



**UniMAP**

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

by

**NOR SHAKIRINA BINTI NADZRI**

**(1130110729)**

A thesis submitted in fulfillment of the requirements for the degree of  
Master of Science (Microelectronic Engineering)

**School of Microelectronic Engineering  
UNIVERSITI MALAYSIA PERLIS**

2015

**GRADUATE SCHOOL  
UNIVERSITI MALAYSIA PERLIS**

**PERMISSION TO USE**

In presenting this thesis in fulfillment of a post graduate degree from Universiti Malaysia Perlis, I agree that permission for copying of this thesis in any manner, in whole or in part, for scholarly purposes may be granted by my supervisor or, in their absence, by Dean of the Graduate School. It is understood that any copying or publication or use of this thesis or parts thereof for financial gain shall not be allowed without my supervisor's written permission. It is also understood that due recognition shall be given to me and to Universiti Malaysia Perlis for any scholarly use which may be made of any material from my thesis.

Requests for permission to copy or make other use of material in whole or in part of this thesis are to be addressed to:

**Dean of Centre for Graduate Studies  
Universiti Malaysia Perlis  
No. 112 & 114, Tingkat 1, Blok A, Taman Pertiwi Indah  
Jalan Kangar-Alor Setar, Seriab  
01000 Kangar  
Perlis Indera Kayangan  
Malaysia**

## ACKNOWLEDGEMENTS

I would like to take this opportunity to express my gratitude to my supervisor, Dr. Vithyacharan Retnasamy and my co-supervisor Assoc Prof Dr. Zaliman Sauli and Mr. Steven Taniselas for their guidance and support throughout the course of this study. They have given me the chance to explore a new knowledge of mine and guided me with valuable suggestions and advices.

In my daily work I have been blessed with a wonderful family and the completion of this work could not have been possible without their support and encouragement. I am very fortunate to have a very supportive husband, Mohd Khairul Nizam who gives endless love and help to finish this study. And also to my parent and my parent-in-law who actively supported me, I am very grateful to have them.

A special thanks to my colleagues and friends, They Yee Chin, Moganraj, Rajendaran, Ong Tee Say, Aaron, Izatul, Zahiyah, Syuhadah, Zarimawaty, Suhaila, Wei Jer, Faradilla, Maziidah, Anishaziela and others for their support and help. Thank you to the Vice Chancellor of UniMAP and the Research and Development Unit of UniMAP for their financial support of my postgraduate study.

## TABLE OF CONTENT

	<b>PAGE</b>
<b>DECLARATION OF THESIS</b>	ii
<b>COPYRIGHT</b>	iii
<b>ACKNOWLEDGEMENTS</b>	iv
<b>TABLE OF CONTENTS</b>	v
<b>LIST OF TABLES</b>	ix
<b>LIST OF FIGURES</b>	x
<b>LIST OF ABBREVIATIONS</b>	xvi
<b>LIST OF SYMBOLS</b>	xvii
<b>ABSTRAK</b>	xix
<b>ABSTRACT</b>	xx
<b>CHAPTER 1: INTRODUCTION</b>	
1.1 Overview	1
1.2 Normal Artery Histology	3
1.3 Atherosclerosis	4
1.4 Problem Statement	6
1.5 Research Objectives	8
1.6 Research Scope	9
1.7 Research Approach	10
1.8 Thesis Organization	11

## CHAPTER 2: LITERATURE REVIEW

2.1	Introduction	12
2.2	Fluid Mechanics	12
2.2.1	Boundary Layer	13
2.2.2	Newtonian and non-Newtonian fluid	13
2.2.3	Laminar and Turbulent Flow	15
2.2.4	Compressibility and Incompressibility	15
2.3	Governing Equations of Fluid Flow	16
2.4	Previous Works on Blood flow within Stenosed Arteries	17
2.4.1	Computational Work	25
2.4.1.1	Single Stenosis	25
2.4.1.2	Multiple Stenoses	34
2.4.2	Experimental Work	37
2.4.2.1	Single Stenosis	37
2.4.2.2	Multiple Stenoses	38
2.4.3	Mathematical Modeling	39
2.4.3.1	Single Stenosis	39
2.4.4	Research Scope of the Previous Works Related with the Present Study	41
2.5	Blood Flow Characteristics in a Stenosed Artery and Application in MEMS	43
2.5.1	Influence of Blood Flow characteristics in the Artery	43
2.5.2	Application of the Knowledge on Fluid Flow Characteristics in MEMS	44

