ARTERIAL FLUID FLOW INVESTIGATION ON DOUBLE STENOSES CONTACT MORPHOLOGY FOR MEDICAL APPLICATION

by

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LIST OF ABBREVIATIONS

CVD	Cardiovascular disease
WHO	World Health Organization
SMC	smooth muscle cells
LDL	low density lipoprotein
IVUS	intravascular ultrasound
CCTA	coronary computed tomography angiography
WSS	wall shear stress
WSSG	gradient of wall shear stress
WNS	wall normal stress
SR	shear rate
Re	Reynolds number
CFD	computational fluid dynamics
LES	Large Eddy simulation
FSI	Fluid-Structure Interaction
RCA	Right Coronary Artery
LAD	Left Artery Descending
FRZ	fluid recirculation zones
H-B	Herschel-Bukley material
FDM	finite difference method
FEM	finite element method
FVM	finite volume method

LIST OF SYMBOLS

D_0	diameter of coronary artery
ρ	fluid density
μ	fluid dynamic viscosity
L_1	length of proximal stenosis
L_2	length of distal stenosis
δ_1	height of proximal stenosis
δ_2	height of distal stenosis
S_{area}	cross sectional area of stenosis
D	distance from center of proximal stenosis to the center of distal stenosis
D1	distance from center of proximal stenosis to the center of distal stenosis with ratio of $\frac{3}{4} L_1$
D2	distance from center of proximal stenosis to the center of distal stenosis with ratio of $\frac{5}{6} L_1$
D3	distance from center of proximal stenosis to the center of distal stenosis with ratio of $\frac{11}{12} L_1$
D4	distance from center of proximal stenosis to the center of distal stenosis with ratio of L_1
D5	distance from center of proximal stenosis to the center of distal stenosis with ratio of $\frac{3}{2} L_1$

D6	distance from center of proximal stenosis to the center of distal stenosis with ratio of 2 L_1
p*	dimensionless wall pressure
U	average velocity at the inlet

Kajian Aliran Bendalir Arteri Untuk Morfologi Sentuhan Stenosis Berganda Dalam Aplikasi Perubatan

ABSTRAK

Penyelidikan pengaliran bendalir telah diusahakan sekian lama sejak bermula kemunculan peranti sistem mikroelektromekanikal (MEMS). Sistem vaskular manusia penting untuk pengangkutan sistem mikroelektromekanikal dengan itu membolehkan kajian dan analisis terhadap penyakit manusia. Aterosklerosis adalah penyakit vascular yang dicirikan oleh pemendapan plak pada dinding arteri. Perkembangan plak aterosklerosis boleh menyebabkan kesan-kesan yang serius seperti serangan jantung dan strok disebabkan oleh gangguan pengaliran darah. Oleh itu, kajian dinamik bendalir adalah aspek penting untuk meramalkan pertumbuhan aterosklerosis. Dalam kajian ini, pengaliran bendalir Newtonian melalui dual stenosis telah dikaji menggunakan perisian Ansys CFX. Untuk kajian kesan-kesan morfologi stenosis, tiga geometri stenosis telah digunakan iaitu stenosis berbentuk kosinus, stenosis berbentuk menjulur dan senosis berbentuk tidak sekata. Setiap geometri yang digunakan mempunyai lebar dan tinggi yang sama tetapi berbeza keluasan. Selain itu, kesan-kesan jarak antara stenosis telah dikaji dengan mengubah jarak antara stenosis dari dekat hingga jauh tanpa mengubah saiz setiap stenosis. Pengaruh nombor Reynolds juga dikaji dalam julat 100 ke 400 berdasarkan aliran fisiologi manusia. Ciri-ciri aliran darah seperti profil halaju, tekanan dinding arteri dan tekanan kepatahan dinding arteri telah dijalankan untk semua kes kajian. Hasil kajian menunjukkan halaju puncak, kejatuhan tekanan dan tegasan ricih dinding dengan nilai 0.7518 ms^{-1}, 398.16 Nm^{-2} dan 15.39 Nm^{-2} masing-masingnya adalah paling tinggi dalam kes dual stenosis berbentuk tak sekata. Menariknya, dual stenosis berbentuk menjulur menunjukkan halaju puncak (0.672 ms-2) dan tegasan ricih dinding (14.90 Nm-2) lebih tinggi daripada dual stenosis berbentuk kosinus dengan halaju puncak, 0.6578 ms^{-1} dan tegasan ricih dinding 13.06 Nm^{-2} walaupun keluasan dual kosinus adalah lebih besar. Penemuan ini membuktikan stenosis yang kritikal lebih bergantung kepada pengaruh morfologi stenosis berbanding peratusan pengurangan diameter arteri atau keluasan stenosis. Analisa terhadap kesan jarak antara stenosis menunjukkan jarak antara stenosis juga penting kepada profil halaju, taburan tegasan ricih dinding dan variasi tekanan kepatahan bendalir. Selain itu, kesan nombor Reynolds juga nyata dalam mengubah corak aliran di mana nombor Reynolds yang lebih tinggi meningkatkan saiz zon peredaran. Zon peredaran kebiasaanya berlaku di dalam arteri yang tersumbat dengan serius. Konklusinya, kajian ini menunjukkan ciri-ciri aliran darah melalui dual stenosis adalah berkait rapat dengan pengaruh morfologi stenosis, jarak antara stenosis dan nombor Reynolds.

