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Impact of Coronary Tortuosity on Coronary Pressure and Wall Shear Stress: an Experimental Study

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Abstract: Coronary tortuosity is a common angiographic finding, but the hemodynamic significance of coronary tortuosity is largely unknown. The impact of coronary tortuosity on coronary pressure and wall shear stress is still unclear. We addressed this issue in the present experimental study. A distorted tube model connected to heart pumping machine was established to simulate the coronary circulation. The pressure of each point was measured with a coronary pressure guidewire. Influence of tortuosity angle and tortuosity number on local pressure was measured. Wall shear stress was calculated accordingly to the pressure of each point. Pressure distribution in this system was affected both by tortuosity angle and tortuosity number. Driving pressure for the coronary tortuosity was positively related with tortuosity number while negatively linked with tortuosity angle. Wall shear stress was higher in proportion to the severity of coronary tortuosity. Coronary tortuosity can lead to more decrease of coronary blood pressure in dependence on the severity of tortuosity, and driving pressure for the coronary tortuosity increased accordingly. Tortuous artery has higher wall shear stress in dependent on the severity of coronary tortuosity, indicated that coronary tortuosity may be a factor for delaying the formation and progression of atherosclerotic plaque.

Keywords: Coronary tortuosity, coronary pressure, wall shear stress.

1 Introduction

Coronary tortuosity (CT) is a common angiographic finding, but the clinical and hemodynamic significance of CT is largely unknown. We previously showed that CT is more often seen in females and positively correlated with hypertension and negatively correlated with coronary atherosclerosis [Li, Shen, Ji et al. (2011)]. Numerical simulation study from our group demonstrated that CT could result in more decrease of coronary blood pressure in proportion to the severity of vessel tortuosity, but the association between CT and coronary ischemia remains unclear now [Li, Shi, Cai et al. (2012); Xie, Wang, Zhu et al. (2013)].

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Local hemodynamic factors are critically related to the development and progression of atherosclerosis [Samady, Eshtehardi, McDaniel et al. (2011); Stone, Coskun, Kinlay et al. (2007); Chatzizisis, Coskun, Jonas et al. (2007)]. Thus, it would of importance to evaluate the local hemodynamical situation in patients with CT to establish the potential relationship between CT and coronary atherosclerosis. Previous computational fluid dynamics study demonstrated that CT has minor influence on coronary blood supply at rest; while during exercise, patients with CT may lack the ability to adjust distal resistance sufficiently to compensate for the extra resistances generated by tortuosity and this may further lead to an ineffective regulation of the blood supply [Xie, Wang, Zhu et al. (2013)]. In the present experimental study, we thus determined the local pressure and wall shear stress (WSS) in a simulated CT model.

2 Materials and Methods

We set up a distorted model with this tube and simulate blood pumping by heart pumping machine (Figure 1). The inner dimension of the tube was 5 mm, designed compatible to LAD coronary artery. The pressure of each point was measured with a coronary pressure guidewire (Pressure Wire Certus™, St. Jude Medical). The following is a schematic diagram of each point. Pressure distribution under different coronary tortuosity number (CTN) and coronary tortuosity angle (CTA) was measured (Figure 2).

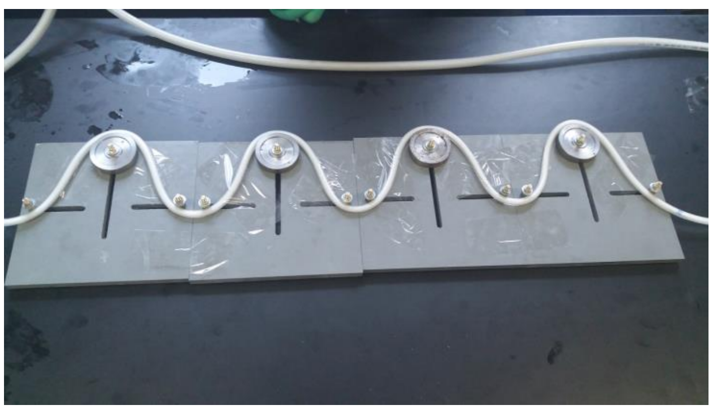

Figure 1: A coronary tortuosity model with tube and simulate blood pumping by heart pumping machine

