CFD Simulation as an alternate diagnostic tool for a blocked artery

Sabbani Manohar

A Dissertation Submitted to
Indian Institute of Technology Hyderabad
In Partial Fulfillment of the Requirements for
The Degree of Master of Technology

भारतीय प्रौद्योगिकी संस्थान हैदराबाद
Indian Institute of Technology Hyderabad

Department of Chemical Engineering

June, 2016

Declaration

I declare that this written submission represents my ideas in my own words, and where others' ideas or words have been included, I have adequately cited and referenced the original sources. I also declare that I have adhered to all principles of academic honesty and integrity and have not misrepresented or fabricated or falsified any idea/data/fact/source in my submission. I understand that any violation of the above will be a cause for disciplinary action by the Institute and can also evoke penal action from the sources that have thus not been properly cited, or from whom proper permission has not been taken when needed.

(Signature)

Sabbani Manohar

(– Student Name –)

Ch14mtech11018

(Roll No)

ii

Approval Sheet

This thesis entitled "**CFD simulation as an alternate diagnostic tool for a blocked artery**" by Sabbani Manohar is approved for the degree of Master of Technology from IIT Hyderabad.

Dr Narasimha Mangadoddy
Examiner

Dr Mahati Chittem
Chairman/ Examiner

Dr Anand Mohan
Adviser

iii

Acknowledgements

I would to like to thank my parents for their endless support which made me stand in IITH. I am very thankful to our guide Dr Anand Mohan for his motivation and encouragement for this project. My work would be meaningless without his supervision. I also want to thank my friends and seniors in IITH for their companionship with me. I feel so grateful to work with our research group (Nanda Kumar, Susree, Laxman, and Ameenuddin) who are going to be memorable part of my IITH life. A special thanks to Kandukuri Koteswara Rao and Tushar Pol for their technical support.

I also thank Apollo Health City for supplying the angiograms and FFR data used in this study as per their Ethics committee. This study was approved by the Institutional Ethics Committee of IIT Hyderabad: accordingly, patient data was anonymized by assigning letter identifiers.

Dedicated to

My parents with so much love.

Abstract

Narrowing or blockage in the coronary arteries supplying blood to the heart muscle manifest as symptoms like chest discomfort or pain and shortness of breath. Symptomatic patients are screened for blocked arteries using coronary angiograms. However, an angiogram provides approximate degree of obstruction. Further, we need to check the significance of obstruction to decide the need for intervention. Interventions like stenting or surgery will depend upon the degree of obstruction and functional impairment. This is evaluated by procedures like measurement of Fractional Flow Reserve (FFR). FFR is the ratio of pressure distal to the stenosis to the pressure proximal to the stenosis. FFR is measured using a specialized probe inserted through a catheter tube, and the technique is expensive. In this study, we propose a workflow to calculate FFR in a non-invasive manner using CFD simulations, and validate it by comparing the results with data from patients.

Nomenclature

CAD: Coronary Artery Disease

CFD: Computational Fluid Dynamics

CTCA: Computed Tomography Coronary Angiogram

CVD: Cardio Vascular Disease

FFR: Fractional Flow Reserve

IHD: Ischemic Heart Disease

MRI: Magnetic Resonance Imaging

QCA: Quantitative Coronary Analysis

Contents

Chapter 1

Introduction

1.1 Atherosclerosis

It is a chronic disease which is due to formation of plaque buildup inside an artery. Arteries are the blood vessels which carries the blood from heart to the other parts of the body. Plaque is made up of cholesterol, fat, calcium and other substances found in the blood. Over a period of time, plaque hardens and narrows the area of the artery. This will limit the blood flow to the other parts of body from heart. So the obstruction in such arteries causes cardiac arrest, stroke or even death.

Atherosclerosis can affect any artery in the body, including arteries in the heart,
brain, arms, legs and kidneys. Different diseases may develop based on which arteries are affected.

1.1.1 Coronary Artery Disease

Coronary artery disease (CAD) is also called as ischemic heart disease (IHD). It is the most common type in group of cardiovascular diseases. Symptoms are like chest pain or discomfort which will travel in to the shoulder, arm, back and neck. Occasionally it may feel like heartburn. Shortness of breath may also occur and sometimes no symptoms are present. Ischemic heart diseases are the most common cause of death in many countries around the world. According to the global burden of disease study in 2010, there is a significant percentage increase of 34.9% in mortality due to ischemic heart disease compared to 1990 [1], and also nearly 24.8% of all deaths in India are attributed to Cardio Vascular Diseases [2] which is a superset of Ischemic heart disease.

1.1.2 Angiography

Angiography is also known as arteriography. It is an X-ray based imaging technique which is used to visualize the inside or lumen of blood vessels and other internal parts of organs of the body. Thereby the defects and diseased portions of that particular area can be detected.

There are different types of angiograms are available which are coronary angiogram, computed tomography coronary angiogram (CTCA) and magnetic resonance imaging (MRI). To detect the coronary artery disease, CTCA has been proven to be better than conventional coronary angiogram and MRI techniques.

1.2 Fractional Flow Reserve (FFR)

The severity of blockage can be assessed using Fractional Flow Reserve (FFR); FFR is measured by inserting a pressure guide wire through a catheter into an artery. This will give the pressure variation in that particular location of blockage. Mathematically, FFR is the ratio of pressure distal to the stenosis to the pressure proximal to the stenosis.

FFR is also defined as the ratio of blood flow in the stenosed artery to the blood flow in unstenosed artery. The value of this ratio decides whether a patient with arterial stenosis has to go for revascularization or not. If the FFR is greater than 0.75 then it is considered as negative case. If the FFR is less than 0.75 then it is considered for intervention. The measurement of FFR is an invasive method.

1.3 Calculation of FFR

FFR is calculated using the following formulae;

$$\text{FFR} = \frac{\text{Pressure distal to the stenosis}}{\text{Pressure proximal to the stenosis}}$$

Or

$$\text{FFR} = \frac{\text{blood flow rate in stenosed artery}}{\text{blood flow rate in unstenosed artery}}$$

Chapter 2

Literature Review

The invasive nature of FFR as an initial diagnostic test reduces its application to majority of population because of its cost. The noninvasive calculation of FFR using standard CTCA images by computational fluid dynamics has been described in [3], and is termed as FFR_{CT}. FFR_{CT} is known as an important tool for the assessment of blood flow in stenosed arteries. FFR_{CT} is the only technique which determines the severity of blockage in coronary arteries with atherosclerosis. The purpose of FFRCT is to check the necessity of interventions like stenting in affected artery, which will expand the role of CTCA in the prediction and management of Coronary artery disease(CAD) [4].

FFR can be defined as the ratio of maximum coronary flow in stenotic artery to the maximum coronary flow in the same artery without any stenosis. The ratio of these two blood flows can also be evaluated as the ratio of two pressures, namely the pressure which is distal to the stenosis and pressure which is proximal to the stenosis. The relation between coronary flow and FFR was examined in the early 1990s.

Computational method for the calculation of noninvasive FFR from CT images requires a 3dimensional anatomic model of the coronary arteries, coronary blood flowrate, and a numerical solution of the laws of fluid dynamics. In this way, application of FFR_{CT} to CTCA enhances the diagnostic accuracy of CTCA by reducing the rate of false positive blockages incorrectly classified by anatomic stenosis severity alone [4].

Few studies were performed to decide the diagnostic behavior of noninvasive FFR derived from CTCA data for the diagnosis of patients with CAD. FFRmeasured using invasivecoronary angiography (ICA) is the gold standard for lesion specific coronary revascularization decisions [5, 6]. The NXT study performed by Norgaard et al. [7] is designed to illustrate the diagnostic accuracy of FFRCT using invasive FFR value as the reference for validation. Analysis of FFR_{CT} was implemented by generating a quantitative 3 dimensional anatomic model of aortic root and coronary arteries using coronary CTCA images. Pressure and blood flow in those arteries were computed using latest version of FFR_{CT} analysis software. A patient was taken as a positive case for the presence of ischemia if an artery, which is more than 2mm in diameter, had an FFR $\leq$ 0.80. Correspondingly, a patient was considered as a negative case if an artery, which is less than 2mm in diameter, had an FFR $\leq$ 0.80. The same rule applied for the assessment of FFR_{CT} [7]. Studies revealed that patients with percentage stenosis of 30% to 70% included more than 90% of overall study population.

Apart from the coronary arteries, there are also carotid arteries where obstruction in the blood flow occurs due to the stenosis. Carotid artery supplies the blood from the heart to brain, blockage in this artery causes stroke. There have been CFD studies which assessed the blood flow patterns and hemodynamic parameters using Cine phase-contrast (PC) magnetic resonance imaging (MRI). Different viscosity models of blood flow were applied for a patient with carotid artery stenosis and the hemodynamic parameters were also examined. Lumped parameter model used for this affected carotid artery. Few of the remarkable factors in this CFD study using MRI were that softness of artery wall, segmentation of the geometrical model and the specific velocity profile at the inlet were considered [8].

In recent years, noteworthy progress has been made on invasive and noninvasive medical imaging techniques to diagnose the anatomical and hemodynamic effect of coronary stenosis [4, 7]. Virtual FFR has been accepted by the US FDA as a class II simulation device; the challenges in developing a suitable workflow for noninvasive computation of FFR (or ‘virtual’ FFR) using CTCA were summarized in [9]. However, there are no trials which have implemented or validated a computational procedure to determine the FFR from angiograms in India; such studies are available outside India [3, 10]. In this thesis, we develop a workflow for the computation of FFR which is highly relevant to Indian conditions.