Arterial Fluid Flow Investigation on Double Stenoses Contact Morphology for Medical Application

ABSTRACT

Fluid flow investigation has been constantly worked upon since the dawn of Microelectromechanical Systems (MEMS) devices. Human vascular system provides the means for MEMS transportation thus enabling study and analysis on human diseases. Atherosclerosis is a vascular disease characterized by deposition of plaques on the arterial wall. The progression of atherosclerotic plaques may cause serious consequences due to disturbance of the blood flow such as heart attack and stroke. Therefore, the study of the fluid dynamics in the stenosed artery bears important aspects to predict the development of atherosclerosis. In this research, the Newtonian fluid through double stenoses has been investigated using Ansys CFX software. To study the effects of stenosis morphology, three different geometries have been used; cosine-shaped, irregular shape and protruding shape. These geometries present different area occlusion but similar configurations of stricture length and height. On the other hand, the effects of restriction spacing have been explored by varying the distance between the double stenoses without changing the size of each stenosis. The effects of Reynolds numbers have been investigated as well in the range of 100 to 400 based on human physiological flow. Hemodynamic characteristics of blood flow such as velocity profiles, wall pressure and wall shear stress distributions have been performed for all cases. The results demonstrate highest peak velocity, pressure drop and peak wall shear stress with the value of 0.7518 ms^{-1}, 398.16 Nm^{-2} and 15.39 Nm^{-2} respectively for the case of double irregular stenoses. It is interesting to find out that double protruding-shaped stenoses exhibit greater peak velocity (0.672 ms^{-1}) and peak wall shear stress (14.90 Nm^{-2}) in comparison with cosine-shaped stenosis with peak velocity, 0.6578 ms^{-1} and peak wall shear stress, 13.06 Nm^{-2} although the area occlusion of cosine shaped is larger instead. These findings indicate that the severity of the stenosis is primarily caused by the morphology of the stenosis rather than percentage of diameter reduction criterion or effects of area occlusion. Analysis on the effects of restriction spacing shows that the distance between a couple of stenoses has a considerable influence on the velocity profile, wall pressure distribution and wall shear stress variation. In addition, the effects of Reynolds numbers are noticeable in changing the flow pattern near the stenotic region whereby the higher Reynolds numbers increase the size of recirculation zone. The recirculation zones usually occur in the severe stenosed artery. In conclusion, the present study shows that the blood flow characteristics through double stenoses are strongly influenced by the stenosis morphology, restriction spacing and Reynolds numbers

CHAPTER 1

INTRODUCTION

1.1 Overview

The study of both air and liquid flow dynamics has led to many new discoveries from aeronautical, gliders, sky-scrapper stability, ships, submarines, irrigation, and many more. These are in the scale of macro, the rules and conditions change for micro scale and below. The emerging of electronic technology with exponential evolution coupling with miniaturization as a catalyst, has led fluid study in micro scale to be an important field of research. The areas whereby requires this application are such as in medical, 3D-printing, MEMS, electronics packaging heat transfer, drug delivery and photonics. In the field of medical, blood flow study has catapulted as an important niche whereby understanding the flow dynamics will enable electronics sensors, stents and MEMS devices to be deployed for better understanding of human blood channel anatomy.