## **CHAPTER 3: RESEARCH METHODOLOGY**

3.1	Introduction	45
3.2	Overview on Computational Fluid Dynamics (CFD)	47
3.3	Design and Modeling of the Stenosed Artery	48
3.3.1	Modeling Details for the Chosen Models of Different Morphology	50
3.3.2	Modeling Details for Analysis on Variation of Restriction Spacing	52
3.3.3	Modeling Details for Analysis on Variation of Reynolds numbers	52
3.3.4	Profile of the Chosen Models	53
3.4	Grid Independence Test	54
3.5	Model Validation	55
3.5.1	Pressure Drop	56
3.5.2	Axial Velocity	57

## **CHAPTER 4: RESULTS AND DISCUSSION**

4.1	Overview	58
4.2	Grid Independence Analysis	58
4.3	Model Validation Analysis	61
4.3.1	Pressure Drop	61
4.3.2	Axial Velocity	62
4.4	Stenosis Morphology Effects on Blood Flow	63
4.4.1	Velocity profiles	64
4.4.2	Wall pressure	69
4.4.3	Wall Shear Stress	71

4.5	Restriction Spacing Variation Analysis	74
4.5.1	Velocity Profiles	74
4.5.2	Wall Pressure	83
4.5.3	Wall Shear Stress	87
4.6	Reynolds numbers (Re) Variation Analysis	91
4.6.1	Velocity Profiles	91
4.6.2	Wall Pressure	97
4.6.3	Wall Shear Stress	100
4.7	Summary	102
<b>CHAPTER 5: CONCLUSION AND FUTURE WORK</b>		
5.1	Conclusion	103
5.2	Future Work	104
<b>REFERENCES</b>		105

## LIST OF TABLES

NO.		PAGE
2.1	Summary of Previous Literatures	18
2.2	Details of Stenosis Model	34
2.3	Review of Previous Studies on Blood Flow Across Multiple Stenoses	42
3.1	Comparison between Simulation and Experimental Method	47
3.2	Restriction Spacing, D Variation	52
3.3	Profile of the Investigated Stenosed Artery	53
4.1	Grid Independence Test Results for Peak Velocity, Pressure Drop and Maximum WSS between Different Mesh Sizes	60
4.2	Variation of Pressure Drop for Various Reynolds Number	62

## LIST OF FIGURES

<b>NO.</b>		<b>PAGE</b>
1.1	Schematic of the cardiovascular system	2
1.2	Schematic of an artery	4
1.3	Development of the atherosclerotic plaque	5
2.1	Boundary layer in a pipe	13
2.2	Shear stress versus shear strain rate for different types of fluids	14
3.1	Flow chart of methodology	46
3.2	Diagram of the stenosed artery model	49
3.3	Stenosis model	51
	(a) Double stenoses with cosine shape and double stenoses with protruding shape	
	(b) Double stenoses with cosine shape and double stenoses with irregular shape	
3.4	Meshing nodes	55
3.5	Stenosis geometry used in previous works	56
3.6	Stenosis geometry used by Andersson et al. (2000)	57
4.1	Dimensionless pressure drop versus Reynold numbers	62
4.2	Variation of axial velocity across the stenosis at Re 1000	63
4.3	Velocity contour and streamline for each model at Re 100	66
	with restriction spacing, $D = \frac{11}{12} L_1$ (a) double cosine stenoses	
	(b) double protrude stenoses (c) double irregular stenoses	
4.4	Axial velocity profile for double cosine stenoses at Re 100	67
	with $D = \frac{11}{12} L_1$	

