# IMPLICATIONS OF INTRAVASCULAR CATHETER IN A BLOOD VESSEL DURING MEDICAL TREATMENT USING COMPUTATIONAL FLUID DYNAMICS

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# IMPLICATIONS OF INTRAVASCULAR CATHETER IN A BLOOD VESSEL DURING MEDICAL TREATMENT USING COMPUTATIONAL FLUID DYNAMICS

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## DECLARATION

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

Signed …  ..... (CHONG SHIN YUN)

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## TABLE OF CONTENTS

## LIST OF TABLES

**Page**

## LIST OF FIGURES

**Page**

## LIST OF ABBREVIATIONS

| | |
|---|---|
| CFD | Computational Fluid Dynamics |
| CVC | Central Venous Catheter |
| DVT | Deep Vein Thrombosis |
| FEA | Finite Element Analysis |
| IV | Intravascular |
| JEPeM | Human Research Ethics Committee of USM (Jawatankuasa Etika Penyelidikan Manusia) |
| PIVC | Peripheral Intravenous Catheter |
| PLI | Platelet Lysis Index |
| SPC | Short Peripheral Catheter |
| SVT | Superficial Vein Thrombosis |
| USM | Universiti Sains Malaysia |
| VOF | Volume of Fluid |
| WSS | Wall Shear Stress |

**IMPLICATIONS OF INTRAVASCULAR CATHETER IN A BLOOD VESSEL DURING MEDICAL TREATMENT USING COMPUTATIONAL FLUID DYNAMICS**

## LIST OF APPENDICES

## ABSTRAK

Kateter intravaskular (IV) merupakan alat perubatan yang sering digunakan dalam rawatan intravena, iaitu pemberian ubat atau cairan ke dalam urat darah pesakit. Ia juga merupakan salah satu prosedur perubatan invasif yang paling kerap digunakan. Kateter IV sering menyebabkan banyak komplikasi yang relevan dan sering mengakibatkan ketidakselesaan pesakit. Kebanyakan penyelidikan semasa adalah berdasarkan eksperimen atau percubaan klinikal terkawal rawak yang melibatkan pesakit dan pengamal perubatan sebenar. Tujuan projek ini adalah untuk menyelidiki kesan perbezaan diameter kateter intravaskular dan halaju kemasukan larutan garam ke dalam urat darah melalui analisis Pengkomputeran Dinamik Bendalir dalam ANSYS Fluent. Simulasi juga telah disahkan dengan data eksperimen. Dari hasilnya, kateter 22G mempunyai tekanan maksimum paling stabil dan terendah di antara lima diameter, manakala kateter 18G dan 22G mempunyai halaju maksimum terendah secara keseluruhan. Nilai halaju larutan garam, 0.7 m/s, mempunyai penurunan halaju maksimum yang konsisten dengan masa berbanding dengan halaju lain, manakala nilai halaju kemasukan, 0.3 m/s, mempunyai tekanan maksimum yang lebih rendah dan konsisten. Secara keseluruhan, kateter 22G dengan nilai halaju kemasukan larutan garam, 0.3m/s, boleh dipilih untuk digunakan dalam rawatan intravena kerana ia membawa risiko yang lebih rendah terhadap urat darah pesakit.

# IMPLICATIONS OF INTRAVASCULAR CATHETER IN A BLOOD VESSEL DURING MEDICAL TREATMENT USING COMPUTATIONAL FLUID DYNAMICS

## ABSTRACT

Intravascular (IV) catheters are a frequently used medical device in intravenous treatment, which is the administration of medications or fluids into a patient's veins. It is also one of the most frequently used invasive medical procedures. IV catheters frequently cause numerous relevant complications, which often result in patient discomfort. Most of the current research is based on experiment or randomised controlled trials involving both real-life patients and medical practitioners. The purpose of this project is to investigate the impact of different diameters of intravascular catheters and saline solution input velocities on the blood vein through Computational Fluid Dynamics (CFD) in ANSYS Fluent. The simulation is also verified against experimental data. From the results, the 22G catheter has the most steady and lowest maximum pressure among the five diameters, whereas the 18G and 22G catheters have the lowest maximum velocity in general. The inlet saline velocity of 0.7 m/s have a consistent decrease in maximum velocities with time compared to other velocities, while the inlet saline velocity of 0.3 m/s has the consistent lower maximum pressures. Overall, the 22G catheter with inlet saline velocity of 0.3 m/s can be chosen to be used in intravenous therapy for patients as it has lower risks of affecting the blood vein of patients.

# CHAPTER 1

# INTRODUCTION

## 1.1 Project Background

Intravascular (IV) catheter is a commonly used medical device in intravenous therapy, which involves the delivery of drugs or fluids into the veins of a patient, also one of the most commonly invasive medical procedures used. Some common IV catheters include peripheral intravenous catheters (PIVC) and short peripheral catheter (SPC).

Current IV catheters have two main failures, insertion failure and failure after insertion. Insertion failures are largely influenced by the medical practitioner involved, while failure after insertions often leads to known complications like infiltration, where the infused fluid inadvertently escapes the vein lumen and/or is infused into the nearby tissues. Phlebitis can also occur when the vessel wall is damaged by the catheter, hence leading to fibrin deposition around it, and may lead to infection [1].

Despite their common use, intravascular catheters often have high rates of complications occurring, such as infiltration [2], thrombophlebitis [3], and air embolism [4]. IV catheters often caused a lot of relevant complications that often causes discomfort in patients [2], and most research are based on experimental or randomised controlled trials, which involves both real-life patients and medical practitioners, and this might cause a limit in sample size as well as causing a need to have a larger study involving more representative samples of population with various conditions [5]. Hence, computational studies started being initiated by various researchers, including simulation of saline injection via a peripheral intravenous catheter [6], catheter-vein interactions [7] and also application of CFD to investigate typical PIVC parameters [1].

## 1.2 Problem Statement

The insertion of an intravascular catheter is a widely used invasive medical procedure in drawing blood or infuse fluids through the blood vessels, but various complications including air embolism and thrombophlebitis often cause discomfort of patients and catheter failure. Methods such as randomized and non-randomized

controlled trials and systematic reviews are often used to study the relation of the factors involved in this procedure to the occurrence of complications. These methods come with possible issues such as the limit in sample size and the need to have a larger study involving more representative samples of population with various conditions. Computational methods thus provided a better way to simulate the situation inside the blood veins during the intravenous therapy. Therefore, this research proposes the effect of mixing to the blood vein, in relation to the diameter size of the catheter and the inlet velocity of saline solution, through computational fluid dynamics (CFD).

## 1.3 Objectives

The objectives of this study are:

1. To analyze the effects of diameter of intravascular catheter to the blood vein using Computational Fluid Dynamics (CFD).
2. To investigate the effects of inlet velocity of saline solution onto the blood vein.
3. To validate the ANSYS Fluent simulation with the experimental results.

## 1.4 Project Scope

The project is mainly simulation-based and analysis of data using Computational Fluid Dynamics through ANSYS Fluent. A model of the blood vein with an intravascular catheter of a certain diameter inserted at a certain angle is drawn. A computational fluid dynamics (CFD) simulation is conducted on the insertion of an intravascular catheter of a certain diameter which transfuses the saline solution into the blood vessel. The CFD simulation is repeated by using intravascular catheters of different diameters to see the effect they had onto the blood vein. Different inlet velocities of saline solution are also simulated to see its effects onto the blood vein.

A validation of the simulation with an experiment is conducted. A store-bought intravenous catheter is then inserted into a long tube at an angle. Then, fluid will be added to the tube, and the results of the experiment are compared with the simulation to prove the simulation results.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Overview

This chapter covers an overview of the effects of using intravascular catheters as well as the various research methods used to investigate the effects of intravascular catheters onto the blood vessel. The methods reviewed include randomized and non-randomized controlled trials, systematic reviews and computational methods.

## 2.2 Effects of Intravascular Catheters

Being the most common invasive hospital procedure performed worldwide, peripheral intravenous catheter insertion is associated with a variety of complications and high overall failure rate of 35% to 50%. According to a review done by Helm er al., in order to understand why IV catheters fail, it is beneficial to view peripheral IV catheter use and care as having three basic component parts: the technology used, such as the catheter, connector, and dressing; the caregiver technique used, which includes all aspects of insertion, use, and care; and the body's response to this technology and technique [8].

In Evans and Ratchford's study, it is noted that peripheral IVs may cause blood clots to form in the veins. Blood clots in the superficial veins are characterised as superficial vein thrombosis (SVT) or deep vein thrombosis (DVT). SVT may cause irritation or inflammation of the vein wall, which may result in the formation of tiny blood clots. DVT normally begins when a layer of clotted blood and blood proteins accumulates around the catheter, preventing blood from being pulled backwards out of the catheter due to the clot becoming a one-way valve. Both types of thrombosis can cause discomfort, swelling, or redness in the arm and hand. [9].