The effect of Diameter Stenosis (DS), stenosis location, and segment length on the values of FFR was studied in [10]. In addition to the DS, stenosis length and its location is also very important as they affect the hemodynamics of blood flow in arteries. In this thesis, we see if there is a correlation if any between percentage stenosis and measured FFR.

Chapter 3

Procedure

3.1 Angiogram

The first step in this model is to collect an angiogram of a patient who has coronary artery disease (CAD). A computed tomography coronary angiogram (as shown in Figure 3.1) is collected from a patient whose left anterior descending artery has a blockage.

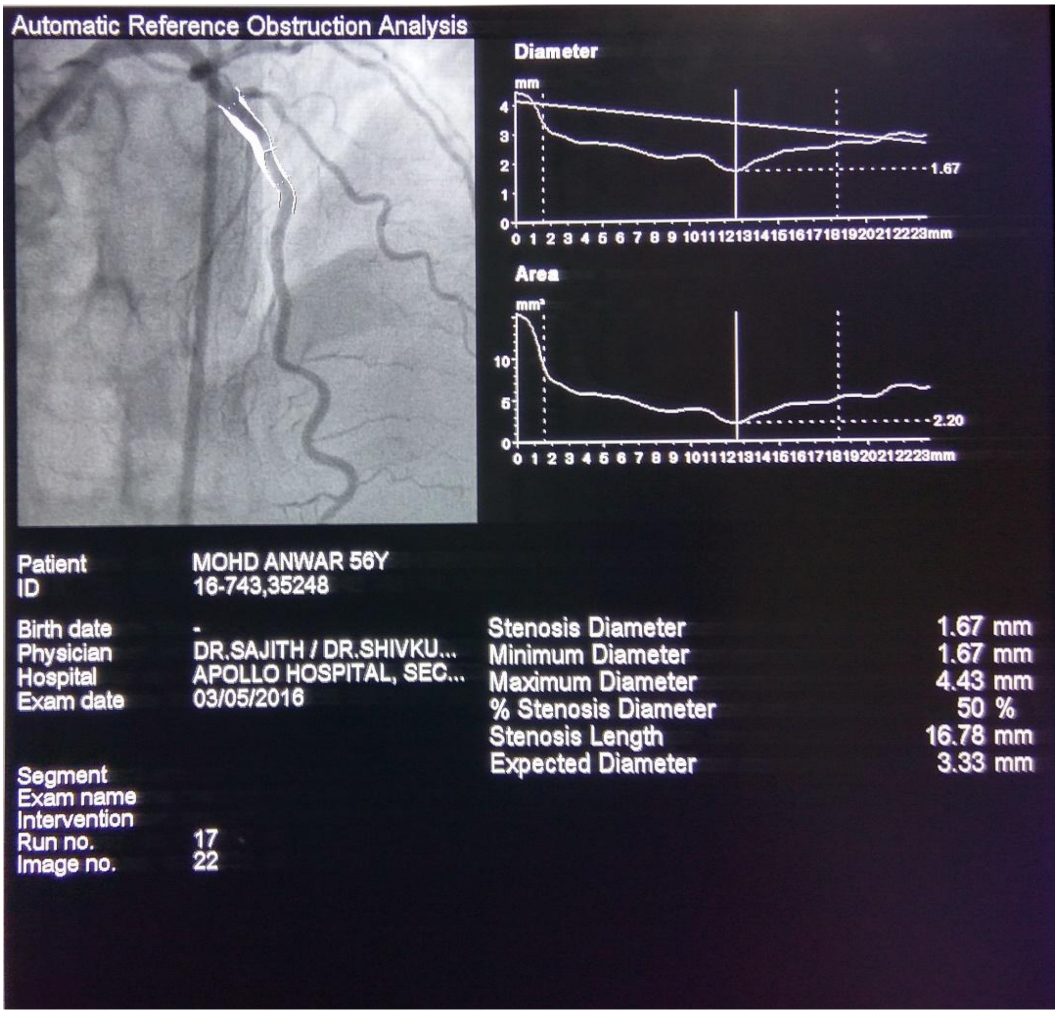

Figure 3.1: CT Angiogram

The location of stenosis can be seen in angiogram and additional information like variation of diameter and area along with the length of the artery is also provided in the Quantitative Coronary Analysis (QCA).

3.2 Geometry

In CFD simulations, creating the geometry is an important step. A virtual geometry (as shown in Figure 3.3) is recreated in ANSYS FLUENT using the dimensions of coronary artery which has blockage. The coordinates of the geometry can be collected from the Figure 3.2 (obtained from QCA) using DIG XY software where length of the artery is taken on X axis and diameter of the same artery is taken on Y axis [11].

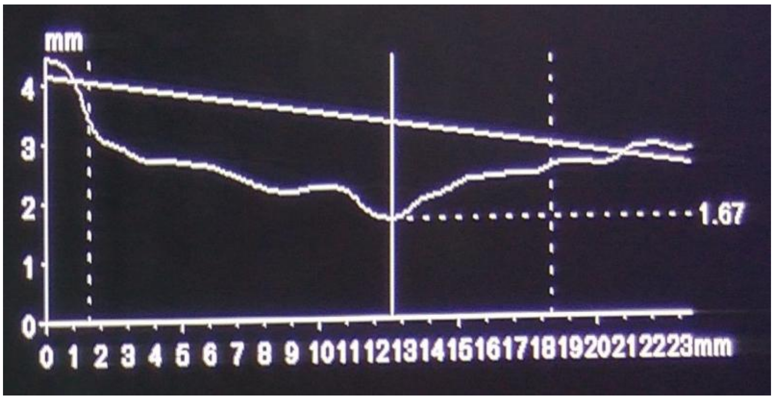

Figure 3.2: Variation of diameter w.r.t length

3.2.1 Recreated geometry

In Ansys Fluent, geometry which is recreated by using the coordinates of diameter and length of the segment is shown in the following Figure 3.3.

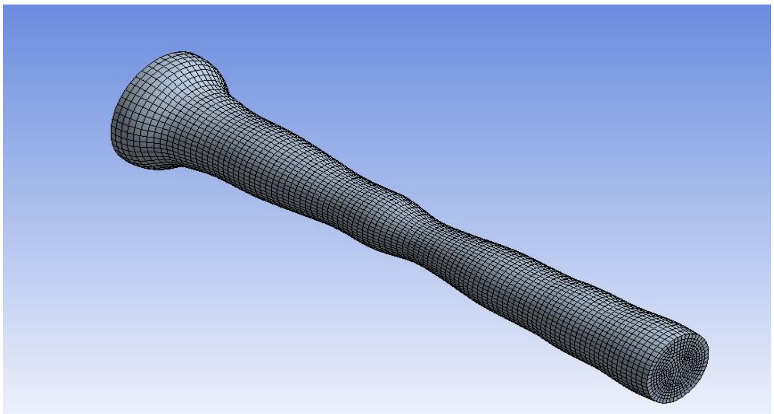

Figure 3.3: Recreated geometry

3.2.2 Mesh

Next step in this simulation is to set proper mesh for the recreated geometry. Design and construction of quality grid plays a crucial role in CFD analysis. As our focus is on blood flow, we suppress the solid surface i.e. wall of the artery. CFD simulations need highly refined mesh such that solution or results should not change for further refinement of the mesh. To avoid the erroneous results in our simulations, refinement of mesh is highly needed activity which is to be performed with different mesh sizes till the solution is converged. The main advantage with this refinement process is that we can use same size of mesh when same type of problem occurs in future. So this can reduce the time for mesh independence study for similar problems. Size of the mesh can be increased by accommodating more number of cells to the geometry.

For steady state simulations, we should check the convergence criteria by setting Absolute convergence criterion of error less than $\mathbf{10^{-3}}$. Convergence also depends upon the size and type of mesh. Mesh which is adjacent to the wall should be fine enough to resolve the boundary layer flow and tetrahedral mesh is applied over the surface of the artery. So the final size of mesh has huge impact on accuracy of the solution.

3.3 Modeling and Simulation

Blood is a shear thinning fluid for which viscosity decreases when shear is applied. We use Power law model for this simulation with material parameters for blood specified in equations 1 and 2 as follows: density=1059kg/m^3; maximum viscosity=0.056pa.s; minimum viscosity=0.00345pa.s; m=0.42pa.s^n; n=0.61. These parameters are obtained from [12]

$$\tau = \mu_{\text{eff}} \left(\frac{\partial u}{\partial y} \right) \tag{1}$$

$$\mu_{\text{eff}} = m \left(\frac{\partial u}{\partial y} \right)^{n-1} \tag{2}$$

We assume the flow in coronary artery is viscous laminar. Coronary blood flow is actually transient and pulsatile in nature. Steady state CFD analysis can be used rather than transient as it runs more quickly, even though it cannot analyze the time dependent behavior of pulsatile blood flow [7]. The CFD simulations use pressure based solver with second order upwind scheme and Semi implicit method for pressure linked equations (SIMPLE) algorithm is applied.