4.5	Axial velocity profile for double protrude stenoses at Re 100	68
	with $D = \frac{11}{12} L_1$	
4.6	Axial velocity profile for double irregular stenoses at Re 100	68
	with $D = \frac{11}{12} L_1$	
4.7	Wall pressure across double cosine stenoses at Re 100	70
	with $D = \frac{11}{12} L_1$	
4.8	Wall pressure across double protrude stenoses at Re 100	70
	with $D = \frac{11}{12} L_1$	
4.9	Wall pressure across double irregular stenoses at Re 100	71
	with $D = \frac{11}{12} L_1$	
4.10	Variation of wall shear stress through double cosine stenoses	72
	model at Re 100 with $D = \frac{11}{12} L_1$	
4.11	Variation of wall shear stress through double protrude stenoses	73
	model at Re 100 with $D = \frac{11}{12} L_1$	
4.12	Variation of wall shear stress through double irregular stenoses model	73
	model at Re 100 with $D = \frac{11}{12} L_1$	
4.13	Variation of centerline velocity for double cosine stenoses	77
	model at Re 100 with different restriction spacing (a) $D = \frac{3}{4} L_1$ ,	
	(b) $D = \frac{5}{6} L_1$ , (c) $D = \frac{11}{12} L_1$ (d) $D = L_1$ , (e) $D = \frac{3}{2} L_1$ , (f) $D = 2 L_1$	

- 4.14 Variation of centerline velocity for double protrude stenoses 78  
 model at Re 100 with different restriction spacing (a)  $D = \frac{3}{4} L_1$ ,  
 (b)  $D = \frac{5}{6} L_1$ , (c)  $D = \frac{11}{12} L_1$  (d)  $D = L_1$ , (e)  $D = \frac{3}{2} L_1$ , (f)  $D = 2 L_1$
- 4.15 Variation of centerline velocity for double irregular stenoses 79  
 model at Re 100 with different restriction spacing (a)  $D = \frac{3}{4} L_1$ ,  
 (b)  $D = \frac{5}{6} L_1$ , (c)  $D = \frac{11}{12} L_1$  (d)  $D = L_1$ , (e)  $D = \frac{3}{2} L_1$ , (f)  $D = 2 L_1$
- 4.16 Velocity streamline for double cosine stenoses at Re 100 80  
 for various distance between stenoses (a)  $D = \frac{3}{4} L_1$ , (b)  $D = \frac{5}{6} L_1$ ,  
 (c)  $D = \frac{11}{12} L_1$  (d)  $D = L_1$ , (e)  $D = \frac{3}{2} L_1$ , (f)  $D = 2 L_1$
- 4.17 Velocity streamline for double protrude stenoses model at Re 100 81  
 for various distance between stenoses (a)  $D = \frac{3}{4} L_1$ , (b)  $D = \frac{5}{6} L_1$ ,  
 (c)  $D = \frac{11}{12} L_1$  (d)  $D = L_1$ , (e)  $D = \frac{3}{2} L_1$ , (f)  $D = 2 L_1$
- 4.18 Velocity streamline for double irregular stenoses model at Re 100 82  
 for various distance between stenoses (a)  $D = \frac{3}{4} L_1$ , (b)  $D = \frac{5}{6} L_1$ ,  
 (c)  $D = \frac{11}{12} L_1$  (d)  $D = L_1$ , (e)  $D = \frac{3}{2} L_1$ , (f)  $D = 2 L_1$
- 4.19 Variation of wall pressure for double cosine stenoses at Re 100 84  
 with different restriction spacing (a)  $D = \frac{3}{4} L_1$ , (b)  $D = \frac{5}{6} L_1$ ,  
 (c)  $D = \frac{11}{12} L_1$  (d)  $D = L_1$ , (e)  $D = \frac{3}{2} L_1$ , (f)  $D = 2 L_1$