Another common complication of PIVCs is phlebitis, which is characterized by redness and warmth around the PIVC insertion site or along the path of the vein. Nagpal et al. stated that phlebitis can be classified as mechanical, chemical, or bacterial in origin. Mechanical phlebitis occurs when the PIVC gauge is bigger than the diameter of the vein lumen or when the PIVC is suddenly displaced. Chemical

phlebitis occurs when a medicine or intravenous fluid, such as antibiotics or potassium chloride, irritates the vein lumen. Bacterial phlebitis is caused by bacterial growth during PIVC insertion as a result of poor cleanliness or a lack of aseptic approach [10]. Suliman et al. discovered that parameters such as the location of admission, the nurses' experience, the insertion site, and the state of the PIVC were statistically significant predictors of the existence of PIVC phlebitis [11].

### 2.3 Randomized and Non-Randomized Controlled Trials

Research has been done on several measures that are used to check out the effectiveness in lowering the risks of complications of intravascular catheter. Most studies are done through randomised controlled trials or non-randomised controlled trials, which involves real-life patients and medical practitioners. Özkula et al. did a randomised trial on the effectiveness of tissue adhesives, which include 115 adult patients of over 65 years, causing the sample size to become small and some data were loss due to the patients that are transferred or discharged half way [12].

One study on the use of intravenous catheter based blood collection also includes 160 surgery patients with the results of study being determined through real blood collection by a nurse and also patients' preference scale, which causes the study to be limited by lack of distribution of practitioner skill level and unable to coordinate the patients' length of stay [13]. Another study was on a non-randomised controlled trial which aimed to establish and evaluate a three-point care bundle intervention method to prevent catheter failure. It was found that a promising approach for reducing the occurrence of catheter failure is through care protocols, including assessment of vein diameter, vein depth, and catheter tip position using ultrasound inspection to minimize mechanical discomfort [14].

A.Bahl et al. also did a randomized comparative study of 120 patients on the catheter survival between the standard IV catheters and the extended dwell catheters, which the extended type came up as the favourable one due to its improved survival rates, though specific complications are not accessed, such as phlebitis [15]. D.Weiss et al. proposed the use of a very short peripheral catheter, which is shorter than the

commercial type, just to minimise contact with opposite wall of vein, which can reduce the risk of catheter-risk thrombophlebitis [16].

## 2.4 Systematic Reviews

Ray-Barruel et al. identified the published studies in relation to intravenous catheter insertion or maintenance bundles. It is said that focusing on evidence-based bundles will be able to improve the guideline adherence for better care and improved patient outcomes. A standardisation will also be needed since all these bundles differed in components and outcome measurement, thus effects may not be generalisable outside the study setting [17].

Erdogan & Denat (2016) conducted a descriptive and cross-sectional study on the neurosurgical clinic on the development of phlebitis and infiltration in patients with peripheral intravenous catheters, as well as the factors that influence it. Phlebitis was found to be more common in patients with cranial diseases, when the catheter site was used frequently, when the catheter dwelt in the vein for 49-72 hours, and when the catheter was inserted by a nurse with a bachelor's degree, whereas infiltration was more common in patients aged 50-59 and in operating room catheterizations [18].

## 2.5 Computational Methods

There are also a number of related research based on computational methods. Piper et al. used computational fluid dynamics (CFD) to see which parameters are most relevant to catheter failure as well as provide biomechanical insights for the failure. The study simulated the infusion of saline solution into a vein while investigating the shear stress of the vein wall and blood damage, with changes to the infusion rate, tip position, angle and size. It was then suggested that the speed of infusion fluid is the main cause, though there are still limitations in the study as ideal geometries are used, and the catheter tip shape is not angled. The study also mentioned that experimental validation can be conducted using ultrasound to measure the flow within the vein while also infusing into a nearby PIVC. The ultrasound could then measure deformation of the vessel when the bolus injections are given, thus validating the downstream flow rates [1]. Figure 2.1 illustrates on the resulting velocity streamlines and wall shear

stress (WSS) due to the infusion of saline into the vein and the scenario without infusion.

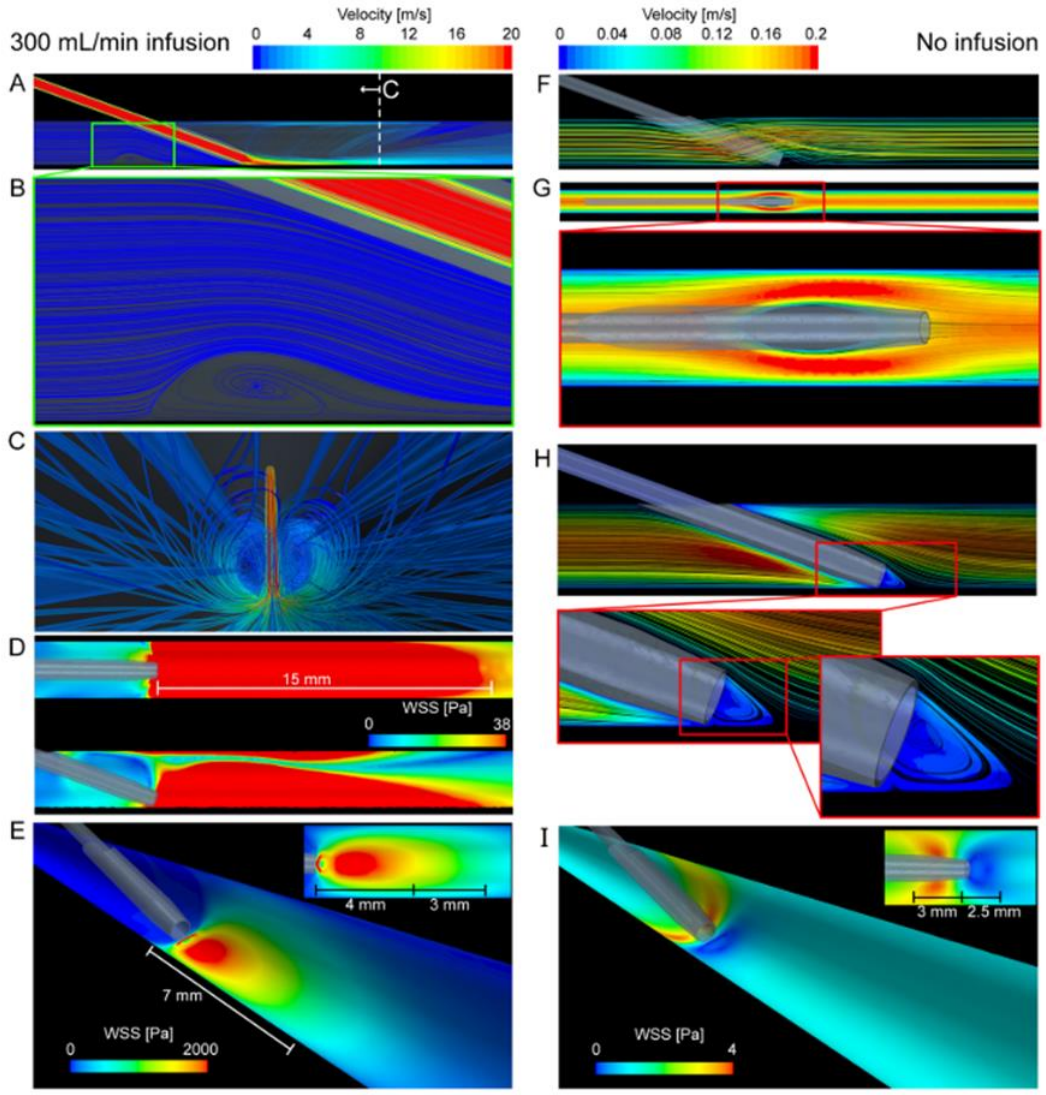



Figure 2.1: Resulting velocity streamlines and wall shear stress (WSS) due to the infusion of saline into the vein (left column) and the scenario without infusion (right column). [1]

Another similar study also focused on the biomechanical aspects of catheter-related thrombophlebitis, and it was indicated that the contact region between the catheter and the vein wall, as well as disturbed blood flow can increase the risk for development of the complication [3]. Cheng et al. presented on the modelling of needle forces during insertion into soft tissue, which was focused on the insertion velocities of needle inserting experiments before doing the simulation on the forces. Finite element simulation and viscous effects are used in the simulation, but it can be improved on the experiment part to try it on real animal tissue [19].

D. Weiss et al. carried out a finite element analysis (FEA) model of catheter-vein biomechanical interactions during the intravenous procedure, and focuses on the effect of various insertion techniques on the deformations of the vein wall [7]. Using ANSYS Fluent software, Ghata et al. studied the effect of a range of parameters that include vessel diameter, blood flow and injection rates on the wall shear stress (WSS), clearance of blood on the optical pathway, and wall pressure. The diameter of the blood vessel is then shown to have the largest influence on WSS and wall pressure changes, while changes in the rate of saline injection from the catheter tip had the second biggest effect on WSS and wall pressure changes [20].