Figure 2: A schematic diagram of each point of pressure was measured

According to the pressure of each point, WSS was obtained. Take CTA=90° degree as an example, value of the inlet velocity, the tube diameter and the liquid viscosity are constant. Pressure at the point A and B can also be measured. Blood flow in the tube is assumed to be Poiseuille flow. As shown in the Figure 3, segment AO is bent while segment OB is straight. Chose the dashed box as research object, as is incompressible fluid, $V_A=V_B$, $Z_A=Z_B$. The resistance between point A and B can be calculated by the equation. The roughness of tube is 0.01 mm and the Reynolds number is $9.35*10^4$. According to Poiseuille's law and the calculation formula, the WSS value was acquired.

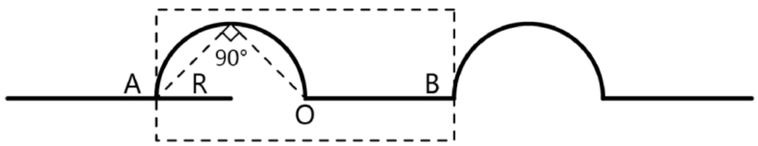

Figure 3: Wall shear stress of each point was calculated

3 Results

The pressure drop was positively related with CTN while negatively linked with CTA, which indicated that the more severity of CT can induce more pressure drop along the coronary artery. Driving pressure for the CT was also positively related with CTN while negatively linked with CTA (Table 1-3). For example, the pressure in A point was higher than F point at CTN=5 and CTA=90° (142 mmHg *vs.* 81 mmHg). Driving pressure in A point was higher in CTN=5 than CTN=1 at CTA=90° (142 mmHg *vs.* 106 mmHg). Driving pressure in A point was higher in CTA=30° than in CTA=90° at CTN=5 (163 mmHg *vs.*142 mmHg).

Table 1: Pressure measurement (mmHg) at CTA=90°

	A	B	C	D	E	F
CTN=0	101					81
CTN=1	106	97				81
CTN=2	115	104	91			82
CTN=3	124	113	106	88		83
CTN=4	131	122	110	97	87	79
CTN=5	142	129	118	111	86	81

Table 2: Pressure measurement (mmHg) at CTA=60°

	A	B	C	D	E	F
CTN=0	101					82
CTN=1	109	98				81

CTN=2	114	102	90			83
CTN=3	123	111	103	89		79
CTN=4	135	120	112	96	86	81
CTN=5	144	132	120	109	87	83

Table 3: Pressure measurement (mmHg) at CTA=30°

	A	B	C	D	E	F
CTN=0	103					80
CTN=1	110	99				79
CTN=2	123	107	94			82
CTN=3	131	121	103	89		80
CTN=4	156	136	122	102	87	81
CTN=5	163	149	131	119	98	80

WSS were higher at in dependent on the severity of CT (Table 4-6). For example, WSS in A point was higher in CTN=5 than CTN=1 at CTA=90° (15.3 Pa *vs.* 14.2 Pa). WSS in A point was higher in CTA=30° than in CTA=90° at CTN=5 (18.3 Pa *vs.* 15.3 Pa).

