Proceedings of the ASME 2010 Summer Bioengineering Conference
SBC2010
June 16-19, 2010, Naples, Florida, USA

SBC2010-19564

Misinterpretation of the Functional Severity of Coronary Stenosis Due To Variability in Arterial Wall Compliance

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ABSTRACT

Effect of arterial wall compliance on the invasive coronary diagnostic parameters for various severities of coronary stenoses was assessed. The Mooney-Rivlin model was used to define the non-linear properties of the arterial wall and the plaque regions. The non-Newtonian viscosity of blood was modeled using the Carreau model. A finite element method was employed to solve the pulsatile fluid (blood)-structure (arterial wall) interaction (FSI) equations. Variability in the diagnostic parameter values can occur near the cut-off value due to change in compliance of stenotic arteries between the range of 84% and 89% area stenosis. This may lead to misdiagnosis and might wrongly lead to postponement of coronary intervention.

INTRODUCTION

Plaque formation in the left anterior descending (LAD) is one of the major causes of angina and heart failure. Researchers have studied the hemodynamics of flow through stenoses in the LAD by modeling it as a rigid [1] and as a compliant artery [2]. In the recent past, the functional diagnostic parameters: *fractional flow reserve* (FFR; the ratio of distal pressure to proximal pressure at a stenotic section), *pressure drop coefficient* (CDP; the ratio of trans-stenotic pressure gradient to distal dynamic pressure) and *lesion flow coefficient* (LFC; a comprehensive endpoint that combines functional CDP and anatomical evidences) have been evaluated by primarily using the fluid dynamics principles to assess the severity of stenosis [1]. However, none have reported the effect of variability of arterial-stenosis wall compliance on the diagnostic parameters. Hence, this study aims to evaluate the effect of arterial-stenosis wall compliance on pressure drop (Δp)-flow, which, in turn, may influence the FFR, CDP, and LFC during cardiovascular intervention.

METHODS

Three models were considered to assess the effect of compliance: a) compliant artery with calcified plaque (CP); b) compliant artery with smooth muscle cell proliferation (SP); and c) rigid artery (RA). Each of these models was computed as a strongly coupled fluid (blood) -structure (arterial wall) interaction (FSI) problem for three levels of blockages having 70%, 80% and 90% area stenoses. The geometry (Fig. 1) and dimensions (Table 1) for the models have been adapted from Wilson et al [4] and Back and Denton et al [5]. The dimensions tabulated in Table 1 are obtained after a 10% axial stretching and pressurizing the artery to the physiological condition. The arterial walls were modeled as incompressible, homogeneous and hyperelastic material. A modified Mooney Rivlin (M-R) equation:

$$W = C_1 (I_1-3) + D_1 [\exp (D_2 (I_1-3)) - 1] + (K_1 / 2K_2) [\exp [K_2 (I_4-1)^2] - 1]$$

which is transversely isotropic [2], was used to model the arterial wall for all cases and for the plaque region in SP. For arterial wall the material constants are, C_1(=8.2917 kPa), D_1(=0.9072 kPa), D_2(=3.1), K_1(=8.8240 kPa), K_2(=3.7) and I_1 and I_4 are the stress invariants. An isotropic M-R model [2] defined the calcified plaque in CP, for which, the material parameter values are C_1 = 281.443 kPa, D_1 = 13.101 kPa, D_2 = 11.5. The blood was modeled as non-Newtonian, incompressible fluid with viscosity modeled using the Carreau model. A pulsatile pressure profile [2] for a human coronary artery was specified at the inlet and an in-vivo measured coronary flow waveform [1] for hyperemic (vasodilated condition) flow, was applied at the outlet for each of the stenoses. The finite element method (ADINA R&D Inc, MA) was used to solve the FSI equations.

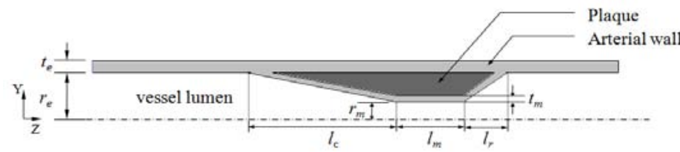

Fig. 1: Geometric model of the coronary artery

% Area Stenosis	All dimensions in mm						
	r_e	t_e	r_m	l_c	l_m	l_r	t_m
70	1.5	1	0.82	6	3	1.5	0.1
80	1.5	1	0.67	6	3	1.5	0.1
90	1.5	1	0.47	6	3	1.5	0.1

Table 1: Dimensions for the geometric model

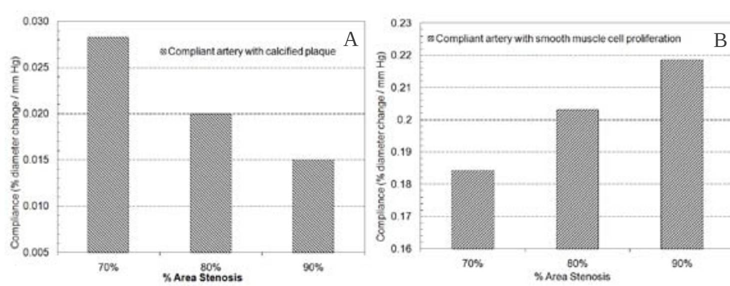

Fig. 2: Compliance of the throat in artery with (A) calcified plaque (B) smooth muscle cell proliferation

RESULTS

The compliance of artery decreased with increase in % area stenosis for calcified plaque (CP), whereas it increased with increase in % area