Another computational study done by Haniel et al. was on determining the tendency for thrombus formation in several central venous catheters (CVC) models in relation to flow rate variation. Using a numerical method of platelet lysis index (PLI) equation, the study established that the higher the catheter's blood flow rate, the higher the risk of thrombus formation [21]. Ararsa and Aldredge examined the spreading effectiveness of numerous catheter-tip designs using CFD modelling and discovered that adding holes to the catheter wall near its tip could further boost fluid spreading and mixing in the blood vessel. In general, a catheter's spreading effectiveness is dictated by the injected fluid's flow rate and is greatest at high flow rates [22].

## 2.6 Study Contributions

Although the literature review presents the topics related to the studies of the effect of intravascular catheters in a variety of methods, this study focuses on investigating the effect of different diameters of intravascular catheters and inlet velocity of saline on the flow in the blood vein by using CFD. Studying these factors can aid in choosing the suitable catheter size and inlet saline velocity for smaller blood veins of 3 mm and below. An experimental study of the similar set-up is also conducted to validate the simulation results with experimental data, which is a step forward as compared to most computational studies.

# CHAPTER 3

# METHODOLOGY

## 3.1 Overview

This chapter explains on the methodology for this project. The project methodology includes determining the dimensions and properties of the fluids, IV catheters and blood vein; designing the IV catheter and blood vessel using ANSYS Design Modeler, meshing and setting up suitable boundary conditions for the simulation in ANSYS Fluent. An experimental validation is then conducted to validate the initial simulation results. The simulation is then repeated for four additional IV catheters with different diameters. The project is also extended to four other inlet velocities of saline solution.

## 3.2 Mathematical Model

### 3.2.1 Calculation of Inlet Velocity

The mean flow rate of cephalic vein is 69.5mL/min [23], which converts to 1158.33 $mm^3/s$. Assuming blood vessel is in perfect cylinder shape and of 3 mm diameter, the cross-sectional area of blood vessel is calculated as below:

$$\begin{aligned} A &= \pi r^2 \\ &= \pi(1.5)^2 \\ &= 7.0686\ mm^2. \end{aligned}$$

The equation below is then used to calculate the flow velocity,

$$Q = vA$$

in which $v$ = flow velocity,

$A$ = cross-sectional area,

The inlet velocity of the blood vessel is then calculated to be 0.16387m/s ≈ 0.16m/s. For 18 G catheter of 1.2mm diameter, the inlet flow velocity is set to be 0.5 m/s.

## 3.3 Computational Approach

The computational approach is shown in Figure 3.1. At the start, the model of the blood vessel and catheter is drawn using ANSYS Design Modular. The model is then meshed and the boundary conditions are set. A mesh independence study is conducted onto the model, before proceeding with a Computational Fluid Dynamics (CFD) analysis. The CFD simulation is then validated through experimental work. The effects of different diameters of intravascular catheters onto the blood vein are then analyzed through CFD. Lastly, the project proceeds with the investigation of the effects of different inlet velocities of saline solution to the blood vein.

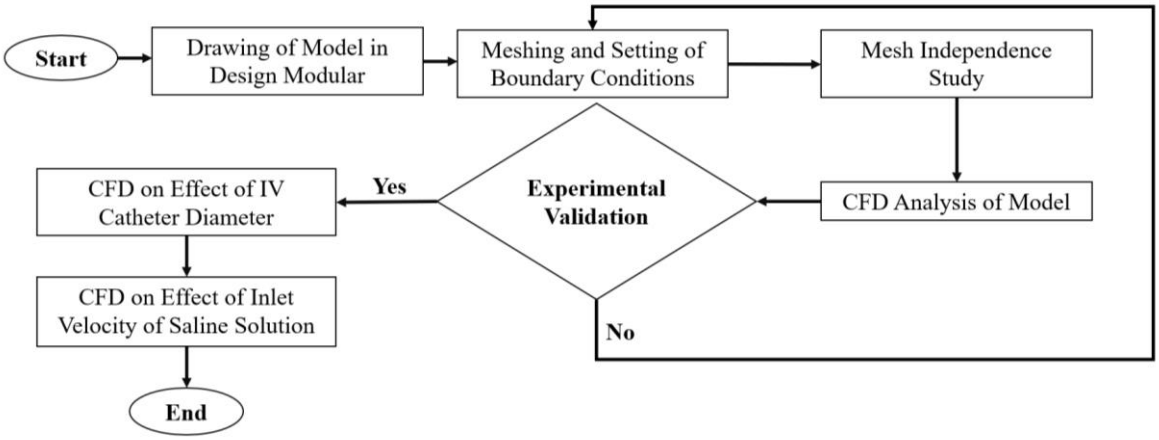



Figure 3.1: Computational approach

## 3.4 Model of Blood Vessel and Catheter

The table below shows the geometry of intravascular catheters chosen for the simulation. All intravascular catheters are assumed to be perfect cylindrical shapes. The external diameter and length of 18G IV catheter is adjusted according to the real needle size as in the experimental set-up.

Table 3.1: Dimensions of IV catheters of different gauge sizes [24]

| Gauge Size of IV Catheter | External Diameter (mm) | Length (mm) |
|---|---|---|
| **16G** | 1.8 | 38 |
| **18G** | 1.2 | 38 |
| **20G** | 1.1 | 38 |
| **22G** | 0.9 | 38 |
| **24G** | 0.7 | 38 |

The model is drawn using ANSYS Design Modular, with the Y-shape being the blood vessel, and the round tube being the catheter. The dimensions of the model (with 18G IV catheter) are shown as in Figure 3.2. The catheter is modelled at a distance of 40mm from the branching of blood vessel happens at an angle of 15º. The angle is chosen at 15º as most practitioners use an angle ranging from 15-30 degrees for a more natural insertion [15]. The catheter tip is also modelled at the middle of the blood vessel without touching the blood vessel walls.

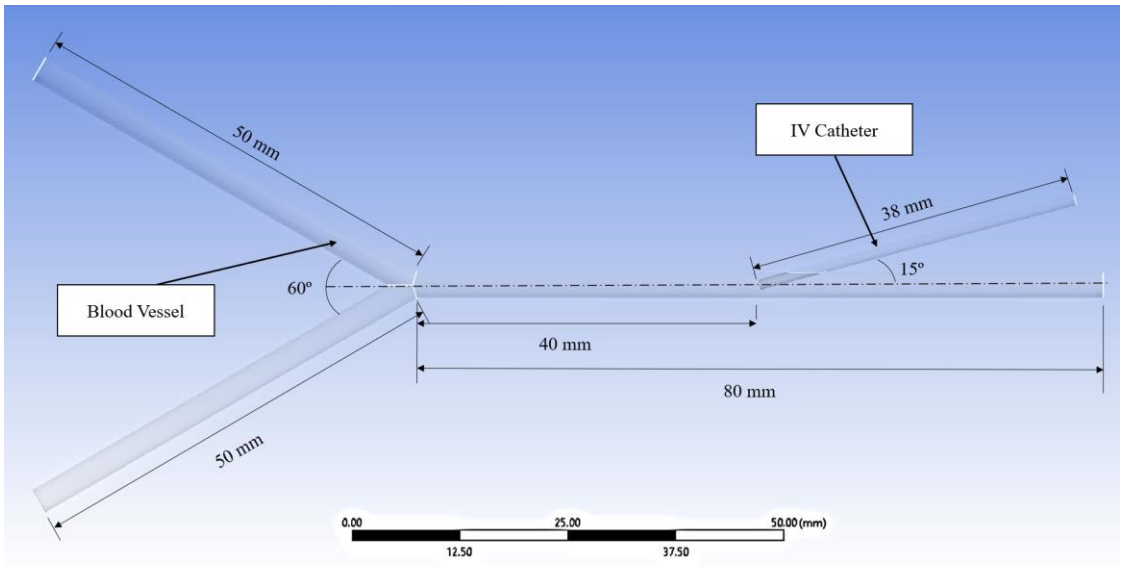



Figure 3.2: Model of Blood Vessel (Y-shape) with IV catheter

## 3.5 Computational Fluid Analysis of the Model

### 3.5.1 Volume of Fluid (VOF) and Viscous Model

The different phases in the ANSYS simulation includes air, blood and saline are shown in Table 3.2. The viscous model of laminar flow is chosen as the flow of blood is taken as a homogenous, Newtonian fluid, and vessels walls are assumed to be rigid.