- 4.20 Variation of wall pressure for double protrude stenoses at Re 100 85  
with different restriction spacing (a)  $D = \frac{3}{4} L_1$ , (b)  $D = \frac{5}{6} L_1$ ,  
(c)  $D = \frac{11}{12} L_1$  (d)  $D = L_1$ , (e)  $D = \frac{3}{2} L_1$ , (f)  $D = 2 L_1$
- 4.21 Variation of wall pressure for double irregular stenoses at Re 200 86  
with different restriction spacing (a)  $D = \frac{3}{4} L_1$ , (b)  $D = \frac{5}{6} L_1$ ,  
(c)  $D = \frac{11}{12} L_1$  (d)  $D = L_1$ , (e)  $D = \frac{3}{2} L_1$ , (f)  $D = 2 L_1$
- 4.22 Variation of wall shear stress for double cosine stenoses at Re 100 88  
with different restriction spacing (a)  $D = \frac{3}{4} L_1$ , (b)  $D = \frac{5}{6} L_1$ ,  
(c)  $D = \frac{11}{12} L_1$  (d)  $D = L_1$ , (e)  $D = \frac{3}{2} L_1$ , (f)  $D = 2 L_1$
- 4.23 Variation of wall shear stress for double protrude stenoses at Re 100 89  
with different restriction spacing (a)  $D = \frac{3}{4} L_1$ , (b)  $D = \frac{5}{6} L_1$ ,  
(c)  $D = \frac{11}{12} L_1$  (d)  $D = L_1$ , (e)  $D = \frac{3}{2} L_1$ , (f)  $D = 2 L_1$
- 4.24 Variation of wall shear stress for double irregular stenoses at Re 100 90  
with different restriction spacing (a)  $D = \frac{3}{4} L_1$ , (b)  $D = \frac{5}{6} L_1$ ,  
(c)  $D = \frac{11}{12} L_1$  (d)  $D = L_1$ , (e)  $D = \frac{3}{2} L_1$ , (f)  $D = 2 L_1$
- 4.25 Variation of centerline velocity across a couple of 92  
cosine stenoses with various Reynolds numbers with  $D = \frac{11}{12} L_1$

4.26	Variation of centerline velocity across a couple of protrude stenoses with various Reynolds numbers with $D = \frac{11}{12} L_1$	92
4.27	Variation of centerline velocity across a couple of irregular stenoses with various Reynolds numbers with $D = \frac{11}{12} L_1$	93
4.28	Velocity streamline for double cosine stenoses at various Reynolds numbers (a) 100, (b) 200, (c) 300 and (d) 400 with $D = \frac{11}{12} L_1$	94
4.29	Velocity streamline for double protrude stenoses at various Reynolds numbers (a) 100, (b) 200, (c) 300 and (d) 400 with $D = \frac{11}{12} L_1$	95
4.30	Velocity streamline for double irregular stenoses at various Reynolds numbers (a) 100, (b) 200, (c) 300 and (d) 400 with $D = \frac{11}{12} L_1$	96
4.31	Wall pressure distribution across a couple of cosine stenoses at various Reynolds numbers with $D = \frac{11}{12} L_1$	98
4.32	Wall pressure distribution across a couple of protrude stenoses at various Reynolds numbers with $D = \frac{11}{12} L_1$	98
4.33	Wall pressure distribution across a couple of irregular stenoses at various Reynolds numbers with $D = \frac{11}{12} L_1$	99
4.34	Dimensionless pressure drop across first and second stenosis for each model with different Reynolds numbers	99
4.35	Variation of wall shear stress across a couple of cosine stenoses for different Reynolds numbers with $D = \frac{11}{12} L_1$	100

- 4.36 Variation of wall shear stress across a couple of protrude stenoses 101  
for different Reynolds numbers with  $D = \frac{11}{12} L_1$
- 4.37 Variation of wall shear stress across a couple of irregular stenoses 101  
for different Reynolds numbers with  $D = \frac{11}{12} L_1$

©This item is protected by original copyright

## 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
$\rho$	fluid density
$\mu$	fluid dynamic viscosity
$L_1$	length of proximal stenosis
$L_2$	length of distal stenosis
$\delta_1$	height of proximal stenosis
$\delta_2$	height of distal stenosis
$S_{\text{area}}$	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

