THREE-DIMENSIONAL MODELLING AND 3D PRINTING OF PATIENT LEFT CORONARY ARTERY USING CT-SCAN

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BACHELOR OF MECHANICAL ENGINEERING TECHNOLOGY (MAINTENANCE TECHNOLOGY) WITH HONOURS

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DECLARATION

I declare that this Choose an item. entitled “Three-Dimensional Modelling And 3D Printing Of Actual Patients Left Coronary Artery Using CT-Scan” is the result of my own research except as cited in the references. The Choose an item. has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : _____

Name : Muhammad Nur Akma Afiq Bin Awang Hamat

Date : June 2024

APPROVAL

I hereby declare that I have checked this thesis and in my opinion, this thesis is adequate in terms of scope and quality for the award of the Bachelor of Maintenance Technology Engineering Technology (specialisation) with Honours.

Signature : _____

Supervisor Name : Dr. Abdulgaphur Athani

Date : June 2024

DEDICATION

This thesis is dedicated to my beloved family, whose unwavering support, encouragement, and patience have been the cornerstone of my journey. To my parents, for their endless sacrifices and belief in my dreams, and to my siblings, for their constant inspiration and motivation. I also extend my heartfelt gratitude to my mentors, lecturers, and supervisor whose guidance and wisdom have profoundly shaped my understanding and fueled my curiosity. To the pioneers and innovators in the field of biomedical engineering, whose relentless pursuit of knowledge continues to push the boundaries of what is possible, and to the patients and their families, whose courage and resilience remind me of the profound impact our work can have. This work is a testament to your influence and an expression of my deepest gratitude and respect.

ABSTRACT

Computational fluid dynamics (CFD) is a broadly used technique in mechanical, biomedical engineering or in medical studies to solve complex problems by analyzing blood flow, heat transfer, and associated diseases analyzation by using computer simulations. Hence, CFD has been increasingly used in medical research of coronary artery disease because of its high-performance computational methods. These simulation tools used to predict the behavior of cardiovascular blood flow in the human anatomy. The methodology used in this project is, firstly we performed the segmented and reconstruction of left coronary artery model from CT scan data using Mimics (Materialize). Then the segmented models were then 3D printed using a TPU-85 (Thermal Plastic Polyurethane-85) material used the Fused Deposition Modeling (FDM) printer. But, we also perform the numerical analysis of 3d printed coronary model using ANSYS version 2022(R2). The reconstructed geometry has been used to analyze the local blood flow fields and flow profiling due to changes of coronary artery geometry, therefore, recognizing risk factors of development and progression of coronary artery disease using CFD simulation techniques. However, use of 3-D printed models based on medical imaging modalities or reconstructed geometries of present project can exactly replicate complex anatomy of left coronary artery and pathologies of the associated for cardiovascular system. In this project another section provided the use of 3-D printing is a tool to produce the patient actual left coronary artery that can be used for both education and surgical planning in these diseases. Hence concludes that, 3D printed patient-specific left coronary can be used in a non-invasive *in vitro* environment to quantify coronary artery ischemia with good correlation and concordance to that of invasive Fractional Flow Reservoir (FFR). However. the numerical analysis results of the present work gives the hemodynamic parameters such as pressure, velocity and Wall Shear Stress (WSS).

ABSTRAK

CFD ialah teknik yang banyak digunakan dalam kejuruteraan mekanikal dan bioperubatan untuk menyelesaikan masalah yang kompleks, seperti menganalisis aliran darah, pemindahan haba, dan penyakit yang berkaitan menggunakan simulasi komputer. Oleh itu, CFD semakin banyak digunakan dalam penyelidikan perubatan mengenai penyakit arteri koronari kerana kaedah pengiraannya yang berprestasi tinggi.Alat simulasi ini digunakan untuk meramalkan tingkah laku aliran darah kardiovaskular dalam anatomi manusia. Dalam projek ini, langkah pertama adalah melakukan segmentasi dan pembinaan semula model arteri koronari kiri daripada data imbasan CT menggunakan Mimics (Materialize). Model yang telah disegmentasi kemudian dicetak 3D menggunakan bahan TPU-85 (Thermal Plastic Polyurethane-85) dengan pencetak FDM (Fused Deposition Modeling).Di samping itu, analisis berangka model arteri koronari yang dicetak 3D juga dilakukan menggunakan perisian ANSYS versi 2022 (R2). Geometri yang telah dibina semula digunakan untuk menganalisis medan aliran darah tempatan dan profil aliran akibat perubahan geometri arteri koronari. Dengan ini, faktor risiko untuk perkembangan dan kemajuan penyakit arteri koronari dapat dikenal pasti melalui teknik simulasi CFD.Walau bagaimanapun, penggunaan model cetakan 3D berdasarkan data pencitraan perubatan atau geometri yang dibina semula dalam projek ini dapat meniru anatomi kompleks arteri koronari kiri dan patologi yang berkaitan dengan sistem kardiovaskular dengan tepat.Projek ini juga menyediakan bahagian tambahan mengenai penggunaan pencetakan 3D sebagai alat untuk menghasilkan model sebenar arteri koronari kiri pesakit. Model ini boleh digunakan untuk tujuan pendidikan dan perancangan pembedahan dalam rawatan penyakit tersebut.Sebagai kesimpulan, model arteri koronari kiri yang dicetak 3D berdasarkan pesakit dapat digunakan dalam persekitaran in vitro tanpa invasif untuk mengukur iskemia arteri koronari dengan ketepatan yang baik, selaras dengan nilai Fractional Flow Reserve (FFR) yang invasif. Selain itu, keputusan analisis berangka dalam kerja ini memberikan parameter hemodinamik seperti tekanan, halaju, dan Tegasan Ricih Dinding (Wall Shear Stress, WSS).