Table 3.2: Multiphase set-up

| Type | Choice | Description |
|---|---|---|
| **Multiphase (Volume of Fluid)** | Number of Eulerian Phases: 3 | Air – Primary Phase<br>Blood – Secondary Phase<br>Saline – Secondary Phase |
| | Phase Interactions | Blood-air: 0.5345 N/m [25]<br>Saline-air: 0.065 N/m |

| | | |
|---|---|---|
| | - | Surface Tension Force Modelling |
| **Viscous Model** | Laminar | |

### 3.5.2 Fluid Properties

The Newtonian properties of blood and saline are employed in this study as shown in Table 3.3, and both are assumed to be an incompressible, homogeneous, Newtonian viscous fluid with constant density and viscosity throughout the simulation. The density and viscosity properties of air is then inputted using the values provided in ANSYS Fluent.

Table 3.3: Fluid properties of saline solution and blood

| **Fluid** | **Density (kg/m$^3$)** | **Viscosity (kg/m-s)** |
|---|---|---|
| **Saline Solution** | 1005 [6] | 0.00102 |
| **Blood** | 1060 [26] | 0.0035 [26] |
| **Air** | 1.225 | $1.7894 \times 10^{-5}$ |

### 3.5.3 Boundary Conditions

The boundary conditions of the blood are summarized in Table 3.4. There are five boundary conditions set, including the inlet, outlet and wall of blood, as well as the inlet and wall of saline. For the blood domain, the volume fraction of blood (vf-blood) is set as 1 and the volume fraction of saline (vf-saline) is set as 0, and vice versa for the saline domain. The setup is to simulate that the blood vessel is entirely filled with blood without any air or saline particles and the intravascular catheter is entirely filled with saline solution. The inlets of blood and saline are also set as velocity-inlets with the values stated.

Table 3.4: Boundary conditions of the ANSYS Fluent Set-Up

| **Domain** | **Boundary Conditions** | **Types** | **Values** |
|---|---|---|---|
| **Blood** | inlet_blood | Velocity-inlet | Velocity magnitude = 0.16m/s<br>Multiphase:<br>vf-blood = 1, vf-saline = 0 |
| | outlet_blood | Pressure-outlet | - |
| | wall-fluid_blood | Wall | - |

| | | | |
|---|---|---|---|
| **Saline** | inlet_saline | Velocity-inlet | Velocity magnitude = 0.1 m/s, 0.3 m/s, 0.5 m/s, 0.7 m/s and 1.0 m/s.<br>Multiphase:<br>vf-saline = 1, vf-blood = 0 |
| | wall-fluid_saline | Wall | - |

### 3.5.4 CFD Set-Up

The solution methods, controls and residual methods are chosen as stated in Table 3.5. The volume fraction of blood is patched at the constant value of 1 within the single fluid zone of fluid_blood using the Patch function. The same Patch function is used in saline phase as well, as the volume fraction of saline is patched at 1 within fluid_saline. The simulation is then ran in a time step size of 0.001s for up to 10000 iterations.

Table 3.5: Set-up for the simulation in ANSYS Fluent

| **Type** | **Choice** | **Description** |
|---|---|---|
| **Solution Methods** | Semi-Implicit Method for Pressure Linked Equations (SIMPLE) | Gradient: Least Squares Cell Based<br>Pressure: PREssure STaggering Option (PRESTO!)<br>Momentum: Second Order Upwind<br>Volume Fraction: Compressive<br>Transient Formulation: Second Order Implicit |
| **Solution Controls (Under-Relaxation Factors)** | Pressure: 0.01<br>Density: 0.1<br>Body Forces: 0.1<br>Momentum: 0.1<br>Volume Fraction: 0.1 | |
| **Residual Monitors** | Untick all Check Convergence | |
| **Initialization** | Standard Initialization | **Patch Function**<br>Phase: Blood<br>Variable: Volume Fraction<br>Value:1<br>Zones to Patch: fluid_blood<br><br>Phase: Saline |

| | |
|---|---|
| | Variable: Volume Fraction<br>Value:1<br>Zones to Patch: fluid_saline |
| **Run Calculation** | Time step size: 0.001s |

### 3.5.5 Meshing of Model

The model is then meshed by setting the edge sizing of the blood vessel model. It is done through adjusting the number of divisions on the edge of blood vessel and intravascular catheter according to the mesh chosen in mesh independency study. The full view and close-up view of mesh are as shown in Figure 3.3 and 3.4.

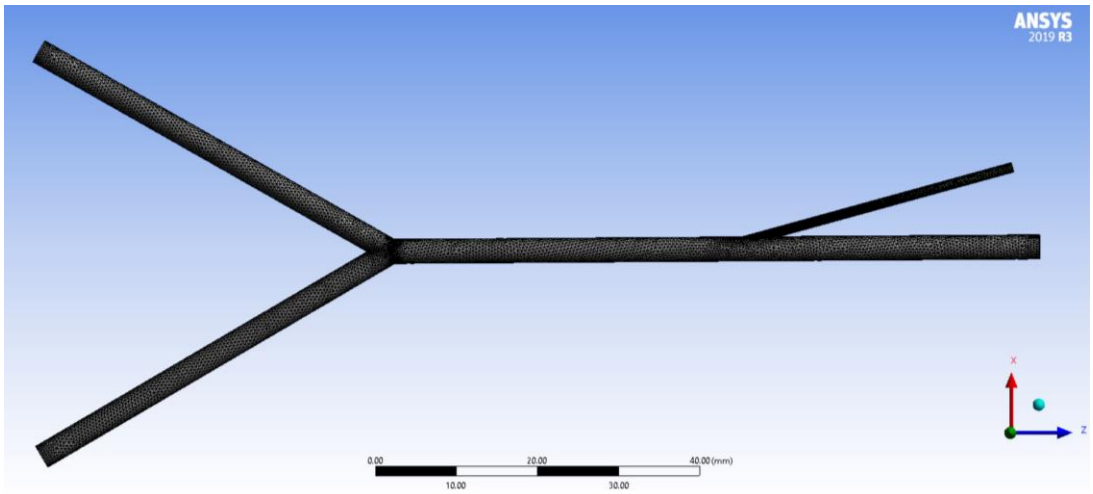



Figure 3.3: Full view of the meshing of model

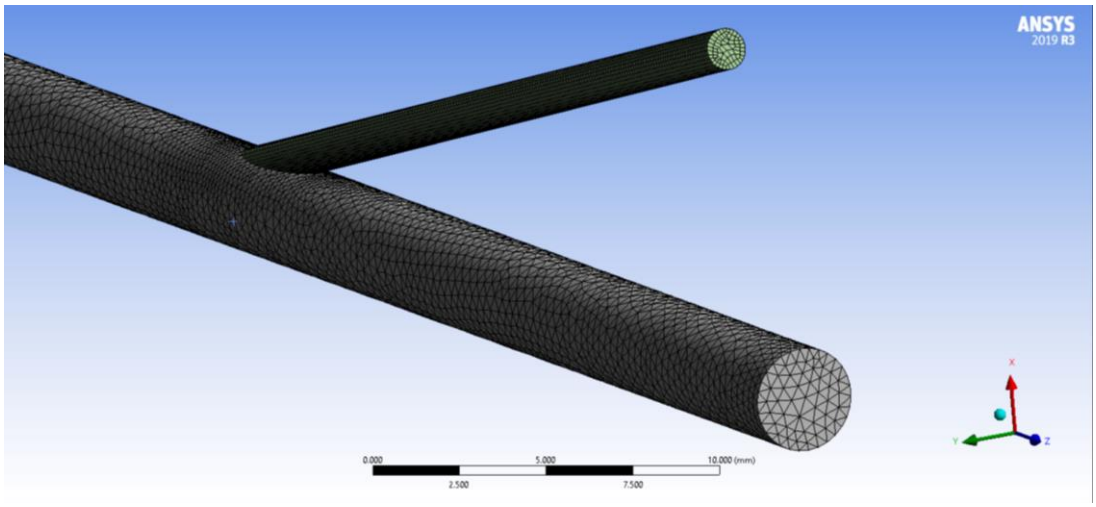



Figure 3.4: Close-up view of the meshing of inlet of blood vein and catheter

### 3.5.6 Mesh Independency Study

Mesh independency study is important to maintain the accuracy of a computational fluid dynamics (CFD) solution and to lower the related computational time. With reference in a study [27], a grid convergence study is done for five different meshes, with the number of nodes ranging from 125524 to 210380. The CFD solution is done to determine the maximum pressure and velocity of the model. This will help in determining how the mesh quality affects the CFD simulation results. The mesh size and the results are considered in choosing the right mesh for the model.

## 3.6 Experimental Validation

### 3.6.1 Experimental Set-Up

A capillary tube of the same inner diameter of 3 mm is used to be the model of the blood vessel. A Y-shaped connector of similar inner diameter of 3 mm is then used to connect the other two pipes as shown in Figure 3.5. The blood vessel model is then sticked onto a piece of cupboard laid with white paper using tape.