©This item is protected by original copyright

## **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 stenosis 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 untuk semua kes kajian. Hasil kajian menunjukkan halaju puncak, kejatuhan tekanan dan tegasan ricih dinding dengan nilai  $0.7518 \text{ ms}^{-1}$ ,  $398.16 \text{ Nm}^{-2}$  dan  $15.39 \text{ Nm}^{-2}$  masing-masingnya adalah paling tinggi dalam kes dual stenosis berbentuk tak sekata. Menariknya, dual stenosis berbentuk menjulur menunjukkan halaju puncak ( $0.672 \text{ ms}^{-1}$ ) dan tegasan ricih dinding ( $14.90 \text{ Nm}^{-2}$ ) lebih tinggi daripada dual stenosis berbentuk kosinus dengan halaju puncak,  $0.6578 \text{ ms}^{-1}$  dan tegasan ricih dinding  $13.06 \text{ Nm}^{-2}$  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 kebiasaannya 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  $0.7518 \text{ ms}^{-1}$ ,  $398.16 \text{ Nm}^{-2}$  and  $15.39 \text{ Nm}^{-2}$  respectively for the case of double irregular stenoses. It is interesting to find out that double protruding-shaped stenoses exhibit greater peak velocity ( $0.672 \text{ ms}^{-1}$ ) and peak wall shear stress ( $14.90 \text{ Nm}^{-2}$ ) in comparison with cosine-shaped stenosis with peak velocity,  $0.6578 \text{ ms}^{-1}$  and peak wall shear stress,  $13.06 \text{ Nm}^{-2}$  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-scraper 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).

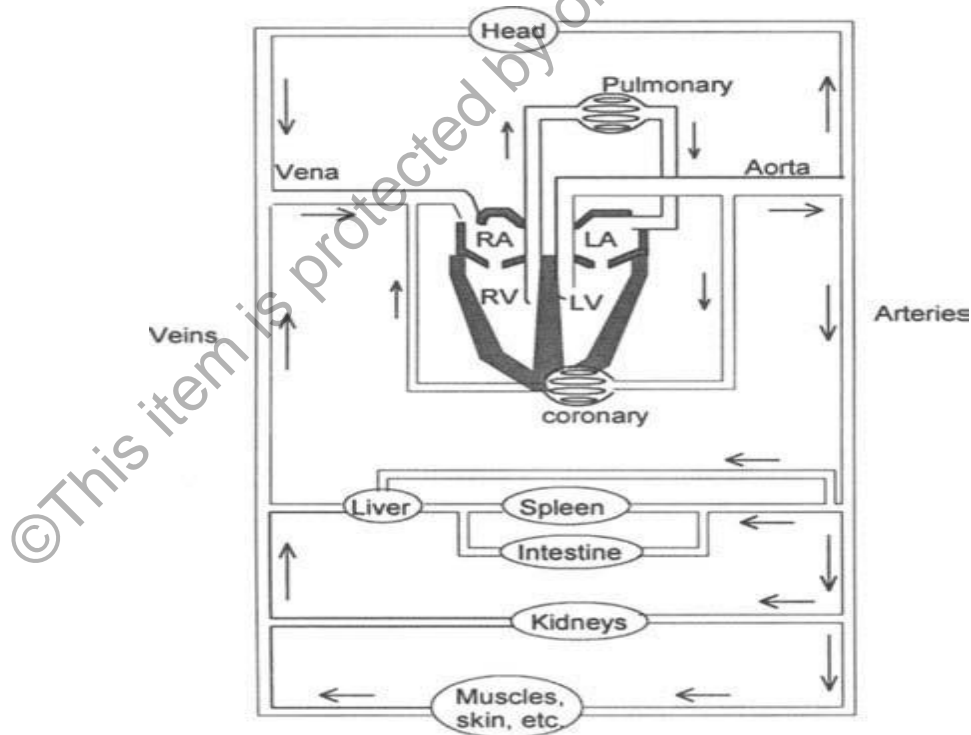


Figure 1.1: Schematic of the cardiovascular system (Devasahayam, 2000)

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  $\mu\text{m}$  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)

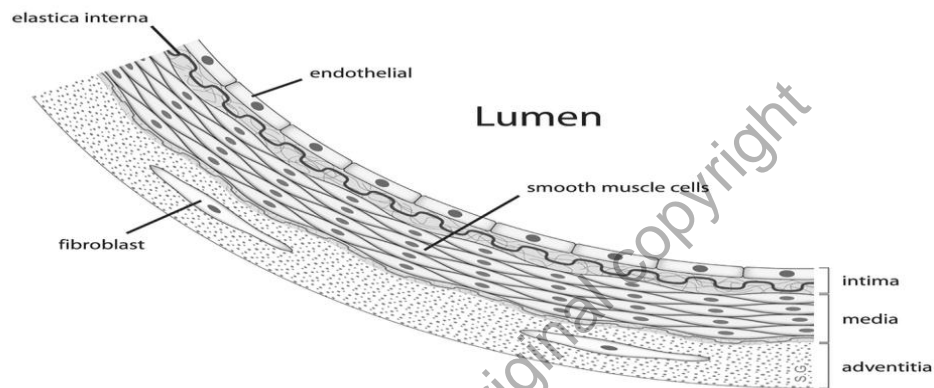


Figure 1.2: Schematic of an artery (Ghesquiere, 2007)