3.3.1 Boundary conditions

We performed steady flow simulations assuming the mean blood flow rate in coronary artery is 250 ml/min which can be used for giving inlet velocity boundary condition. Zero gauge pressure is taken for the outlet boundary condition as the geometry is assumed to be open to atmosphere: Tests revealed that calculated FFR is insensitive to the value of pressure specified at the outlet boundary. We also specify no slip boundary condition at the wall as the surface of the artery wall is assumed to be rigid.

3.3.2 Calculation of FFR

Results from the simulation of stenosed artery using above boundary conditions gives us total gauge pressure at the inlet. After the pressure values have been reported, we have to generate the geometry of unstenosed artery which has same diameter and same segment length like stenosed artery of the same patient. Mesh independence study has to be implemented or performed for this geometry too. We need to give total inlet gauge pressure of stenosed artery as the inlet pressure boundary condition to the unstenosed artery. Zero gauge pressure at the outlet is given as outlet boundary condition for this unstenosed artery as it is done for stenosed artery. We have performed simulations for this geometry to get the velocity of blood in unstenosed artery. We can get the maximum velocity from the simulations, and this is used to calculate the mean velocity of blood using the below formula:

$$\frac{Vmax}{Vmean} = \frac{3n+1}{n+1}$$

Where n= 0.61 for blood which is a shear thinning fluid.

From this mean velocity, we can calculate the volumetric blood flow rate in unstenosed artery. Now we have both blood flow rate in stenosed and unstenosed arteries. The ratio of these two blood flow rates give Fractional Flow Reserve (FFR) value for that specific patient whose CTCA we have analyzed.

$$\text{FFR} = \frac{\text{blood flow rate in stenosed artery}}{\text{blood flow rate in unstenosed artery}}$$

Chapter 4

Results and Discussions

4.1 Patient A

This is the case of a patient with 50% stenosis in coronary artery with the radius of 2.18mm.

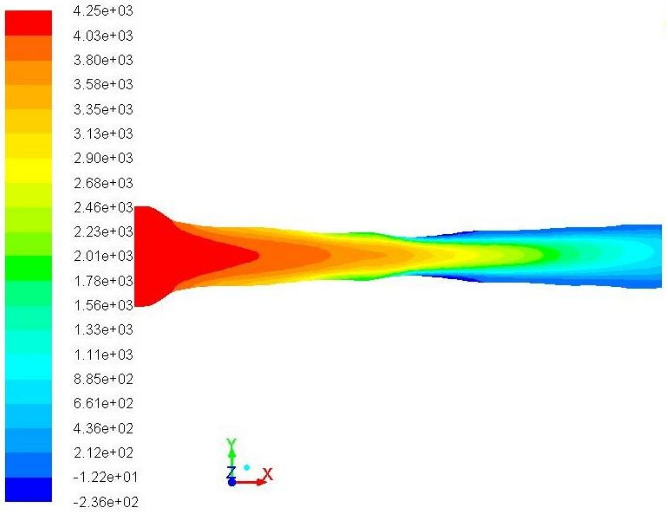

Figure 4.1.1: Pressure contours in stenosed artery (in Pascal)

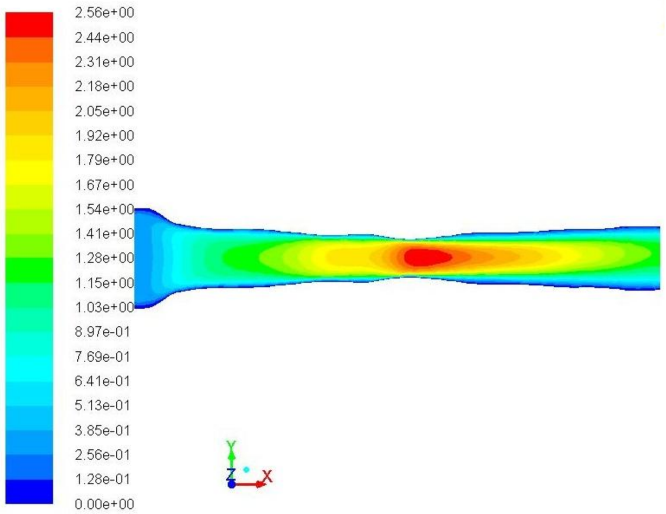

Figure 4.1.2: Velocity contours in stenosed artery (in m/s)

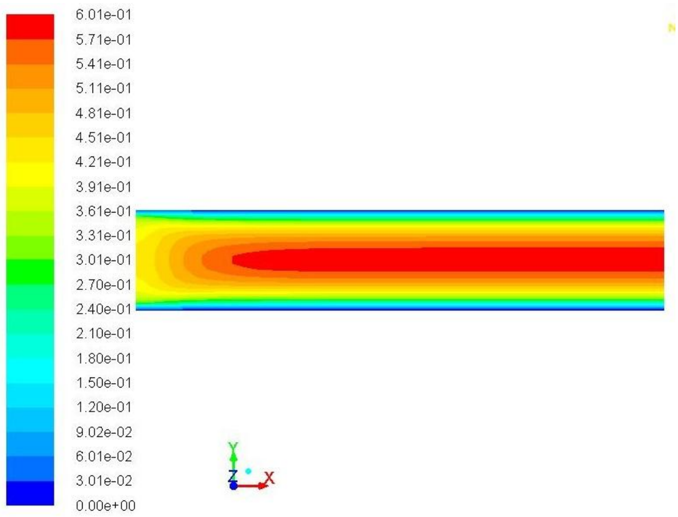

Figure 4.1.3: Velocity contours in unstenosed artery (in m/s)

We can see how pressure is being changed in stenosed artery in Figure 4.1.1 and velocity contours are also shown in Figure 4.1.2. Using same total inlet gauge pressure of stenosed artery, we get the velocity contours for unstenosed artery as shown in Figure 4.1.3. So the maximum velocity from the contours is 0.601 m/s for patient-A. We will calculate mean velocity, volumetric blood flow rate and FFR by following procedure.

$$\frac{Vmax}{Vmean} = \frac{3n+1}{n+1}$$

$$\frac{0.601}{\text{Vmean}} = \frac{3(0.61)+1}{0.61+1}$$

V_{mean} =0.346 m/s

Volumetric blood flow rate in unstenosed artery (Qunstenosed) = Area × Vmean

$= \pi(0.218 \text{ cm})^2 \times (34.6\text{cm/s}) \times (60 \text{ s/min})$

= 310 ml/min

Volumetric blood flow rate in stenosed artery (Qstenosed) = 250 ml/min

$$\text{Fractional Flow Reserve (FFR)} = \frac{\text{blood flow rate in stenosed artery}}{\text{blood flow rate in unstenosed artery}}$$

$$= \frac{\mathbf{250}}{\mathbf{310}}$$

Calculated FFR (Noninvasive) = 0.81

Measured FFR (invasive) = 0.84

4.2 Patient B

This is the case of a patient with 44% stenosis in coronary artery with the radius of 1.67mm.

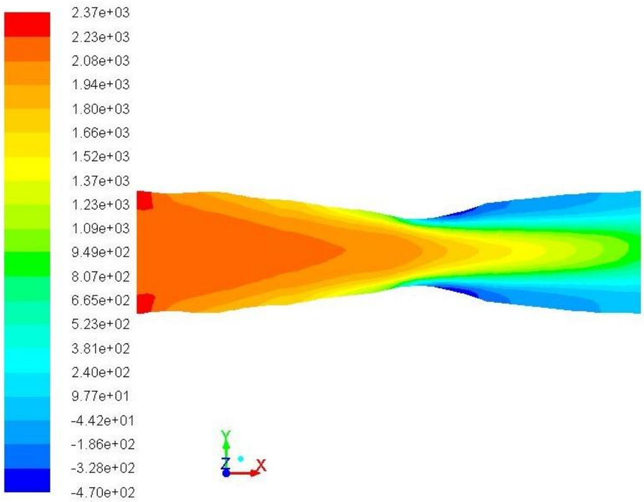

Figure 4.2.1: Pressure contours in stenosed artery (in Pascal)

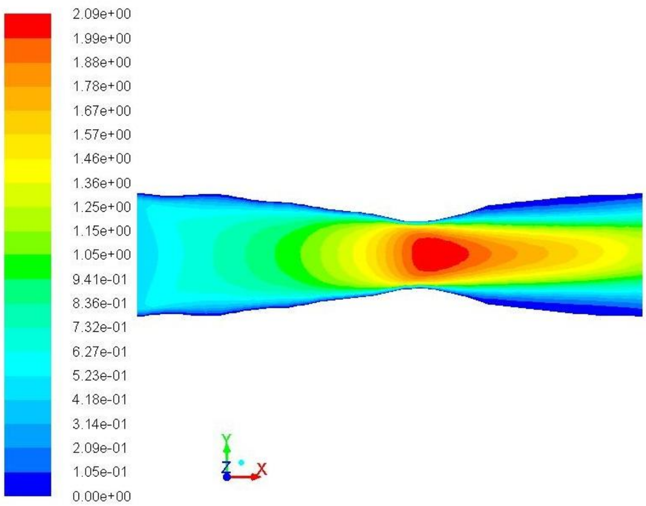

Figure 4.2.2: Velocity contours in stenosed artery (in m/s)