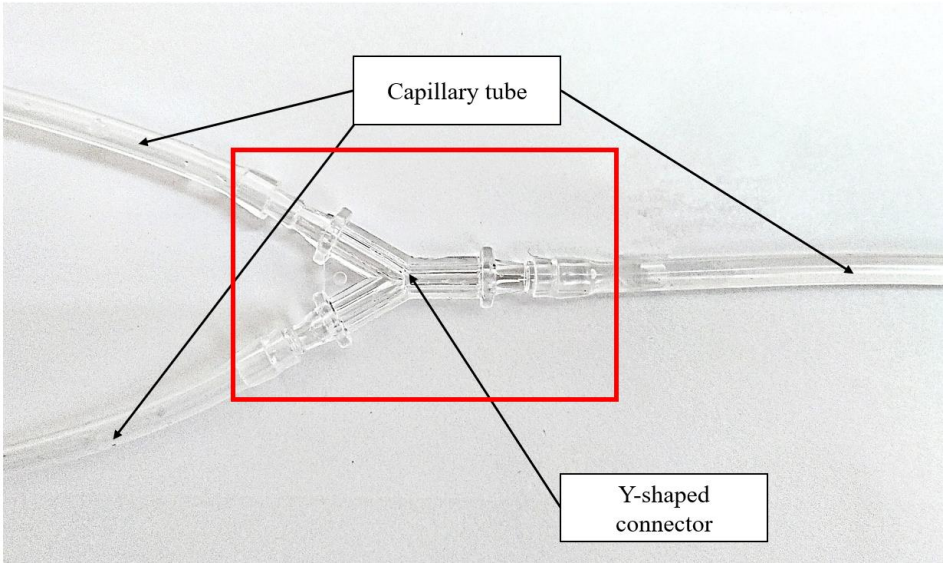



Figure 3.5: The connection of the capillary tubes with the Y-shaped connector (squared in red)

Then, two different types of fluid as shown in Figure 3.6 is injected, with the blood vessel model being filled with Fluid X, while the Terumo 18G syringe being filled with 0.9% saline solution. Fluid X is chosen as it has the same viscosity as blood, and approval by the Human Research Ethics Committee of USM (JEPeM) is needed

if human samples such as blood is involved in the research. Dye is added to the saline solution and Fluid X to enhance the contrast of the two fluids.


Figure 3.6: Fluid X (left) and saline solution (right) used in experimental set-up

The 18G syringe needle is then inserted into the blood vessel model at an angle of 15º at a distance of 40 mm from the middle area of the Y-shaped connector. The experiment is set up as in Figure 3.7, and the schematic diagram is shown in Figure 3.8, in which the ends of the blood vessel model are connected to a bottle.

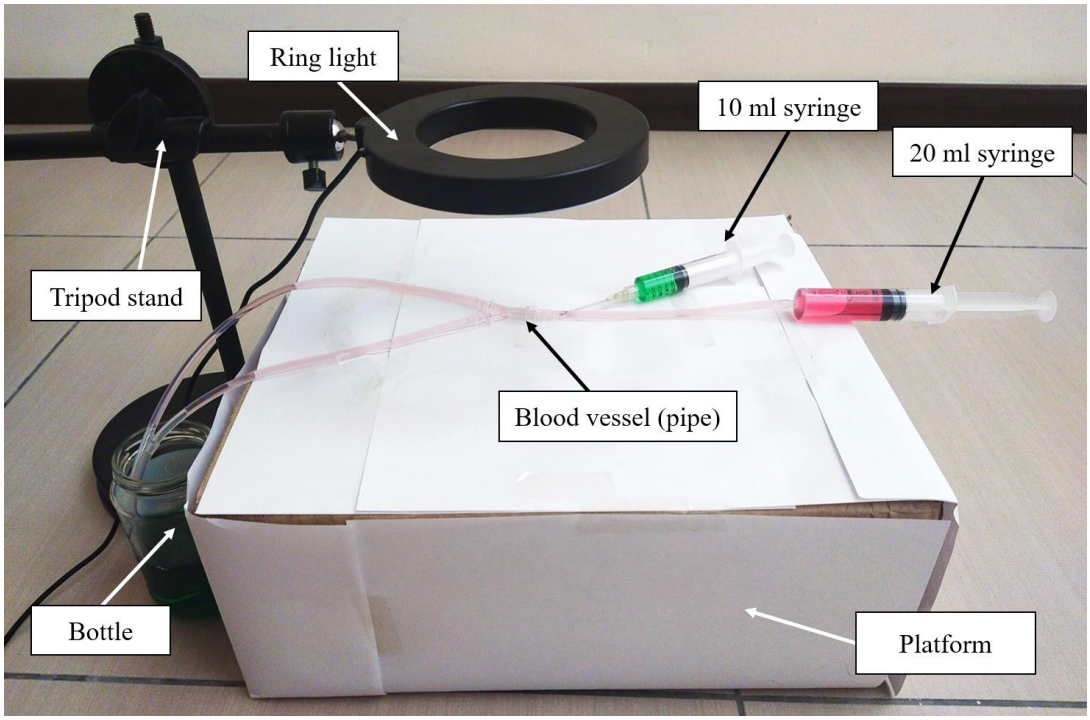



Figure 3.7: Front view of experimental set-up

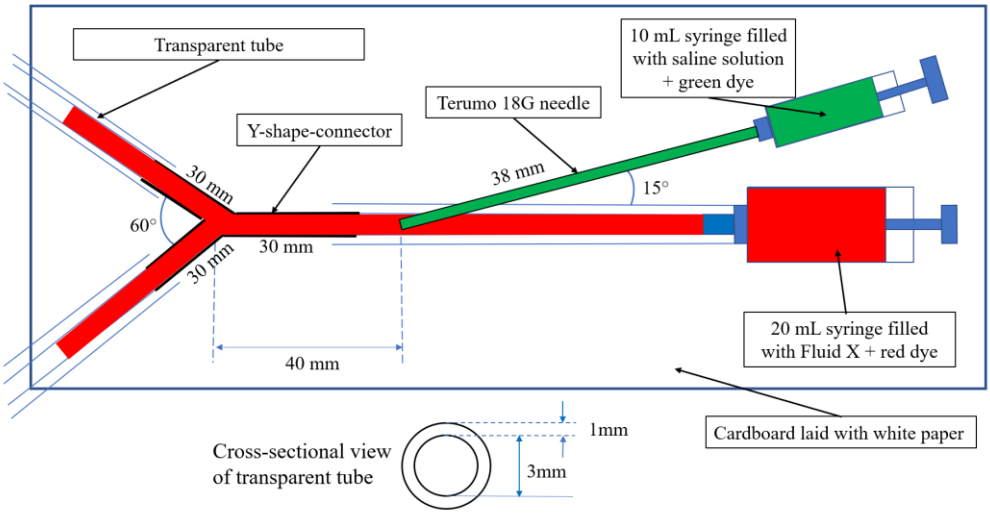



Figure 3.8: Schematic diagram of the experimental set-up

As this experiment is used to validate the simulation of 18G catheter with the inlet velocity of blood set as 0.16 m/s and inlet velocity of saline solution set as 0.5m/s, thus the injection flow rate for Fluid X is calculated to be 1.12 mL/s and injection flow rate of saline solution is 0.56 mL/s. The injection flow rate is done manually by person to ensure the constant flow rate of both the shampoo and saline solution. A camera is then placed in the position as in Figure 3.9 to record from the top view of the experiment set-up, particularly focusing on the Y-shaped connector and the injection site as shown in Figure 3.10. The ring light is switched on throughout the experiment to ensure the experiment can be seen clearly.

