

# Table of Contents

Page No.

## Chapter 1

<b>Introduction.....</b>	<b>01-38</b>
1.1 Modeling and simulations of cardiovascular system.....	01
1.2 Cardiovascular system .....	04
1.2.1 Heart .....	06
1.2.2 Cardiac structure.....	07
1.2.3 Blood Vessels.....	08
1.2.4 Arteries.....	09
1.2.5 Arteries Morphology.....	10
1.2.6 Blood.....	12
1.2.7 Blood Pressure.....	13
1.3 Cardiovascular disease.....	14
1.3.1 coronary artery disease.....	15
1.3.2 Peripheral arterial disease.....	16
1.3.3 Cerebrovascular disease.....	17
1.3.4 Renal artery stenosis.....	18
1.3.5 Aortic aneurysm.....	19
1.3.6 Left heart dysfunction.....	21
1.4 Computational fluid dynamics (CFD).....	21
1.4.1 Governing Equations of blood flow.....	22
1.4.2 Finite element method (FEM).....	23
1.4.3 Finite volume method (FVM).....	26
<b>1.5 Literature review .....</b>	<b>27</b>
1.5.1 Recent advancement on cardiovascular disease modelling and Simulation.....	28
1.5.2 Aortic aneurysm analysis (AAA).....	29
1.5.3 coronary artery disease analysis (CAD).....	30
1.5.4 Arterial stenosis.....	32

1.5.5 Left ventricle hemodynamics.....	33
1.6 Purpose of study: Motivation.....	34
1.7 Research Objectives.....	36
1.8 Contributions of work.....	37
1.9 Thesis Structure.....	38

## **Chapter 2**

### **The pulsatile 3D-Hemodynamics in a doubly afflicted human descending abdominal artery with iliac branching .....39-73**

2.1 Introduction.....	40
2.2 Methods.....	44
2.2.1 Geometric Model .....	45
2.2.2 Discretization and mesh independency check.....	48
2.2.3 Computational methods .....	51
2.2.4 Governing equations for blood flow simulation .....	51
2.2.5 Simulation setup.....	52
2.3 Result and discussion .....	53
2.3.1 Pressure distribution in healthy and unhealthy condition.....	54
2.3.2 Velocity profile in healthy and unhealthy artery.....	57
2.3.3 Wall Shear Stress (WSS) distribution in healthy and unhealthy artery.....	59
2.3.3.1 WSS Waveform.....	59
2.3.3.2 WSS Contour Distribution .....	60
2.3.3.3 Local WSS contour distribution in unhealthy artery.....	60
2.3.4 Wall Shear Stress (WSS) distribution in healthy and unhealthy artery.....	64
2.3.4.1 WPs waveform.....	64
2.3.4.2 WPs contour distribution.....	65
2.3.5 Streamlines of blood flow during peak of systolic phase.....	67
2.3.6 Core vorticity and Swirling strength distribution.....	68
2.3.6.1 Vorticity distribution.....	68
2.3.6.2 Swirling strength distribution.....	69
2.3.6.3 Locally scaled axial velocity contour.....	69

2.4 Summary.....	71
------------------	----

### **Chapter 3**

<b>Effect of rheological models on pulsatile hemodynamics in a multiply afflicted descending human aortic network.....</b>	<b>74-125</b>
--	---------------

3.1 Introduction.....	75
3.2 Methods.....	79
3.2.1 Geometric model.....	79
3.2.2 Governing equations for blood flow simulation .....	81
3.2.3 Non-Newtonian rheological models for blood.....	82
3.2.4 Initial and boundary conditions.....	83
3.2.5 Discretization and mesh independency check.....	83
3.2.6 Simulation setup.....	84
3.2.7 Validation.....	85
3.3 Results.....	87
3.3.1 Centerline velocity and pressure profile during the peak of systole.....	88
3.3.1.1 Centerline velocity.....	88
3.3.1.2 Centerline pressure.....	89
3.3.2 Wall shear stress effect during crucial cardiac instant.....	91
3.3.3 Wall pressure (WPs) effect during crucial cardiac instant.....	94
3.3.4 Wall shear stress contour (WSS) distribution.....	97
3.3.4.1 Cross model WSS .....	97
3.3.4.2 Carreau model WSS.....	98
3.3.4.3 Power model WSS.....	99
3.3.4.4 Herschel-Buckley model WSS.....	100
3.3.4.5 Newtonian model WSS.....	101
3.3.5 Sensitivity of the WSSs.....	102
3.3.6 Non-Newtonian importance factor.....	106
3.3.7 Non-Newtonian effect factor.....	109
3.3.8 Axial velocity contours.....	112
3.3.9 Streamlines of blood flow.....	115