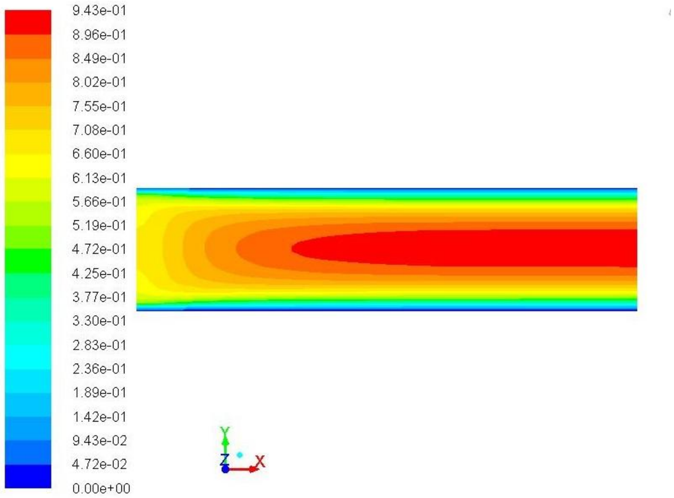

Figure 4.2.3: Velocity contours in unstenosed artery

We can see how pressure is being changed in stenosed artery in Figure 4.2.1 and velocity contours are also shown in Figure 4.2.2. Using same total inlet gauge pressure of stenosed artery, we get the velocity contours for unstenosed artery as shown in Figure 4.2.3. So the maximum velocity from the contours is 0.943 m/s for patient-B. We will calculate mean velocity, volumetric blood flow rate and FFR by following procedure.

$$\frac{Vmax}{Vmean} = \frac{3n+1}{n+1}$$

$$\frac{0.943}{\text{Vmean}} = \frac{3(0.61)+1}{0.61+1}$$

V_{mean} = 0.54 m/s

Volumetric blood flow rate in unstenosed artery (Qunstenosed) = Area × Vmean

$= \pi(0.167\text{cm})^2 \times (54\text{cm/s}) \times (60 \text{ s/min})$

= 283.7 ml/min

Volumetric blood flow rate in stenosed artery (Qstenosed) = 250 ml/min

$$\text{Fractional Flow Reserve (FFR)} = \frac{\text{blood flow rate in stenosed artery}}{\text{blood flow rate in unstenosed artery}}$$

$$= \frac{\mathbf{250}}{\mathbf{283.7}}$$

Calculated FFR (noninvasive) = 0.88

Measured FFR (invasive) = 0.91

4.3 Patient C

This is the case of a patient with 32% stenosis in coronary artery with the radius of 1.49mm.

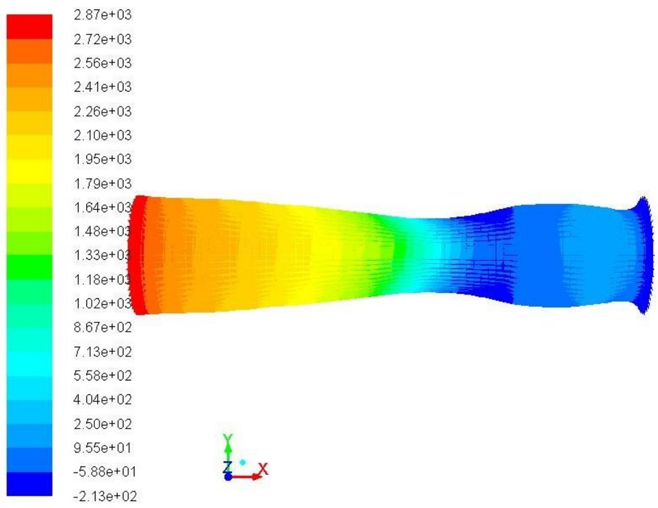

Figure 4.3.1: Pressure contours in stenosed artery (in Pascal)

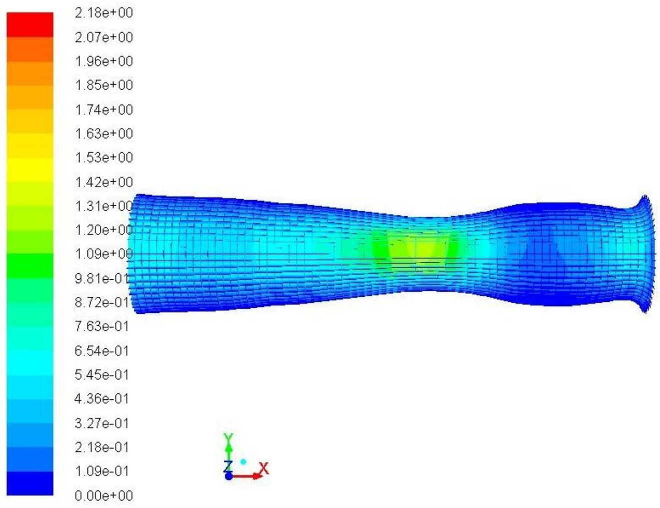

Figure 4.3.2: Velocity contours in stenosed artery (in m/s)

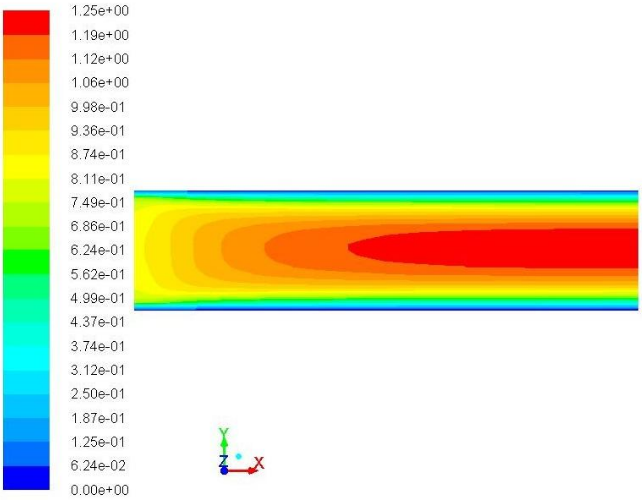

Figure 4.3.3: Velocity contours in unstenosed artery (in m/s)

We can see how pressure is being changed in stenosed artery in Figure 4.3.1 and velocity contours are also shown in Figure 4.3.2. Using same total inlet gauge pressure of stenosed artery, we get the velocity contours for unstenosed artery as shown in Figure 4.3.3. So the maximum velocity from the contours is 1.25 m/s for patient-B. We will calculate mean velocity, volumetric blood flow rate and FFR by following procedure.

$$\frac{Vmax}{Vmean} = \frac{3n+1}{n+1}$$

$$\frac{\mathbf{1.25}}{\mathbf{Vmean}} = \frac{\mathbf{3(0.61)+1}}{\mathbf{0.61+1}}$$

$$V_{mean} = 0.714 \text{ m/s}$$

Volumetric blood flow rate in unstenosed artery (Qunstenosed) = Area × Vmean

$$= \pi(0.149\text{cm})^2 \times (71.4\text{cm/s}) \times (60 \text{ s/min})$$

$$= 290 \text{ ml/min}$$

Volumetric blood flow rate in stenosed artery (Qstenosed) = 250 ml/min

$$\text{Fractional Flow Reserve (FFR)} = \frac{\text{blood flow rate in stenosed artery}}{\text{blood flow rate in unstenosed artery}}$$

$$= \frac{250}{290}$$

Calculated FFR (noninvasive) = 0.86

Measured FFR (invasive) = 0.93

4.4 Patient D

This is the case of a patient with 30% stenosis in coronary artery with the radius of 1.75mm.

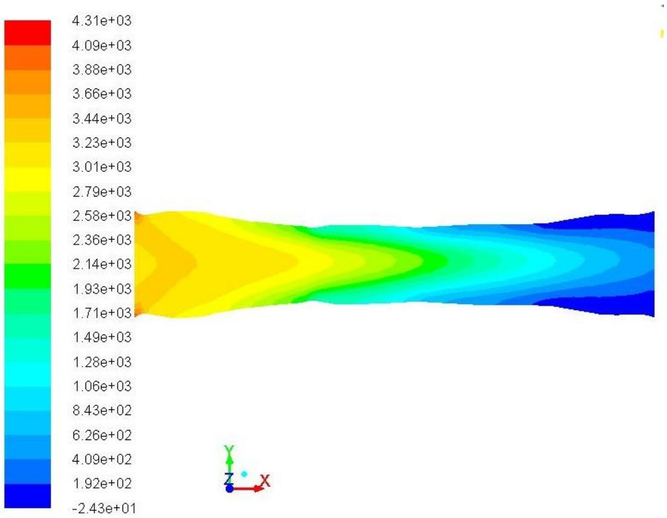

Figure 4.4.1: Pressure contours in stenosed artery (in Pascal)

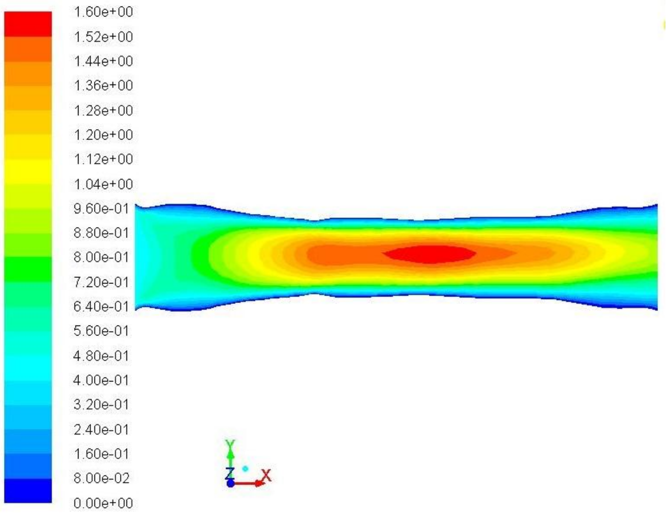

Figure 4.4.2: Velocity contours in stenosed artery (in m/s)