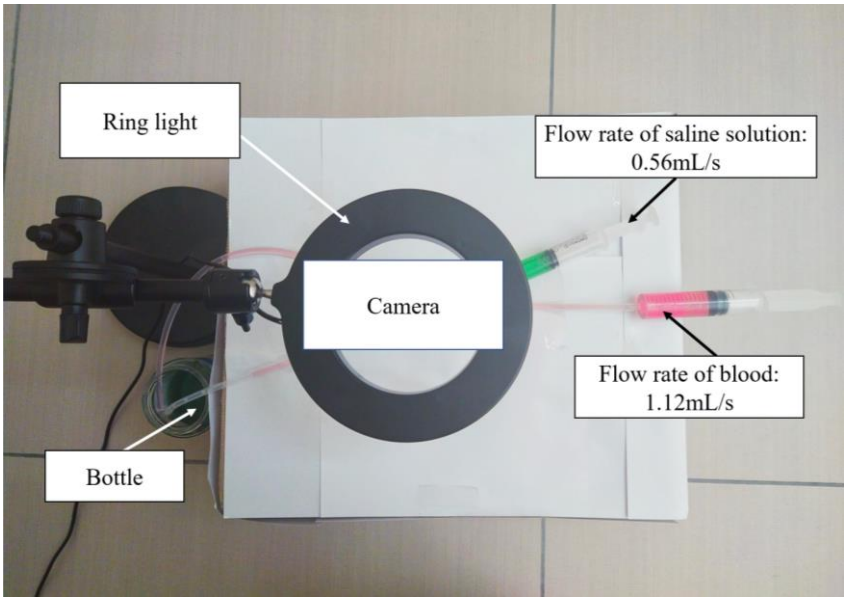



Figure 3.9: Top view of experimental set-up

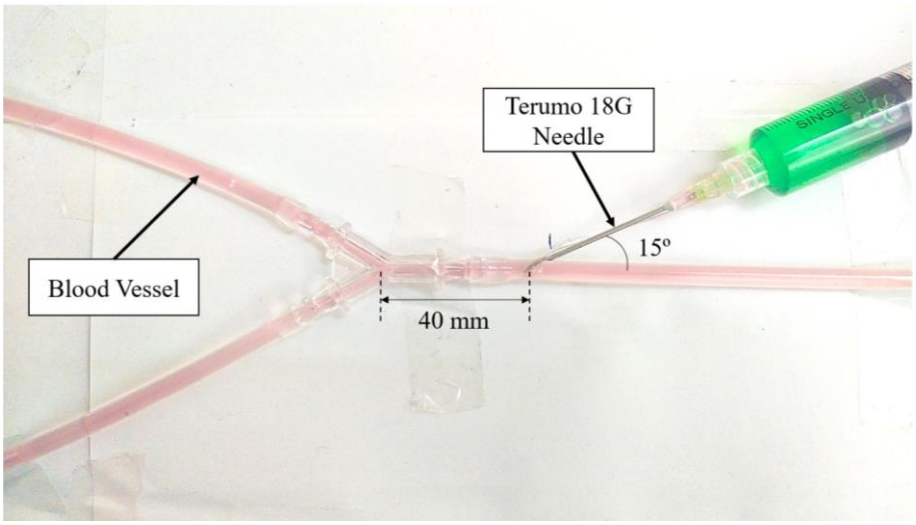



Figure 3.10: Close-up view of the experiment set-up

Figure 3.11 shows the post-processing procedure of the images extracted from the video, in which the image background is removed and the colour contrast and white highlights of the image is enhanced to ensure that the fluid flow can be seen even clearly. The percentage of blood, saline and saline mixture with blood are then compared for both experimental and simulation.

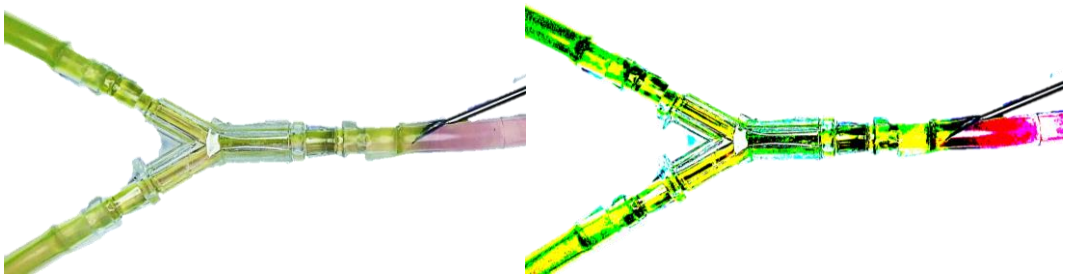


Figure 3.11: Processing of the photo taken during experimental validation (Left image: Removal of background, Right image: Increase of colour contrast and highlights to see the fluid flow)

# CHAPTER 4

# RESULTS AND DISCUSSION

## 4.1 Overview

The results for the CFD analysis are discussed in this chapter. There are two parameters considered in this study, which are the diameter of intravascular catheter and the inlet velocity of saline solution. Thus, five different diameters of intravascular catheters (16G, 18G, 20G, 22G and 24G), and five different inlet velocities of saline solution (0.1 m/s, 0.3 m/s, 0.5 m/s, 0.7 m/s and 1.0 m/s) are simulated through CFD. The data is then analysed and compared to get the optimal pressure and velocity from various diameters and inlet velocities of saline. This will assist in determining the best diameter and inlet saline velocity with lower risks and therefore ensure the fluid flow ability. The experimental validation data for the simulation is also shown in this chapter.

## 4.2 Mesh Independency Study

A total of five meshes were done by adjusting the number of divisions at the edges of the model, and the meshes ranged from 125524 to 210380 elements from coarse mesh to fine mesh as shown in Table 4.1.

Table 4.1: Parameters used in mesh independency study

| | **Mesh 1** | **Mesh 2** | **Mesh 3** | **Mesh 4** | **Mesh 5** |
|---|---|---|---|---|---|
| **No. of Divisions (Blood Vein)** | 10 | 20 | 30 | 35 | 40 |
| **No. of Divisions (Catheter)** | 5 | 10 | 20 | 25 | 30 |
| **Nodes** | 40647 | 41291 | 43211 | 50318 | 96648 |
| **Elements** | 125524 | 128811 | 138123 | 152461 | 210380 |

The different meshes are used to determine how the mesh quality affects the CFD simulation results. The CFD simulation result obtained is the maximum pressure in the inlet saline area. From Figure 4.1 and Table 4.2, Mesh 5 and Mesh 2 can be considered as outliers, as the maximum pressure values have the biggest percentage difference of 4.017% and -1.6414%. Mesh 1 also has a higher percentage difference among the remaining three meshes of -1.1584%.

Comparing Mesh 3 and 4, the two meshes exhibit almost similar values for maximum pressure, but Mesh 3 is chosen due to its lower computational costs and time and it is further used for the CFD analysis.

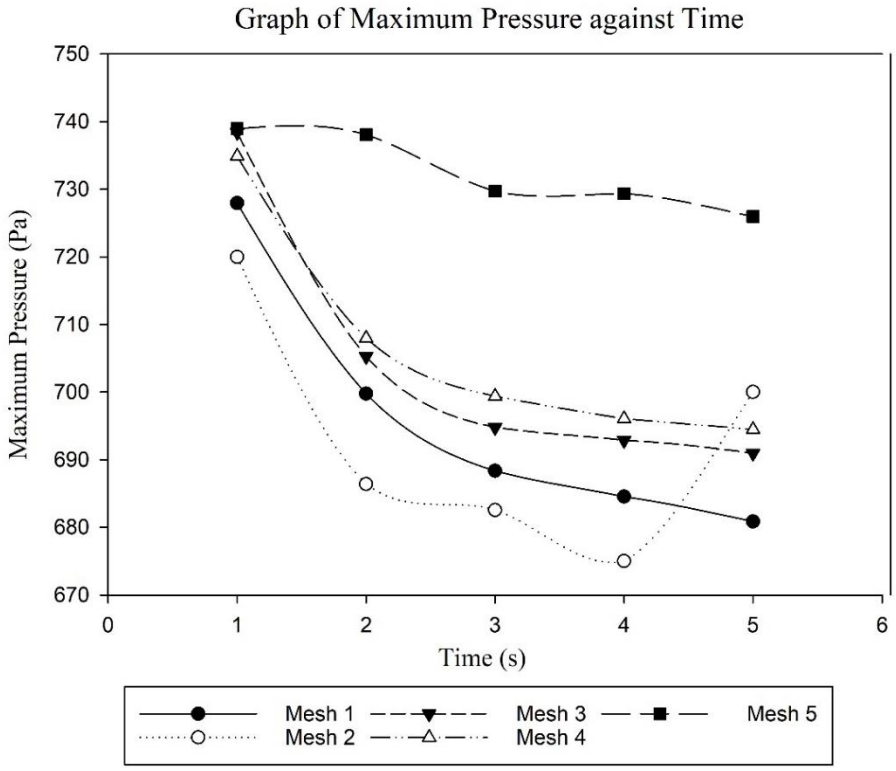



Figure 4.1: Graph of Maximum Pressure against Time

Table 4.2: Percentage difference of maximum pressure values for different meshes

| **Mesh** | **1** | **2** | **3** | **4** | **5** |
|---|---|---|---|---|---|
| **Time (s)** | **Percentage Difference (%)** | | | | |
| **1.0** | -1.420 | -2.497 | 0 | -0.478 | 0.074 |
| **2.0** | -0.784 | -2.681 | 0 | 0.384 | 4.650 |
| **3.0** | -0.927 | -1.761 | 0 | 0.660 | 5.031 |
| **4.0** | -1.199 | -2.577 | 0 | 0.461 | 5.268 |
| **5.0** | -1.462 | 1.309 | 0 | 0.507 | 5.062 |
| **Average** | -1.1584 | -1.6414 | 0 | 0.3068 | 4.017 |

## 4.3 Simulation Results

### 4.3.1 Effect of Diameter of Intravascular Catheter

Figure 4.2 showed the labelling of different area in the ANSYS simulation, in which there is the main branch, middle area, branched area and Position X.