### 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)

from media to intima. In addition, monocytes divide into macrophages and engulf oxidized LDL. As a sequence, inflammation occurs and promotes the accumulation and proliferation of SMC and macrophages. This process creates development of the fatty streak and induces plaque growth (see Figure 1.3). As a result, a constriction (in medical is referred as stenosis) in the artery occurs (Srivastava, Rastogi and Vishnoi, 2010). In the critical arteries, the plaques may rupture and provoke acute myocardial infarction and stroke (Sunagawa, Kanai, Koiwa, & Tanaka, 2002; Zhi-Yong & Gillard, 2007). From above review, it is obvious that the atherosclerosis may cause dramatic changes on the structures and mechanical properties of the arterial wall which significantly affect the blood flow conditions.

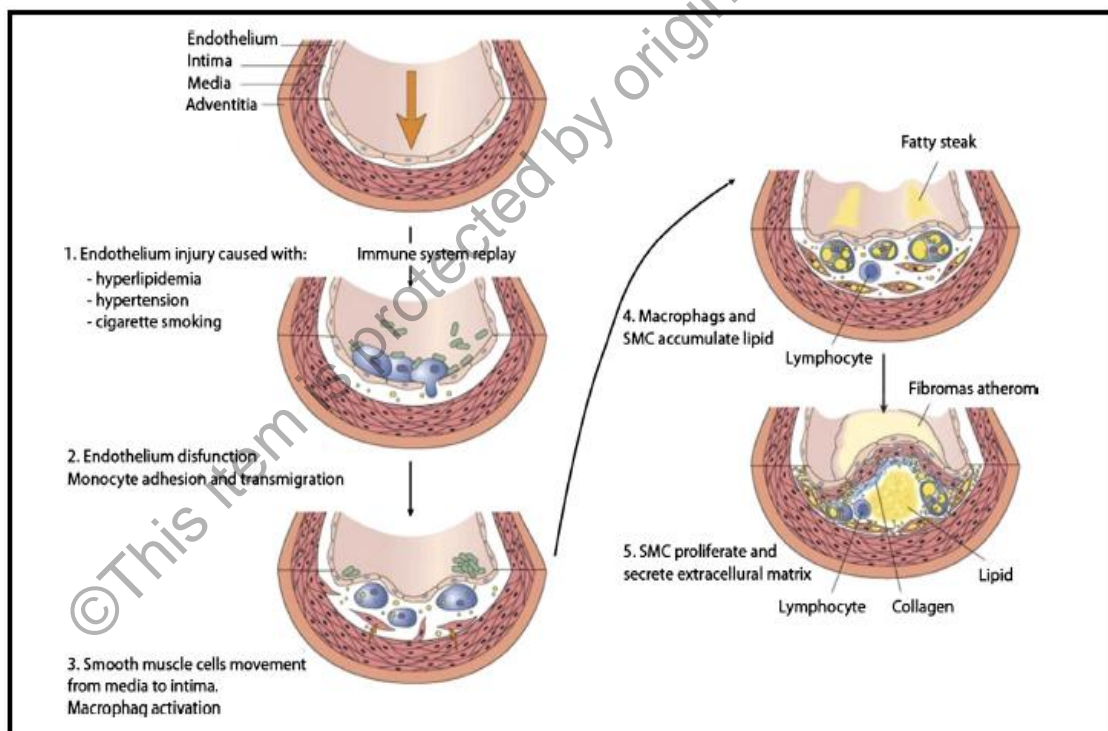


Figure 1.3: Development of the atherosclerotic plaque (Filipovic et al., 2013)

In medical applications, common diagnostic techniques used for assessment of stenosed coronary artery are coronary angiography, computed tomography and intravascular ultrasound (IVUS). Coronary angiography is an invasive diagnostic technique provides two-dimensional image of the vessel lumen but restricted on the