Cardiovascular disease (CVD) has become a leading cause of global death. According to World Health Organization (WHO) statistics in 2012, an approximate of 17.5 million people died from CVD mainly due to heart attack (7.4 million) and stroke (6.7 million) (WHO, 2015). A heart attack normally occurs when the coronary artery is occluded and a stroke happens when the carotid artery is hampered (Tian, Zhu, Fok, & Lu, 2013). CVD is prevalent among elderly population aged above 65 years resulting in fatal complications (Sommer, 2008). On top of that, both public and private institutions have to bear a huge amount of CVD health care costs, plus indirect costs for example productivity loss (Sommer, 2008). Schematic of the cardiovascular system comprises the heart and vital components of the circulatory system are illustrated as in Figure 1.1.

The whole cardiovascular system is responsible to deliver blood and control its flow throughout the body (Devasahayam, 2000). Basically, the blood vessels possess different structures and functions to sustain the proper circulation. Blood is extremely important to carry nutrients and oxygen to various parts of the body and wastes to the excretory organs. However, the efficiency of the cardiovascular system for blood delivery will be less under pathological conditions where the elasticity of the vessel wall is reduced and diameter of the vessel is decreased due to deposits on the inner surface (Devasahayam, 2000). These conditions also called as atherosclerosis (Paeng, 2013).

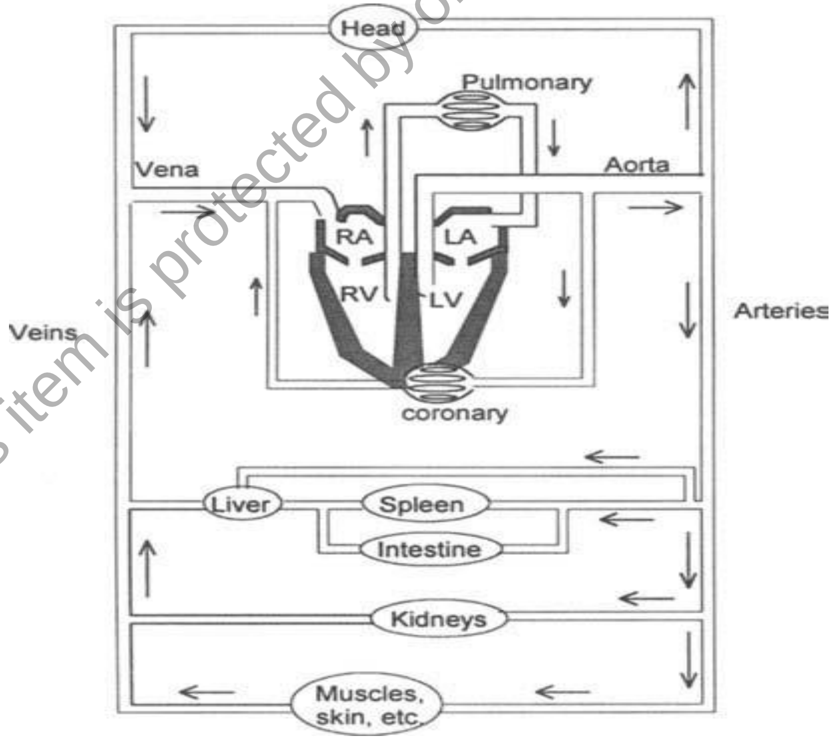

Figure 1.1: Schematic of the cardiovascular system (Devasahayam, 2000)