ACKNOWLEDGEMENTS

In the Name of Allah, the Most Gracious, the Most Merciful

In the name of the Almighty, the Most Merciful and Generous, Allah My supervisor, Dr. Abdulgaphur Athani, has provided me with essential advice, encouragement, and support during this research endeavor, for which I am truly grateful. I want to express my gratitude to my family for their continuous understanding and support throughout my academic career. Without their love and patience, I could not have finished this journey. Their encouragement has been a continual source of strength. Additionally, I would want to express my gratitude to Scholarship, which is MARa, for their ongoing financial assistance and provision of a much-needed sense of community. Finally, I would like to express my gratitude to Universiti Teknikal Malaysia Melaka for lending me the tools and space needed to complete this study. We are very grateful for the help that the administrative and academic staff has provided. We are grateful to everyone who has made any kind of contribution to this thesis. Your encouragement and support have been tremendous, and I sincerely appreciate the part you have all done in making this happen.

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LIST OF SYMBOLS AND ABBREVIATIONS

CAD	-	Coronary Artery Disease
MRI	-	Magnetic Resonance Imaging
ASTM	-	American Standard Testing Materials
FDA	-	Food and Drug Administration
FDM	-	Fused Deposition Modeling
SLA	-	Stereo Lithography Apparatus
SLS	-	Selective Laser Sintering
DLP	-	Digital Light Processing
EHD	-	Electro Hydrodynamics
HDPE	-	High-Density Polyethylene
PS	-	Polystyrene
PMMA	-	Poly(Methyl Methacrylate)
PC	-	Polycarbonate
ABS	-	Acrylonitrile Butadiene Styrene
HIPS	-	High Impact Polystyrene
DMLS	-	Direct Metal Laser Sintering
SLM	-	Selective Laser Sintering
EBM	-	Electron Beam Melting
SHS	-	Selective Heat Sintering
LOM	-	Laminated Object Manufacturing
UC	-	Ultrasonic Consolidation
LMD	-	Laser Melting Deposition
UV	-	Ultra-Violet
PBF	-	Powder Bed Fusion
VPP	-	Vat-Photo Polymerization
STL	-	Standard Tessellation Language
CCTA	-	Coronary Computed Tomography Angiography
CT	-	Computed Tomography
WSS	-	Wall Shear Stress
LCA	-	Left Coronary Artery

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CHAPTER 1

INTRODUCTION

1.1 Background

Additive manufacturing also referred to as three-dimensional (3D) printing, has become a disruptive technology that is revolutionizing several industries, including healthcare. 3D printing has created new opportunities for innovation in the medical industry by making it possible to create intricate and personalized anatomical models, implants tailored to each patient, surgical guides, and prosthetics with previously unheard-of accuracy and precision.

Early in the new millennium, advances in imaging technology like computed tomography (CT) and magnetic resonance imaging (MRI) gave rise to the idea of 3D printing in medicine. These imaging methods made it possible to provide digital anatomical data with high resolution and patient specificity that could be easily converted into 3D printable forms. The 3D printing industry has recently surged due to lower manufacturing costs of 3D printers and enhancements in their printing precision and speed. These improvements have led to significant advancements in medical equipment, implant materials, and cell printing. Utilizing a patient's imaging data from CT or MRI scans, 3D printing technology enables the creation of organ models, rapid production of personalized scaffolds, and direct printing at defect sites Yan et al (2018).