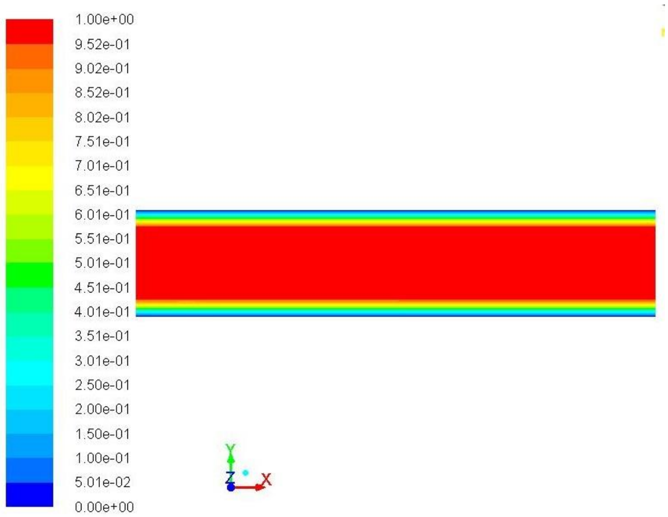

Figure 4.4.3: Velocity contours in unstenosed artery (in m/s)

We can see how pressure is being changed in stenosed artery in Figure 4.4.1 and velocity contours are also shown in Figure 4.4.2. Using same total inlet gauge pressure of stenosed artery, we get the velocity contours for unstenosed artery as shown in Figure 4.4.3. So the maximum velocity from the contours is 1.00 m/s for patient-B. We will calculate mean velocity, volumetric blood flow rate and FFR by following procedure.

$$\frac{Vmax}{Vmean} = \frac{3n+1}{n+1}$$

$$\frac{1.00}{\text{Vmean}} = \frac{3(0.61)+1}{0.61+1}$$

$$V_{mean} = 0.56 \text{ m/s}$$

Volumetric blood flow rate in unstenosed artery (Qunstenosed) = Area × Vmean

$$= \pi(0.175\text{cm})^2 \times (56\text{cm/s}) \times (60 \text{ s/min})$$

$$= 323 \text{ ml/min}$$

Volumetric blood flow rate in stenosed artery (Qstenosed) = 250 ml/min

$$\text{Fractional Flow Reserve (FFR)} = \frac{\text{blood flow rate in stenosed artery}}{\text{blood flow rate in unstenosed artery}}$$

$$= \frac{\mathbf{250}}{\mathbf{323}}$$

Calculated FFR (noninvasive) = 0.78

Measured FFR (invasive) = 0.88

4.5 Patient E

This is the case of a patient with 19% stenosis in coronary artery with the radius of 1.69mm.

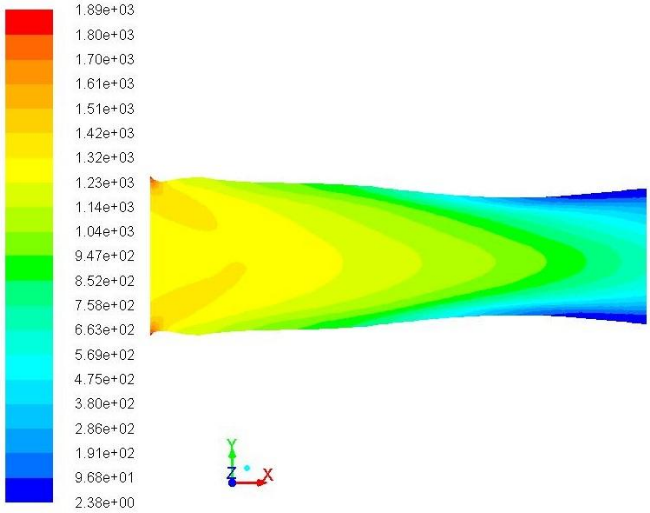

Figure 4.5.2: Pressure contours in stenosed artery (in Pascal)

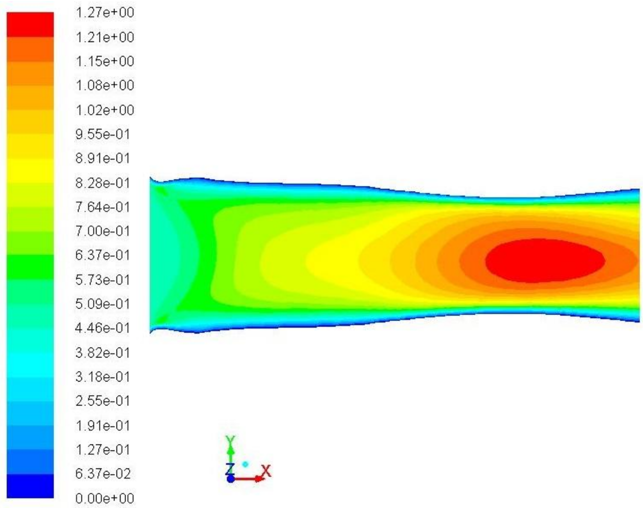

Figure 4.5.2: Velocity contours in stenosed artery (in m/s)

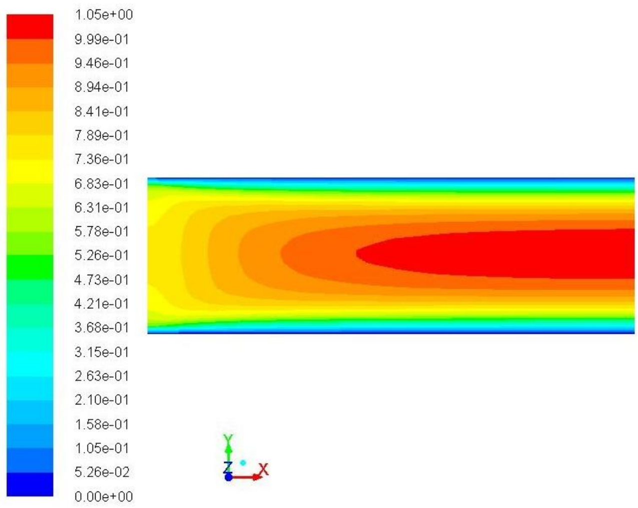

Figure 4.5.3: Velocity contours in unstenosed artery (in m/s)

We can see how pressure is being changed in stenosed artery in Figure 4.5.1 and velocity contours are also shown in Figure 4.5.2. Using same total inlet gauge pressure of stenosed artery, we get the velocity contours for unstenosed artery as shown in Figure 4.5.3. So the maximum velocity from the contours is 1.05 m/s for patient-B. We will calculate mean velocity, volumetric blood flow rate and FFR by following procedure.

$$\frac{Vmax}{Vmean} = \frac{3n+1}{n+1}$$

$$\frac{1.05}{\text{Vmean}} = \frac{3(0.61)+1}{0.61+1}$$

$$V_{mean} = 0.59 \text{ m/s}$$

Volumetric blood flow rate in unstenosed artery (Qunstenosed) = Area × Vmean

$$= \pi(0.169\text{cm})^2 \times (59\text{cm/s}) \times (60 \text{ s/min})$$

$$= 317.6 \text{ ml/min}$$

Volumetric blood flow rate in stenosed artery (Qstenosed) = 250 ml/min

$$\text{Fractional Flow Reserve (FFR)} = \frac{\text{blood flow rate in stenosed artery}}{\text{blood flow rate in unstenosed artery}}$$

$$= \frac{250}{317.6}$$

Calculated FFR (noninvasive) = 0.79

Measured FFR (invasive) = 0.84

4.6 Patient F

This is the case of a patient with 30% stenosis in coronary artery with the radius of 1.55mm.