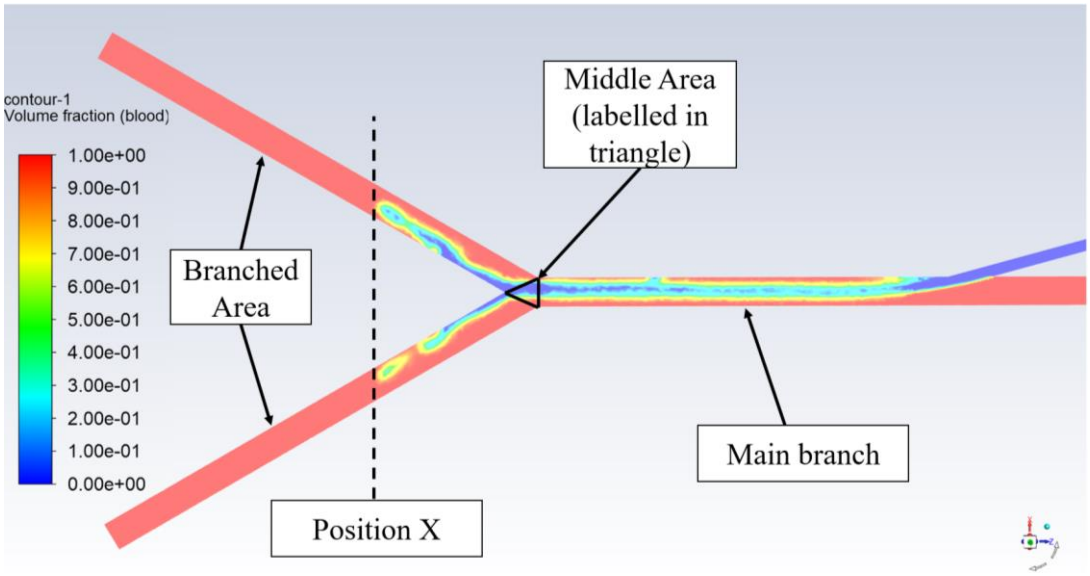



Figure 4.2: Labelling of different areas in the ANSYS simulation

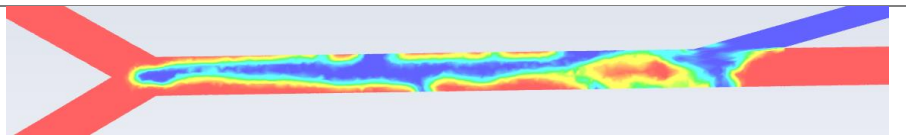
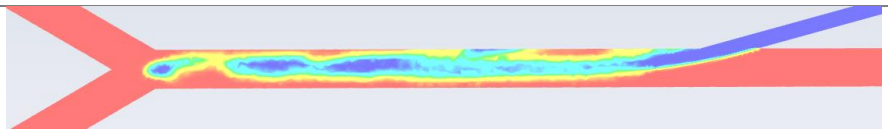
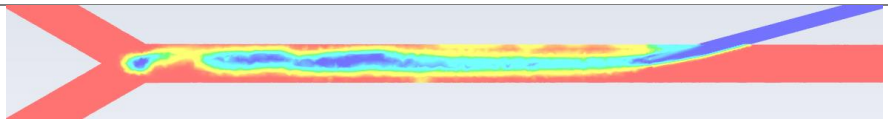
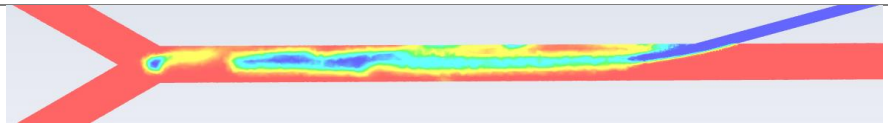
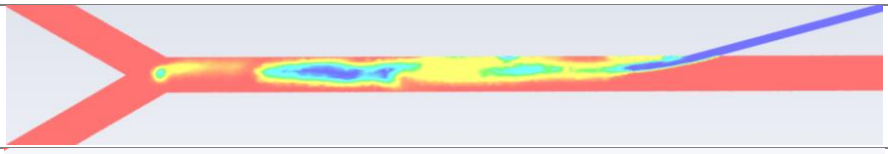
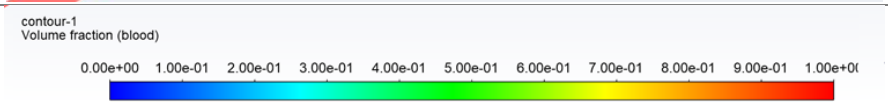
The time taken for the saline mixture to reach the middle area as well as the time taken to reach Position X in branch by the saline mixture at branch for each catheter are as shown in Table 4.3. From a general view, as the diameter of catheter decreases, the time taken to reach the middle area in the blood vein also increases. A linear increase of time is depicted in the flow at the main branch, but at the branched area, it seems that the medium sized catheters of 18G and 20G needed a significantly longer time to reach Position X as compared to the 16G catheter.

Table 4.3: Time taken to reach the middle area and time taken to reach the Position X at branched area for different catheter sizes

| Catheter Size | Time taken to reach the middle area (s) | Time taken to reach Position X at branched area (s) |
|---|---|---|
| **16G** | 3.8 | 5.6 |
| **18G** | 4.2 | 6.6 |
| **20G** | 4.4 | 6.6 |
| **22G** | 4.6 | 7.0 |
| **24G** | 4.8 | 7.6 |

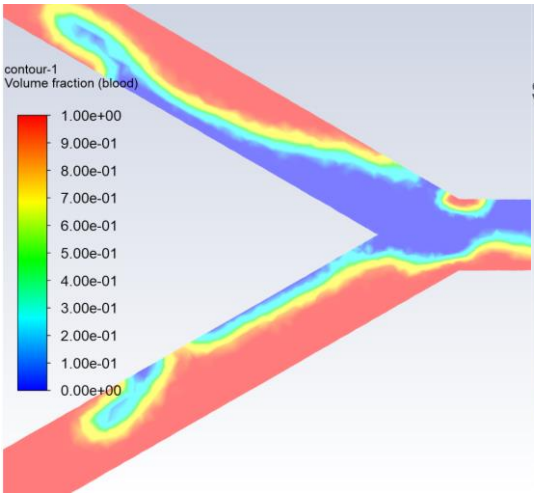
The volume fraction of blood is primarily used to determine the blood-to-saline ratio, which is used to estimate the efficiency of saline and blood mixing inside the blood vein. From Table 4.4, it can be seen that the volume fraction of saline (as indicated in blue colour) has actually decrease as the diameter decreases, with 16G having the highest percentage of saline concentration contour. The middle range of the volume fraction of blood (0.40-0.50) is indicated as green, which can be seen to be increasing as the diameter decreases. This shows that the performance of mixing of saline and blood increases as the diameter decreases, with exception on 24G which has a lower saline concentration contour in general, which might be due to its lower flow rate.

Table 4.4: Phase contour of blood in main branch for different catheter sizes

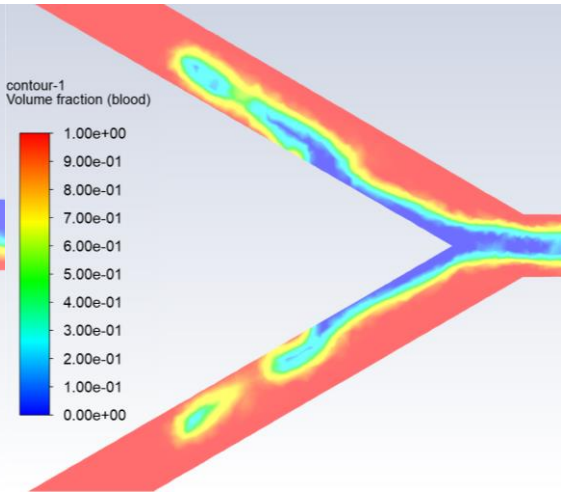
| Catheter Size | Volume fraction of blood with same inlet saline velocity = 0.5 m/s |
|---|---|
| 16G |  |
| 18G |  |
| 20G |  |
| 22G |  |
| 24G |  |
| Legend of volume fraction of blood |   |

The separation of saline mixture with blood into the two branches of the blood vein up to Position X is seen in Figure 4.3. For all five diameters, it can be seen that the saline mixture has higher tendency to move to the upward branch as compared to the lower branch, though in general the separation is still uniform, with the most

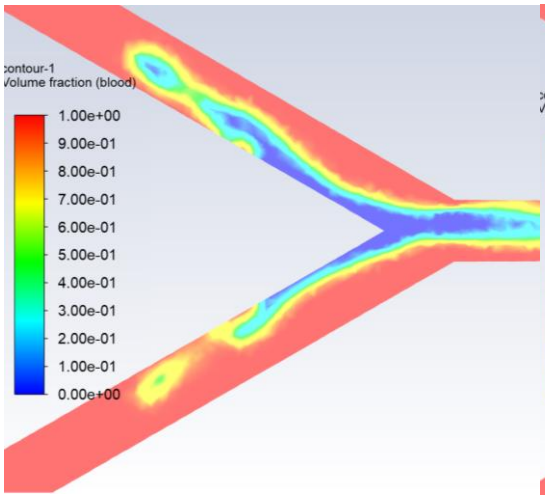
uniform separation being the 18G catheter. The middle range of saline concentration contour (green in colour) also had the higher percentages in 18G, 20G and 22G. This shows the mixing of blood and saline is better in relatively smaller catheter sizes, and this ensures that the fluids are mixed well together in the shortest distance possible before the blood vein branches out.