Surgical planning and simulation is one of the most important uses of 3D printing in medicine. Nowadays, surgeons may plan complex surgical procedures, see intricate features in patients' anatomy, and practice surgical methods on 3D printed models of the patient's anatomy before the real operation. By optimizing surgical accuracy, cutting down on

operating time, and lowering the chance of complications, this patient-specific strategy improves patient outcomes in the long run.

In addition, 3D printing has made it easier to create medical devices and implants that are specifically designed for each patient. Examples of these include coronary artery, heart bypass, and aorta surgery. By customizing these devices to each patient's unique anatomy, 3D printing has helped to lower the risk of implant rejection and increase long-term implant success rates.

In conclusion, 3D printing has completely changed the medical industry by giving medical personnel new tools to maximize treatment outcomes, increase surgical planning precision, improve diagnostic accuracy, and provide patients with individualized care. The potential uses of 3D printing in medicine are anticipated to grow as the technology develops and becomes more widely available, significantly altering healthcare delivery and opening the door for the creation of novel approaches to challenging medical problems.

1.2 Problem Statement

The creation of precise, patient-specific anatomical models is required for preoperative planning, simulation, and training due to the growing need for individualized medical care and surgical procedures. However, the accuracy, adaptability, and flexibility needed to accurately mimic the complex and distinctive vascular systems of individuals are sometimes lacking from conventional methods of producing anatomical models that use cadaveric specimens or general anatomical atlases. Moreover, knowing and navigating the patient's vascular anatomy during surgical procedures is made extremely difficult for healthcare professionals by the limitations of visualizing and interpreting complex three-dimensional (3D) vascular anatomy from two-dimensional (2D) imaging modalities, such

as computed tomography (CT) and magnetic resonance imaging (MRI).

Therefore, in order to produce high-fidelity, patient-specific 3D printed models of artery structures, there is an urgent need for creative and cutting-edge approaches that make use of the capabilities of medical imaging technology, 3D modeling software, and additive manufacturing processes. Developing precise and dependable segmentation algorithms to remove vascular anatomy from medical imaging data, the choice of suitable materials and printing technologies to create bio-compatible and anatomically accurate arterial models, and the rigorous testing, evaluation, and validation procedures for the printed models before they are used in clinical settings are just a few of the technical, logistical, and clinical challenges that need to be addressed despite the potential benefits of 3D printed arterial models in improving surgical planning, optimizing surgical outcomes, and improving patient care.

The need to provide a reliable, precise, and therapeutically applicable technology for modeling and 3D printing patient-specific vascular structures using medical imaging data is the main focus of the issue statement. In addition to facilitating the development of tailored anatomical models for bettering surgical planning and patient outcomes, tackling this challenge will open new avenues for research in vascular anatomy and surgery, medical education, and personalized medicine.

1.3 Research Objective

The main aim of this research is to research about the patients heart arteries(based on the CT-scan data) and replicate the arteries using appropriate 3D-printing machine. Specifically, the objectives are as follows:

a) Reconstruction of Left Coronary Artery (LCA) using Patient's CT-Scan data (Using MIMICS Materialize software) and 3D modeling and analysis of LCA using ANSYS 2022 (R2).
b) The developed model has been used to produce protype using 3D print techniques.
c) Analysis of LCA model for Hemodynamic parameters such as evaluation of Pressure. Velocity & WSS.

1.4 Scope of Research

The main investigation is focusing on the patient left coronary artery and recreate those arteries using 3D printing to make the analysis. This research's scope was divided to three stage. The first stage of the study is collecting the patient left coronary artery data from the CT-Scan machines (Computed Tomography). This data will include the diameter and the thickness of the arteries. The collected data then will be inserted into the simulation software to replicate the actual drawing of the artery. The actual drawing then will be transferred to the suitable 3D printing drawing format. The third scope of this research is making the prototype of the arteries by using a 3D printing machine. Lastly, the final scope of the

research is testing the finished prototype. The properties of the material such as tensile and flexibility will be tested using the ASTM(American Standard of Testing Materials).

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Three-dimensional (3D) printing, also known as additive manufacturing, has revolutionized the medical field by enabling the production of highly customized and complex medical devices, prosthetics, and implants. This technology's ability to create patient-specific models and tools has significantly enhanced precision in medical treatments and surgical procedures. Over the past decade, extensive research has been conducted to explore the various applications and benefits of 3D printing in medicine, leading to a growing body of literature that highlights its transformative impact on healthcare.