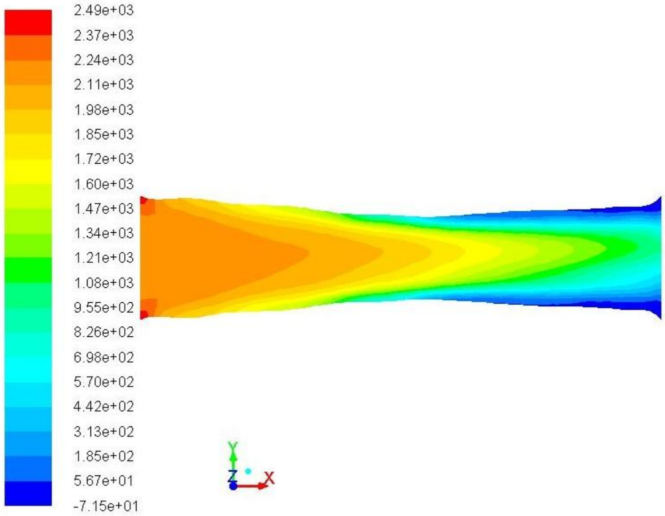

Figure 4.6.1: Pressure contours in stenosed artery (in Pascal)

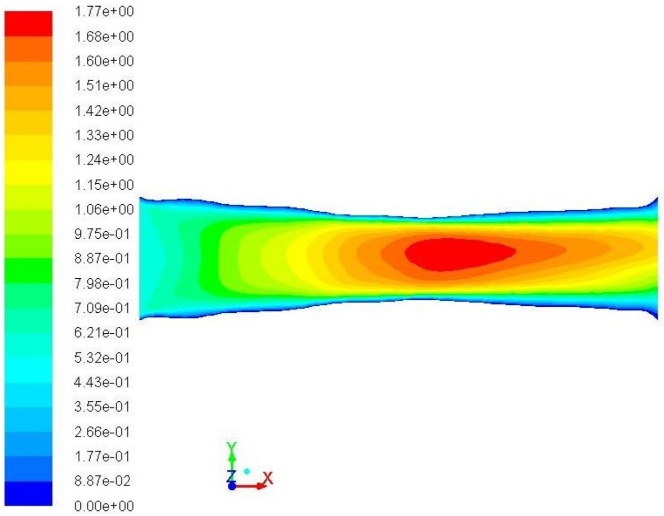

Figure 4.6.2: Velocity contours in stenosed artery (in m/s)

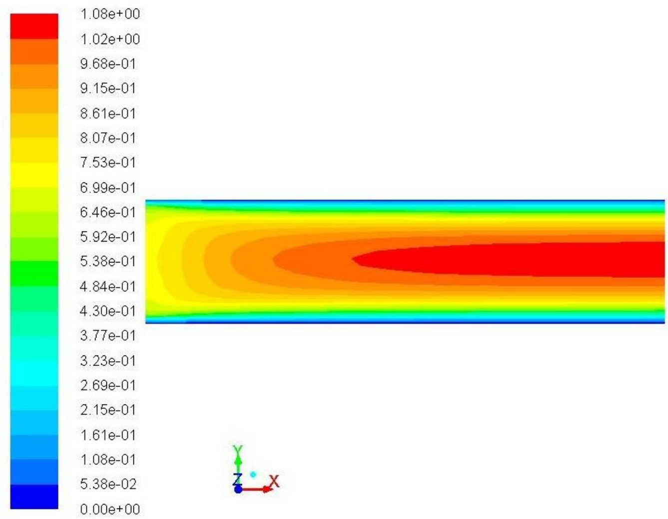

Figure 4.6.3: Velocity contours in unstenosed artery (in m/s)

We can see how pressure is being changed in stenosed artery in Figure 4.6.1 and velocity contours are also shown in Figure 4.6.2. Using same total inlet gauge pressure of stenosed artery, we get the velocity contours for unstenosed artery as shown in Figure 4.6.3. So the maximum velocity from the contours is 1.08 m/s for patient-B. We will calculate mean velocity, volumetric blood flow rate and FFR by following procedure.

$$\frac{Vmax}{Vmean} = \frac{3n+1}{n+1}$$

$$\frac{1.08}{\text{Vmean}} = \frac{3(0.61)+1}{0.61+1}$$

V_{mean} =0.617 m/s

Volumetric blood flow rate in unstenosed artery (Qunstenosed) = Area × Vmean

$= \pi(0.155\text{cm})^2 \times (61.7\text{cm/s}) \times (60 \text{ s/min})$

= 280 ml/min

Volumetric blood flow rate in stenosed artery (Qstenosed) = 250 ml/min

$$\text{Fractional Flow Reserve (FFR)} = \frac{\text{blood flow rate in stenosed artery}}{\text{blood flow rate in unstenosed artery}}$$

$$= \frac{250}{280}$$

Calculated FFR (noninvasive) = 0.90

Measured FFR (invasive) = 0.95

4.7 Patient G

This is the case of a patient with 34% stenosis in coronary artery with the radius of 2.09mm.

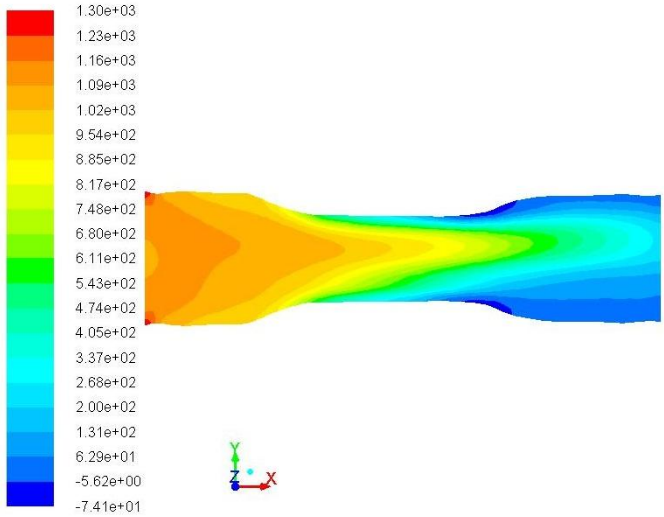

Figure 4.7.1: Pressure contours in stenosed artery (in Pascal)

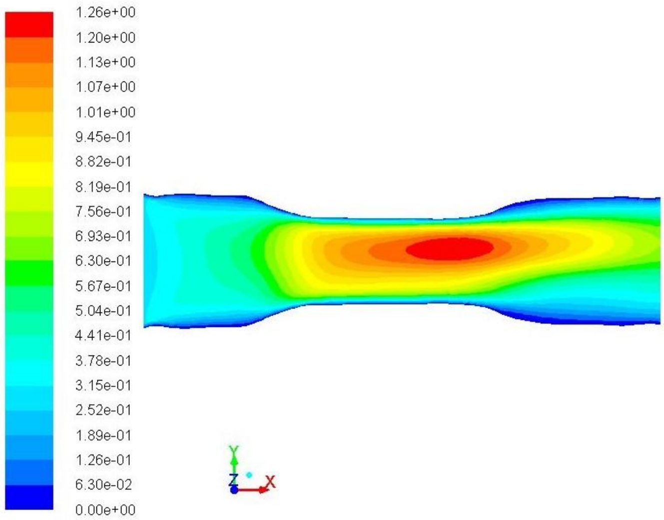

Figure 4.7.2: Velocity contours in stenosed artery (in m/s)

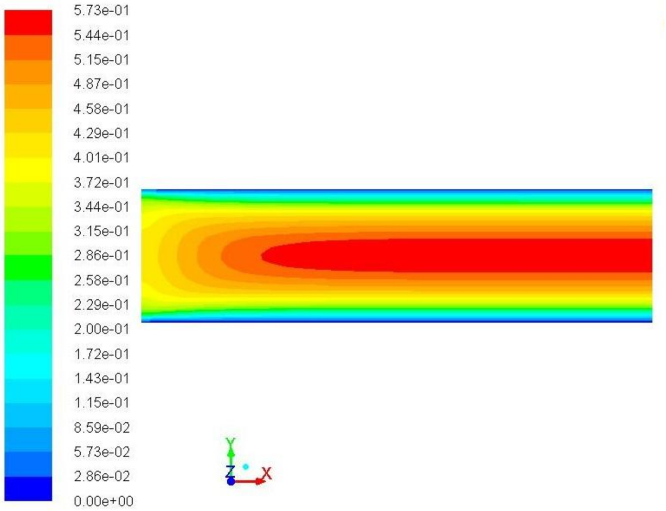

Figure 4.7.3: Velocity contours in unstenosed artery (in m/s)

We can see how pressure is being changed in stenosed artery in Figure 4.7.1 and velocity contours are also shown in Figure 4.7.2. Using same total inlet gauge pressure of stenosed artery, we get the velocity contours for unstenosed artery as shown in Figure 4.7.3. So the maximum velocity from the contours is 0.573 m/s for patient-B. We will calculate mean velocity, volumetric blood flow rate and FFR by following procedure.

$$\frac{Vmax}{Vmean} = \frac{3n+1}{n+1}$$

$$\frac{0.573}{\text{Vmean}} = \frac{3(0.61)+1}{0.61+1}$$

$$V_{mean} = 0.327 \text{ m/s}$$

Volumetric blood flow rate in unstenosed artery (Qunstenosed) = Area × Vmean

$= \pi(0.209\text{cm})^2 \times (32.7\text{cm/s}) \times (60 \text{ s/min})$

$= 269$ ml/min

Volumetric blood flow rate in stenosed artery (Qstenosed) = 250 ml/min

$$\text{Fractional Flow Reserve (FFR)} = \frac{\text{blood flow rate in stenosed artery}}{\text{blood flow rate in unstenosed artery}}$$

$$= \frac{250}{269}$$

Calculated FFR (noninvasive) = 0.92

Measured FFR (invasive) = 0.95

4.8 Patient H

This is the case of a patient with 44% stenosis in coronary artery with the radius of 1.52mm.