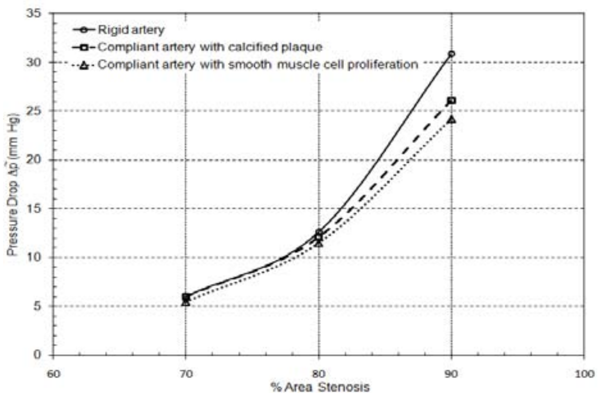

Fig. 3: Pressure drop (Δp) across the stenosis for each compliant models

stenosis for smooth cell proliferation (SP; Figs. 2A and 2B). In Fig. 3, the Δp for the rigid artery (RA) was found to be higher than the compliant cases (CP and SP). As seen in the Fig. 3, Δp values show a wider variation for the 90% stenosis case. The compliance at the throat for the CP and SP cases is the cause for a lesser Δp in the compliant cases (Figs. 2A and 2B). The SP shows a lesser Δp as compared to CP due to the higher throat compliance.

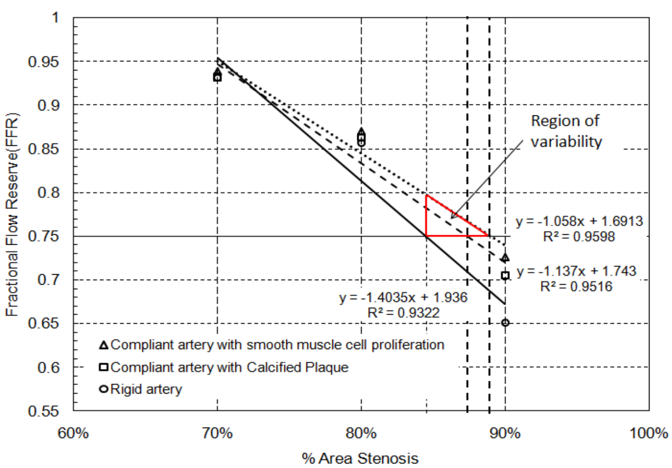

Fig. 4: Variation in the FFR for different compliant models. Cut-off value of FFR is 0.75.

The effect of compliance on the diagnostic parameters is illustrated in Figures 4, 5 and 6. An FFR cut-off (threshold) value of less than 0.75 leads to coronary intervention [3]. The FFR values obtained here showed a linear correlation ($R^2 > 0.9$). The FFR values consistently decreased with increase in stenosis-severity. The difference between FFR values for the compliant cases increased with stenosis severity. In RA, an FFR value of 0.75 was observed at 84.5% area stenosis while the compliant cases showed an FFR > 0.75 for the same area stenosis (Fig. 4). An FFR of 0.75 was obtained for CP at 87.3% and for SP at 89% area stenoses. The marked section in Figure 4 is the region where a variation in the FFR values could occur due to the variation in compliance of the artery. For a fixed %AS, the compliant cases could misinterpret FFR by showing lesser severity of stenosis.

The CDP values decreased as arterial compliance changed from RA to SP for the three stenosis-severities (Fig. 5). The CDP values for RA, CP and SP increased with the increase in stenosis severity. The LFC values increased as compliance changes from RA to SP for the three severities (Fig. 6). It was observed that the LFC values increased with % stenosis severity for RA, CP and SP.

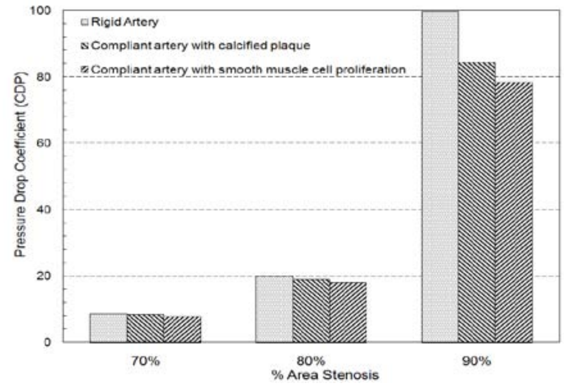

Fig. 5: Variation in CDP for different compliant models

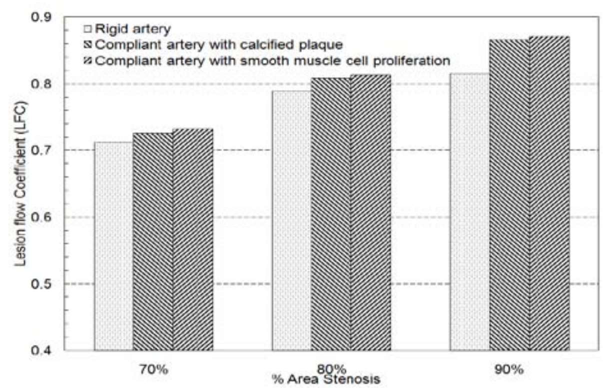

Fig. 6: Variation in LFC for different compliant models

CONCLUSION

Our results illustrates that a variability in the diagnostic parameter values can occur near the cut-off value due to compliance effect of the stenotic arteries between the stenosis range of 84.5 and 89% area stenosis. This may lead to misdiagnosis and might wrongly lead to postponement of coronary intervention.

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