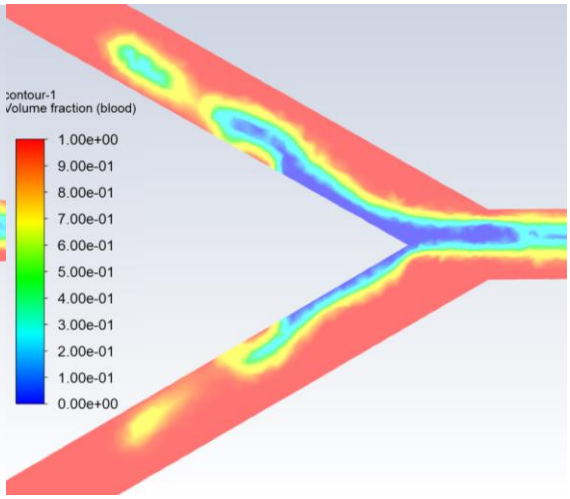

(a) 16G



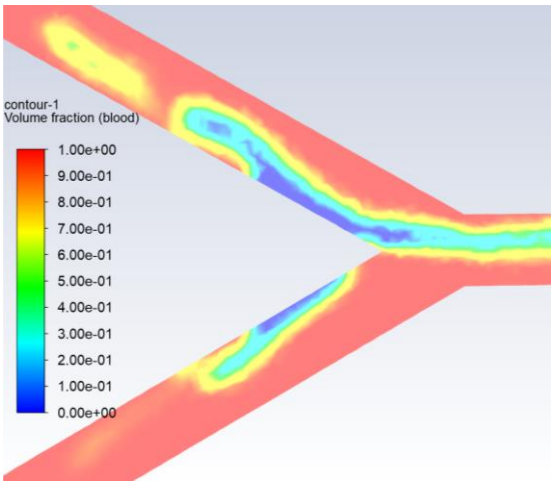

(b) 18G




(c) 20G



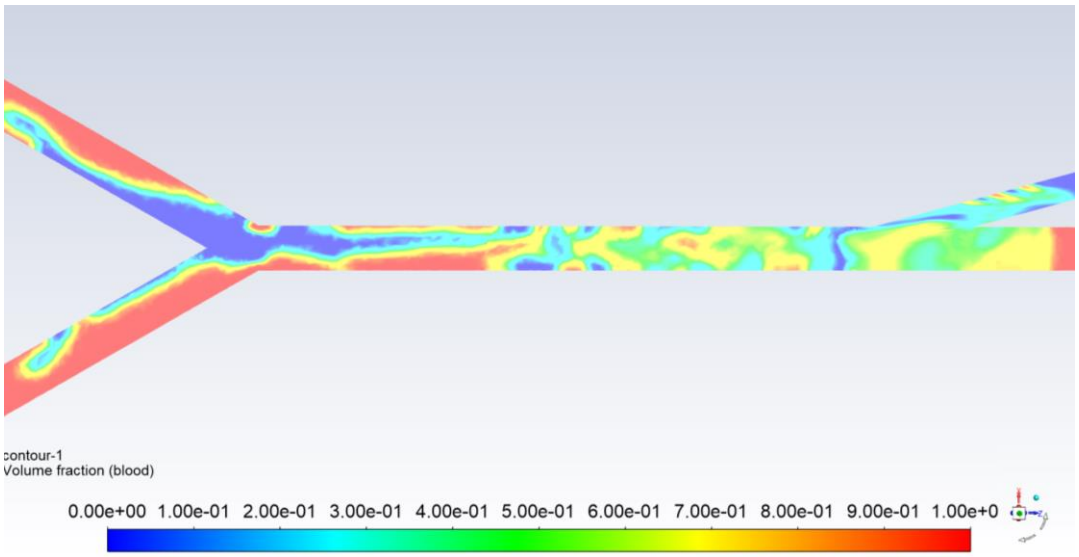

(d) 22G




(e) 24G

Figure 4.3: Phase contour of blood for different catheter sizes when saline reaches the Position X in the branched area

The vortex behaviour of blood is seen in Figure 4.4, in which the velocity vector showed a swirling phenomenon and the velocity at the injection side go up to $6.00 \times 10^6$ m/s, which can cause high wall shear stress. Backflow is also noticed as labelled in the velocity vector of blood, which shows that the 16G catheter may not be suitable to use for blood vein that are of size 3 mm or below due to its high flow rate even though the time taken is shorter.



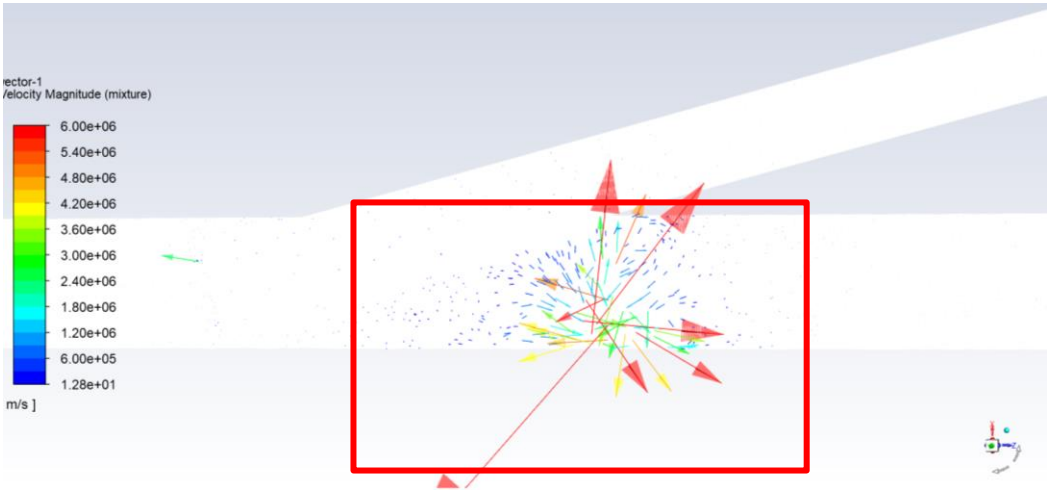
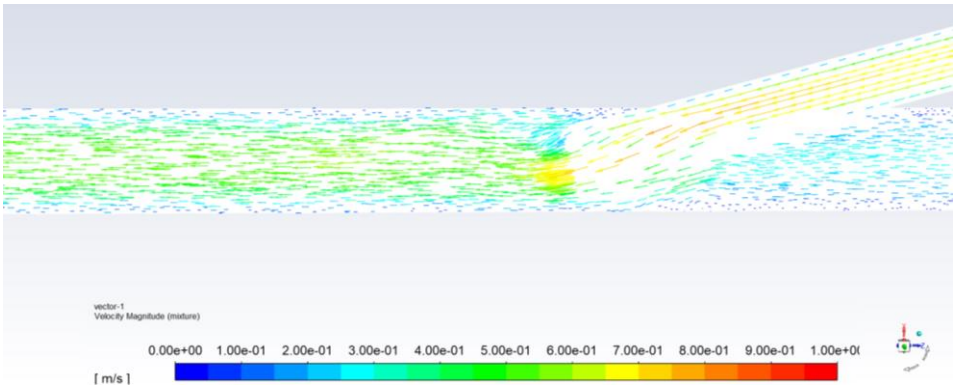



Figure 4.4: The phase contour of blood when using 16G catheter at t = 5.6s (first image), and the velocity vector of the part enclosed by red box (second image)

In Figure 4.5, the higher velocity value of 0.4-0.5 m/s for 16G catheter is seen to be at the blood vein, which indicates the high flow rate of saline solution into the blood vein. This quick flush of saline solution may increase the possibility of thrombogenic potential as the flow rate is high. A study by Fulker et al. (2017) stated that higher flow rates of the catheter would cause high wall shear stresses, thus the flow control needed to be taken into account for the thrombogenic potential [28]. Whereas for 18G to 24G catheter model, the majority of velocity vectors of high velocity seems to be focused at the injection area. This shows that the initial flow rate at the injection area is very high for most catheters.




(a) 16G