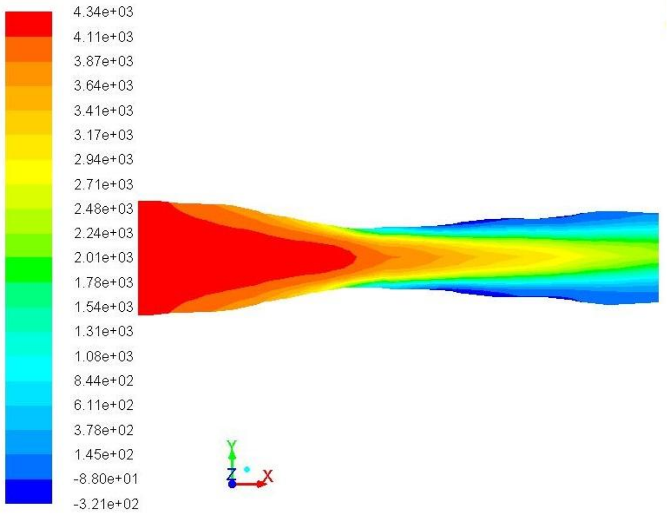

Figure 4.8.1: Pressure contours in stenosed artery (in Pascal)

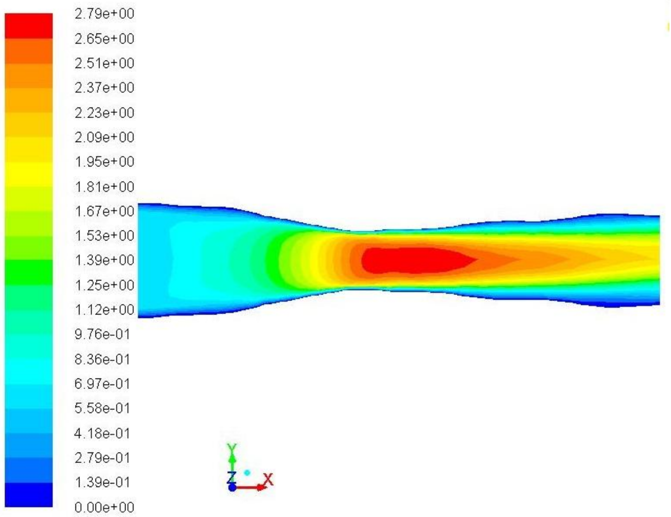

Figure 4.8.2: Velocity contours in stenosed artery (in m/s)

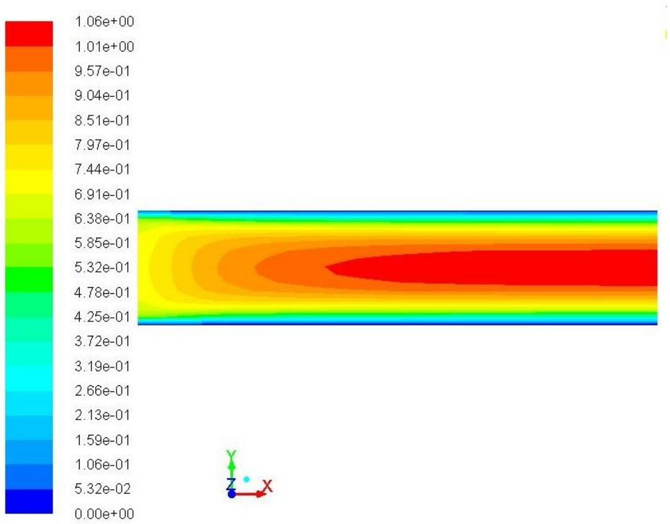

Figure 4.8.3: Velocity contours in unstenosed artery (in m/s)

We can see how pressure is being changed in stenosed artery in Figure 4.8.1 and velocity contours are also shown in Figure 4.8.2. Using same total inlet gauge pressure of stenosed artery, we get the velocity contours for unstenosed artery as shown in Figure 4.8.3. So the maximum velocity from the contours is 1.06 m/s for patient-B. We will calculate mean velocity, volumetric blood flow rate and FFR by following procedure.

$$\frac{Vmax}{Vmean} = \frac{3n+1}{n+1}$$

$$\frac{1.06}{\text{Vmean}} = \frac{3(0.61)+1}{0.61+1}$$

$$V_{mean} = 0.605 \text{ m/s}$$

Volumetric blood flow rate in unstenosed artery (Qunstenosed) = Area × Vmean

$$= \pi(0.152\text{cm})^2 \times (60.5\text{cm/s}) \times (60 \text{ s/min})$$

$$= 263 \text{ ml/min}$$

Volumetric blood flow rate in stenosed artery (Qstenosed) = 250 ml/min

$$\text{Fractional Flow Reserve (FFR)} = \frac{\text{blood flow rate in stenosed artery}}{\text{blood flow rate in unstenosed artery}}$$

$$= \frac{250}{263}$$

Calculated FFR (noninvasive) = 0.95

Measured FFR (invasive) = 0.98

4.9 Patient I

This is the case of a patient with 30% stenosis in coronary artery with the radius of 1.38mm.

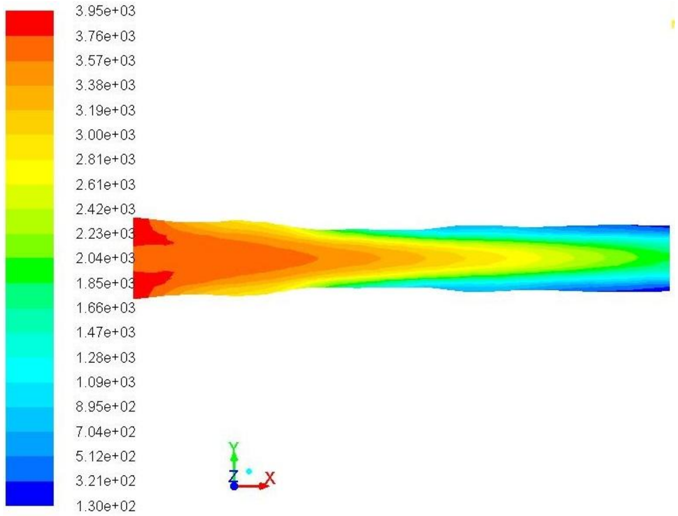

Figure 4.9.1: Pressure contours in stenosed artery (in Pascal)

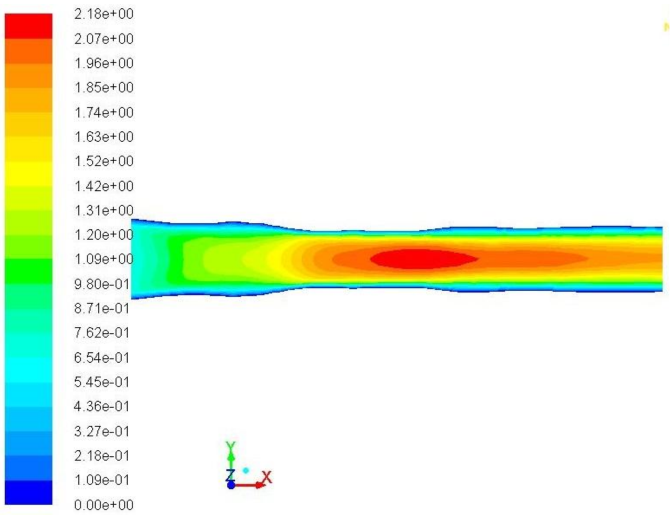

Figure 4.9.2: Velocity contours in stenosed artery (in m/s)

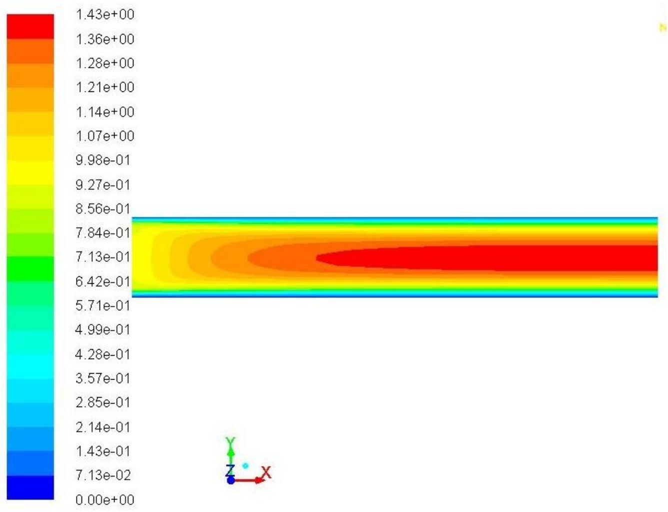

Figure 4.9.3: Velocity contours in unstenosed artery (in m/s)

We can see how pressure is being changed in stenosed artery in Figure 4.9.1 and velocity contours are also shown in Figure 4.9.2. Using same total inlet gauge pressure of stenosed artery, we get the velocity contours for unstenosed artery as shown in Figure 4.9.3. So the maximum velocity from the contours is 1.43 m/s for patient-B. We will calculate mean velocity, volumetric blood flow rate and FFR by following procedure.

$$\frac{Vmax}{Vmean} = \frac{3n+1}{n+1}$$

$$\frac{1.43}{\text{Vmean}} = \frac{3(0.61)+1}{0.61+1}$$

$$V_{mean} = 0.81 \text{ m/s}$$

Volumetric blood flow rate in unstenosed artery (Qunstenosed) = Area × Vmean

$$= \pi(0.138\text{cm})^2 \times (81\text{cm/s}) \times (60 \text{ s/min})$$

$$= 290 \text{ ml/min}$$

Volumetric blood flow rate in stenosed artery (Qstenosed) = 250 ml/min

$$\text{Fractional Flow Reserve (FFR)} = \frac{\text{blood flow rate in stenosed artery}}{\text{blood flow rate in unstenosed artery}}$$

$$= \frac{250}{290}$$

Calculated FFR (noninvasive) = 0.86

Measured FFR (invasive) = 0.91

4.10 Overview

FFR values have been calculated for all the 9 patients and they are reported in Table 4.1 which gives an overview of variation of FFR measured and calculated values with % blockage.