3.3.10 Vorticity and Swirling Strength distribution.....	117
3.3.10.1 Vorticity.....	117
3.3.10.2 Swirling effect.....	117
3.4 Discussion .....	118
3.5 Principle Findings.....	120
3.6 Limitations and extesnsions.....	122
3.7 Summary.....	123

## **Chapter 4**

### **Influence of abdominal aortic aneurysm shape on hemodynamics in human aortofemoral arteries: A transient open-loop study.....126-165**

4.1 Introduction.....	127
4.2 Methodolgy.....	132
4.2.1 Geometry .....	132
4.2.2 Discretization .....	137
4.2.3 Governing equautions.....	138
4.2.4 Simulation setup.....	144
4.2.5 Hemodynamic parameter calculation.....	147
4.2.5.1 Time average wall shear Stress (TAWSS).....	147
4.2.5.2 Oscillatory shear index (OSI).....	147
4.2.5.3 Vortex structures.....	148
4.3 Results and discussion .....	148
4.3.1 Effect of aneurysms vessels dilation on velocity distributions.....	150
4.3.2 Effect of the neck angle and aneurysm's location on the velocity distribution.....	153
4.3.3 Effect of neck angle and aneurysm's location on flowlines.....	155
4.3.4 Effect of bifurcation angle on flowlines.....	157
4.3.5 Effect of neck angle on wall shear stress .....	159
4.3.6 Effect of aneurysm shape on hemodynamics parameters.....	161
4.3.6.1 TAWSS distribution.....	161
4.3.6.2 OSI distribution.....	162
4.3.6.3 Vortex distribution.....	163

4.4 Summary.....	164
------------------	-----

## **Chapter 5**

### **Patient-Specific Blood Flow and Pressure Modelling of Suspected Coronary Artery Disease Using Open Loop System.....166-204**

5.1 Introduction.....	167
5.2 Materials and Methods.....	171
5.2.1 Patient information .....	171
5.2.2 Image-based three-dimensional geometrical modelling.....	172
5.2.2.1 Path Planning .....	173
5.2.2.2 Segmentation.....	174
5.2.2.3 Lofting.....	175
5.2.2.4 Solid modelling.....	176
5.2.3 Meshing.....	177
5.2.4 Mesh Independency Test.....	180
5.2.5 Open Loop (0-3D) Finite Element Modelling.....	180
5.2.6 Governing Equations & Simulation Setup.....	182
5.2.7 Hemodynamic Parameters.....	183
5.2.8 Boundary Conditions.....	183
5.2.9 Inlet Boundary Condition.....	186
5.2.10 Coronary Boundary Conditions.....	187
5.2.11 RCR Boundary Conditions.....	191
5.3 Results .....	192
5.3.1 Flow rate and pressure distribution.....	192
5.3.1.1 On the outlet of the cap RCA.....	192
5.3.1.2 On the outlet of the cap LCA.....	193
5.3.2. Streamline visualization in the RCA during cardiac cycle.....	196
5.3.3 Wall shear stress (WSS) contour during cardiac cycle.....	197
5.3.4 Oscillatory Shear Index (OSI).....	198
5.3.5 Time average wall shear stress (TAWSS).....	199
5.3.6 Relative Residence Time (RRT) distribution.....	200

5.4 Discussion.....	201
5.5 Summary.....	204

**Chapter 6**

**Image based modelling and simulation of hemodynamics in static LV human left ventricle using CT data .....205-233**

6.1 Introduction.....	206
6.2 Methods.....	211
6.2.1 Geometry reconstruction.....	212
6.2.1.1 Image acquisition.....	212
6.2.1.2 Preparing the acquired CT Data.....	215
6.2.1.3 Manual segmentation and 3D model generation.....	217
6.2.1.4 Automatic segmentation and 3D model generation (Deep learning method).....	220
6.2.1.5 Model compatible for CFD simulations.....	223
6.2.2 Mesh Generation.....	224
6.2.3 Pulsatile boundary conditions.....	225
6.2.4 Numerical modelling.....	226
6.3 Results & discussion.....	227
6.3.1 Velocity & streamlines.....	227
6.3.2 Velocity contours of blood flow (M <sub>1</sub> ).....	228
6.3.3 Wall pressure.....	229
6.3.4 Wall Shear stress.....	230
6.3.5 Vortex's core structures.....	231
6.4 Summary.....	232

**Chapter 7**

**Conclusion and future work .....234-239**

7.1 Conclusion.....	235
7.2 Future work.....	238
References.....	240
Ethical clearance.....	273
List of publications.....	274

Conferences/workshops/seminars.....	275
Research work in press news .....	276