Table 4: WSS (Pa) at CTA=90°

	A	B	C	D	E	F
CTN=0	10.1					
CTN=1	14.2	9.7				
CTN=2	14.3	13.7	10.6			
CTN=3	14.6	14.3	13.6	10.0		
CTN=4	15.7	15.6	14.2	13.8	10.3	
CTN=5	15.3	15.1	14.6	13.7	13.2	9.8

Table 5: WSS (Pa) at CTA=60°

	A	B	C	D	E	F
CTN=0	10.3					
CTN=1	14.8	10.6				
CTN=2	13.6	13.8	9.7			
CTN=3	15.7	14.2	13.4	10.7		
CTN=4	15.0	14.6	13.7	13.6	10.6	
CTN=5	15.2	15.1	13.2	14.2	13.1	10.1

Table 6: WSS (Pa) at CTA=30°

	A	B	C	D	E	F
CTN=0	10.6					
CTN=1	16.7	10.2				
CTN=2	17.1	16.9	10.4			
CTN=3	17.6	16.7	16.3	10.7		
CTN=4	18.2	17.7	16.9	16.3	10.4	
CTN=5	18.3	17.9	17.2	16.2	16.1	9.7

4 Discussion

To the best of our knowledge, this is the first study to determine the impact of CT on coronary pressure and WSS distribution by an experimental study. The result is in keeping with the results of ours previous numerical simulation study [Li, Shi, Cai et al. (2012)]. The relationship between CT and coronary ischemia is still unknown [Li, Shi, Cai et al. (2012); Li, Liu, Gu et al. (2012); Zegers, Meursing, Zegers et al. (2007)]. Computational study found that CT has minor influence on coronary blood supply at rest, but CT may lack the ability to adjust distal resistance sufficiently to compensate for the extra resistances generated by tortuosity while during exercise [Xie, Wang, Zhu et al. (2013)]. The resistance of the coronary arteries increased up to 92% due to the CT during exercise [Xie, Wang and Zhou (2013)]. Our study demonstrated that CT can lead more pressure drop in dependence on the severity of tortuosity. And driving pressure for the CT also increased as compared to the NCT.

Our obsevatioanal study found that CT is negatively correlated with coronary atherosclerosis [Li, Shen, Ji et al. (2011)]. Low ESS play an important role in the progression of coronary atherosclerosis and differentiation to high-risk plaque [Samady, Eshtehardi, McDaniel et al. (2011); Stone, Coskun, Kinlay et al. (2007); Chatzizisis, Coskun, Jonas et al. (2007)]. The effect of CT on coronary atherosclerosis may through changed ESS distribution influenced by tortuous artery.

A Computational morphological parametric study found that severe CT with the small center line radius or the length between two adjust bends would lead to the formation of abnormal WSS regions at the bend sections and providing these regions with favorable conditions for the onset and/or progression of atherosclerosis[Xie, Wang, Zhu et al. (2014)]. Low WSS region was formed at the inner wall downstream of the bend section when the bend angle was larger than 120°, indicated that the severe CT may be a risk factor for atherosclerosis [Xie, Wang and Zhou (2013)]. But, higher WSS were observed at the CT area in our study, indicated that CT may be a factor for delaying the formation and progression of atherosclerotic plaque. Fluid shear stresses were considered as a mechnial role in platelet aggregation. Analysis of blood flow dynamics revealed that discoid platelets preferentially adhere in low-shear zones at the downstream face of forming thrombi, with stabilization of aggregates dependent on the dynamic restructuring of membrane tethers [Nesbitt, Westein, Tovar-Lopez et al. (2009)]. High shear alone is likely to be insufficient in inducing platelet activation and aggregation, but acts synergistically with other stimuli [Zhang, Bergeron, Yu et al. (2003)]. CT could not enhance the platelet activation even with extreme high fluid shear stresses existing at bend sections during the strenuous exercise condition [Xie, Wang, Zhu et al. (2015)].

Limitations: The length of tubes used in our research is longer than clinical coronary artey. The true decrease of coronary blood pressure may be smaller. In addition, driving pressure for the CT also increased, and coronary blood flow have the ability of auto regulation in the presence of coronary ischemia. A digital and microfluidic three-dimensional models based on a real clinical tortuous coronary artery can be established to investigate the pressure and WSS distribution [Wang, Liu, Zheng et al. (2015)].

In conclusion, CT can result in more decrease of coronary blood pressure in dependence on the severity of tortuosity by experimental study. WSS distribution is higher in tortuous coronary which can play a role in delaying the progression of atherosclerotic plaque.

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