Table 4.1: Relation between % blockage and FFR

Patient ID	**% blockage (CTCA)**	**FFR measured**	**FFR calculated**
A	50	0.84	0.81
B	44	0.91	0.88
C	32	0.93	0.86
D	30	0.88	0.82
E	19	0.84	0.79
F	30	0.95	0.90
G	34	0.95	0.92
H	44	0.98	0.95
I	30	0.91	0.86

The comparison of FFR calculated and FFR measured is show in Figure 4.10, and the root mean square error of model predictions from data is 0.046 which is significantly less.

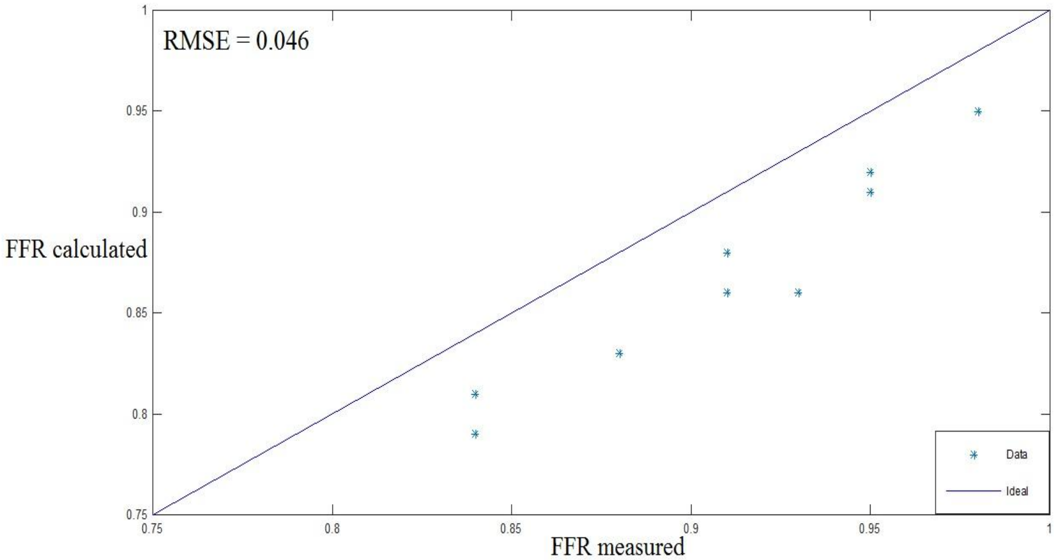

Figure 4.10: FFR calculated vs FFR measured

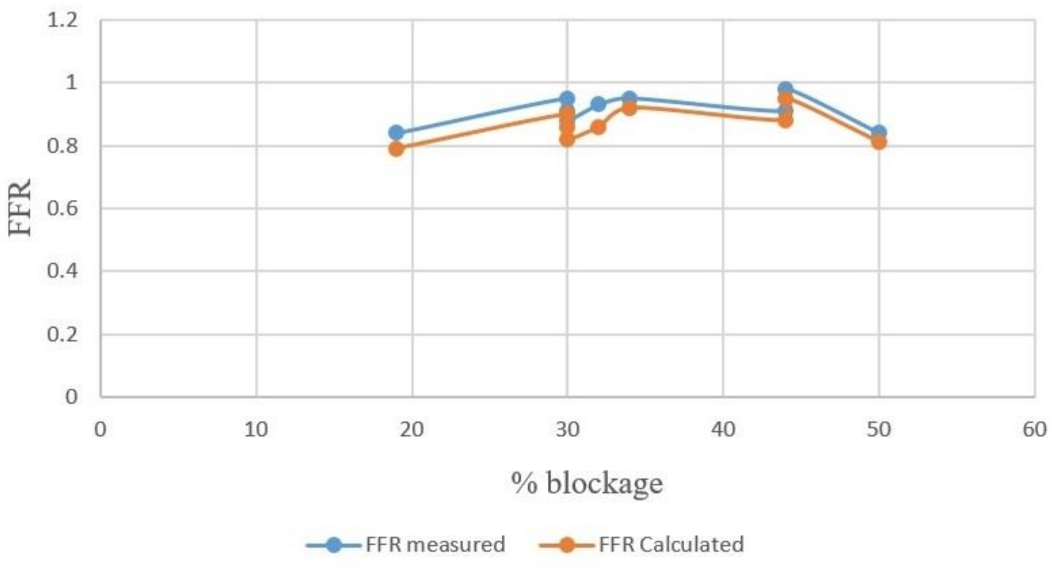

Figure 4.11: FFR vs % blockage (CTCA)

It is believed that percentage blockage from CTCA is the major factor which decides the value of FFR, but in reality it is not. The above graph in Figure 4.11 shows how FFR values are changing with the amount of blockage or stenosis in coronary artery. It is following an irregular pattern which shows that there are several factors that influence the FFR.

Chapter 5

Conclusions and Future study

We developed the workflow for calculation of FFR which is noninvasive that means no insertion of pressure guide wire through a catheter is required. CFD studies in calculating FFR has given the results that are almost in line with the measured FFR values with an RMSE value of 0.046. We can conclude from our study that Percentage stenosis is not the only major factor which influences FFR value, but there are factors like location of stenosis and size of the coronary artery that also have to be taken into consideration. One of the important limitations for this study is that all the case are FFR negative, and this needs to be corrected by obtaining the data from more patients.

The accuracy for this model can be improvised by taking few factors in to account, so that calculation of FFR using CFD model can be suggested as diagnostic tool for measuring FFR. The assumption i.e. coronary flow of 250 ml/min is taken for all patients needs to be made patient specific by measuring the actual coronary flow, and using that value to calculate the inlet velocity. The curvature of coronary artery has been neglected and the walls of artery are assumed to be rigid, this is not valid in real situations as walls are flexible. Non Newtonian power law model which has been used for these simulations has power law index of 0.61, which needs to be corrected for each patient by collecting the blood samples and measuring the properties of blood using rheometer.

References

[1] R. Lozano, M. Naghavi, K. Foreman, S. Lim, K. Shibuya, V. Aboyans, J. Abraham, T. Adair, R. Aggarwal, S.Y. Ahn, and others , 2013. Global and regional mortality from 235 causes of death for 20 age groups in 1990 and 2010: a systematic analysis for the global burden of disease study 2010. The Lancet, 380(9859):2095-2128.

[2] D. Prabhakaran, P. Jeemon, and A. Roy, 2016. Cardiovascular diseases in india current epidemiology and future directions. Circulation, 133(16):1605-1620.

[3] C.A. Taylor, T.A. Fonte, and J.K. Min, 2013. Computational fluid dynamics applied to cardiac computed tomography for noninvasive quantification of fractional flow reserve: scientific basis. J AM COLL CARDIOL, 61(22):2233-2241.

[4] I. Danad, L. Baskaran, and J.K. Min, 2015. Noninvasive fractional flow reserve derived from coronary computed tomography angiography for the diagnosis of lesion-specific ischemia. Interventional Cardiology Clinics, 4(4):481-489.

[5] P.R. Moreno and J. Narula, 2014. Thinking outside the lumen: fractional flow reserve versus intravascular imaging for major adverse cardiac event prediction. J AM COLL CARDIOL, 63(12):1141-1144.

[6] D.R. Lynch and W.F. Fearon, 2015. Landmark fractional flow reserve trials. Interventional Cardiology Clinics, 4(4):435-441.

[7] B.L. Norgaard, J. Leipsic, S. Gaur, S. Seneviratne, B.S. Ko, H. Ito, J.M. Jensen, L. Mauri, B. De Bruyne, H. Bezerra, and others , 2014. Diagnostic performance of noninvasive fractional flow reserve derived from coronary computed tomography angiography in suspected coronary artery disease: the nxt trial (analysis of coronary blood flow using CT angiography: Next steps). J AM COLL CARDIOL, 63(12):1145-1155.

[8] H. Gharahi, A.Z. Byron, Z.C. David, D.J. Kevin, and S. Beak.2015, Computational fluid dynamic simulation of human carotid artery bifurcation based on anatomy and blood flow velocity measured with MRI. International journal of Advances in Engineering Sciences and Applied Mathematics.

[9] P.D. Morris, van de Vosse F.N. , P.V. Lawford, D.R. Hose, and J.P. Gunn, 2015. Virtual (computed) fractional flow reserve: current challenges and limitations. JACC: Cardiovascular Interventions, 8(8):1009-1017.

[10] J. Zhang, L. Zhong, T. Luo, Y. Huo, S.Y. Tan, A.S.L. Wong, B. Su, M. Wan, X. Zhao, G.S. Kassab, and others, 2014. Numerical simulation and clinical implications of stenosis in coronary blood flow BioMed research international, 2014(514729).
[11] A.K. Baghel, Naik S., A. Rajagopal, and M. Anand. 2014, Simulation of blood flow in the stenosed left coronary artery. In International Conference on Computational Systems in Engineering and Technology, Chennai, INDIA, 2014.
[12] Y.I. Cho and K.R. Kensey, 1991. Effects of the non-newtonian viscosity of blood on flows in a diseased arterial vessel. Part 1: Steady flows. Biorheology, 28(3-4):241-262.