries and then cause susceptible factors, which might negatively make coronary arteries more vulnerable to those perioperative complications.

To test this hypothesis, a realistic coronary artery model was reconstructed based on CT scan images. Seven successive stages in the catheter insertion process were defined and the hemodynamic environment at these stages was numerically simulated. The main objective of the present study was to investigate the influence of catheter insertion process on hemodynamic environment in coronary arteries.

2. Materials and methods

2.1. Artery model

The realistic left coronary arterial model was reconstructed based on the computed tomography (CT) scan images with Mimics software (v9.0, Materialise, Ann Arbor, MI, USA). The CT-relevant parameters were described below: 0.9 mm slice thickness, 0.45 mm slice increment, 0.324 mm pixel size, a 512×512 image resolution and total 293 slices. Subsequently simple smoothing and surfacing processes were applied to the model with Geomagic Studio 2012(3D Systems, Morrisville, NC, USA). The left coronary artery (LCA) in this study was a trifurcation, which composed of LAD, left circumflex artery (LCxA) and left intermediate branch artery (LIA).

The contact collision or frictional forces between artery vessel and catheter were temporarily irrespective in this study. Seven successive stages of the catheter insertion process in LCA were defined (Fig. 1), and the diameter of catheter was set to 1.2 mm according to previous studies [3,33]. The models of different stages were modified based on the original 3D LCA model using Solidworks (Solidworks Corporation, Boston, MA, USA). The artery model in this study was assumed to be rigid wall.

2.2. Mesh generation

Models meshes were generated in ICEM software (ANSYS, Inc., Canonsburg, PA, USA), using mixed up tetrahedral and hexahedral volume meshes. The maximum and minimum sizes of the mesh were set to 0.05 mm and 0.01 mm respectively. Four layers of fined meshes were used, with height ratio 1.2 and the initial height 0.01 mm. The element numbers in all models were showed in Table 1.

2.3. Boundary conditions

Simulations were computed under steady flow conditions, and the inlet flow rate was 3.55 ml/s (Reynolds number 313) referring to the study conducted by Frauenfelder T et al. [34].

The Outflow condition, which represented fully developed flow at the outlet, was used for all outlets. The flow ratios of outlets were calculated according to the relationship between the diameter ratio of two daughter branches and the flow ratio through the branches, which conducted by van der Giessen et al. [35]:

$$\frac{q_{D1}}{q_{D2}} = \left(\frac{d_{D1}}{d_{D2}}\right)^{2.27} \tag{1}$$

where q_{D1} and q_{D2} were the blood flow through the daughter branches D1 and D2, and $d_{D1}$and d_{D2} were the average diameters of the branches. According to van der Giessen et al. study [35], this trifurcation could be treated to have two daughter branches: LCxA and the second branch including LAD and LIA. Final calculation results were: 49.7% for the LAD, 29.8% for LIA and 20.5% for the LCxA.

2.4. Assumptions and governing equations

Blood was modeled as a Newtonian fluid and assumed to be homogeneous and incompressible [36,37]. The numerical simulations were based on a three-dimensional incompressible Navier–Stokes equation and the conservation of mass:

$$\rho\left(\vec{u}\cdot\nabla\right)\vec{u} + \nabla p - \mu\Delta\vec{u} = 0 \tag{2}$$

$$\nabla\cdot\vec{u} = 0 \tag{3}$$

where $\vec{u}$ and p respectively represented the fluid velocity vector and the pressure. ρ and μ were the density and viscosity of blood ($\rho = 1060\ \mathrm{kg/m^3}$ and $\mu = 3.5\times10^{-3}\ \mathrm{kg/m{\cdot}s}$) [38].