The knowledge and analysis of blood flow characterization for CVD problems is crucial to develop effective MEMS devices such as electronic stent, wireless CardioMEMS and MEMS shear stress sensor. Currently, the invention of electronic stent allows the measurement of blood pressure inside a blockage artery and thus may predicts the incidence of restenosis. With the advanced of MEMS technology, periodic invasive surgery which is traditionally needed to monitor the occurrence of restenosis will be unnecessary. On the other hand, MEMS has been successfully implemented for CardioMEMS monitoring device where heart rates and artery pressures can be monitored daily by a portable electronic unit (Khan and Rich, 2015). Measurement of wall shear stress exerted by the flowing blood in cardiovascular disease also has been extensively studied in this decade to improve the MEMS sensor design which is operated based on heat transfer principle and fabricated with biocompatible materials (Soundararajan, G., Hsiai, T. K., DeMaio, L., Chang, M., & Chang, S, 2004; Yu et al., 2007) .

1.2 Normal Artery Histology

A basic understanding of a healthy artery is needed prior to narrating a stenosed artery. The artery is basically composed of three concentric layers (tunics): intima, media and adventitia as shown in Figure 1.2. The intima, innermost layer contains a lining of endothelial cells with thickness of 0.2 to 0.5 µm surrounding the central space (lumen). A thick layer of elastic fibers called the internal elastic lamina is formed between the intima and media. The middle layer, tunica media, is the thickest layer of the arterial wall. It is made up of smooth muscle cells (SMC) and elastin. The inner half of the SMC layer gets its nutrients from the lumen through diffusion process. On the other hand, the media is separated from the adventitia (outer layer) by the external elastic lamina. The tunica adventitia consists mainly a dense network of collagen fibers with nerves, fibroblasts and vasa vasorum (Dunnen et al., 2009; Humphrey, 2002; Kalita & Schaefer, 2008; Labrosse, 2007)

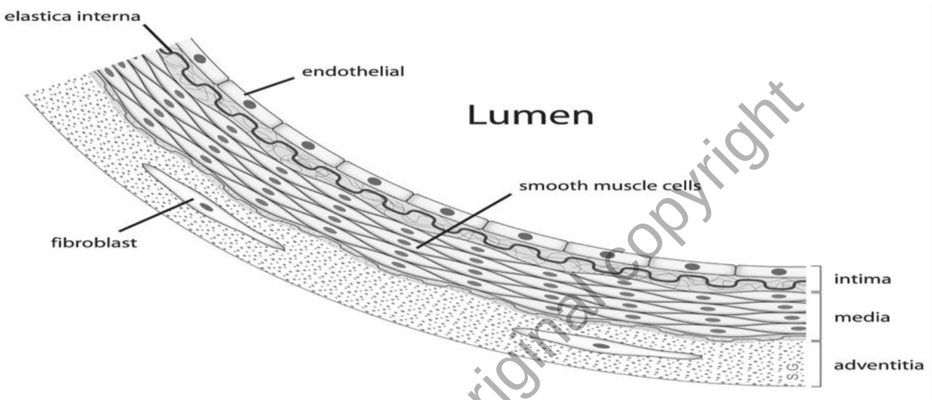

Figure 1.2: Schematic of an artery (Ghesquiere, 2007)

1.3 Atherosclerosis

The progression of atherosclerosis disease induced by accumulation of lipids and fibrous elements on the arterial wall create abnormality on the blood flow (Filipovic et al., 2013; Mihai, Youn, & Seshaiyer, 2012). The root causes of atherosclerosis are still unclear, but it is believed that unhealthy diet is one of the behavioral factors (Chan, 2006). The progression of atherosclerosis can be characterized by two fundamental processes; deposition of lipid and inflammation (Halvorsen et al., 2008). Low density lipoprotein (LDL) in the intima is prominent in initial formation of atherosclerosis as it may diffuse through endothelium (Paeng, 2013). Oxidized LDL may cause dysfunctional of the endothelium and stimulates recruitment of monocytes into the intima layer. Dysfunctional of the endothelium exposes smooth muscle cells (SMC)