One of the primary areas where 3D printing has made significant strides is in the creation of patient-specific implants and prosthetics. Traditional manufacturing methods often fall short in producing customized solutions that fit the unique anatomical structures of individual patients. 3D printing, however, allows for the precise fabrication of implants tailored to the patient's anatomy, improving the fit and functionality. Studies have shown that 3D-printed implants, such as cranial plates and hip implants, not only reduce the risk of complications but also shorten surgery times and enhance recovery rates. Additionally, the ability to produce these implants using biocompatible materials has further expanded their application, offering new possibilities in reconstructive surgery and orthopedics.

Another significant application of 3D printing in medicine is in the development of surgical guides and models. Surgeons can now use 3D-printed models of patient anatomy, based on medical imaging data, to plan and practice complex surgeries. This pre-surgical planning tool has been shown to improve surgical outcomes by allowing surgeons to anticipate potential challenges and refine their techniques. The use of 3D-printed guides during surgery also enhances precision, particularly in procedures involving delicate structures such as the spine or the maxillofacial region. Literature suggests that this approach not only improves the accuracy of surgical interventions but also reduces operative time and associated costs.

In the field of regenerative medicine, 3D bioprinting is an emerging area of research with promising potential. Bioprinting involves the layer-by-layer deposition of bio-inks, which are mixtures of living cells and biocompatible materials, to create tissue-like structures. Researchers have made significant progress in bioprinting tissues such as skin, cartilage, and even vascular structures. Although still in the experimental stage, the ultimate goal of bioprinting is to fabricate functional organs for transplantation, addressing the critical shortage of donor organs. Recent advancements in this area have demonstrated the feasibility of creating complex tissue architectures, paving the way for future breakthroughs in organ regeneration and transplantation.

In conclusion, the literature on 3D printing for medical purposes underscores its profound impact on modern healthcare. The ability to produce patient-specific implants, surgical guides, and bioprinted tissues represents a paradigm shift in medical practice, offering enhanced precision, customization, and potential for innovation. As research continues to advance, the integration of 3D printing into clinical practice is expected to grow, further transforming patient care and expanding the horizons of medical science.

2.2 Coronary Artery

The coronary arteries are crucial blood vessels that is used to transfer high content of oxygen-rich blood to the heart muscle (myocardium). These arteries are located from the base of the aorta and branch into the left and right coronary arteries, which further divide into smaller arteries to cover the entire heart. The left of the coronary artery divides into the left anterior descending artery and the circumflex artery, while the right of the coronary artery gives rise to the right marginal artery and the posterior descending artery. Their main function was to deliver oxygen and important nutrients to the heart muscle, ensuring it to pump blood efficiently throughout the body. Additionally, it also play a major role in removing waste products like carbon dioxide from the heart muscle.

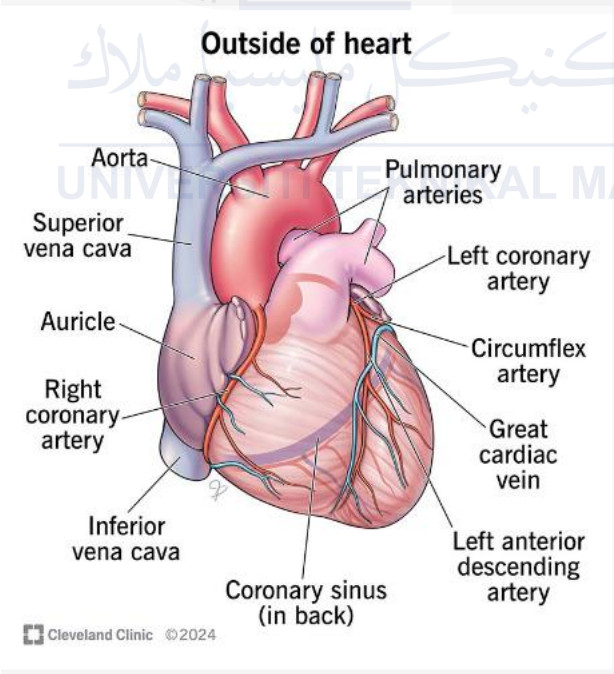


Figure 2.1 Heart anatomy

2.3 Coronary Artery Disease

Coronary artery disease is a complex condition that affects the blood vessels supplying the heart. It is primarily caused by atherosclerosis, a progressive buildup of plaque in the arterial walls. This plaque is made up of cholesterol, fatty deposits, calcium, and other substances. Over time, the plaque hardens and narrows the coronary arteries, reducing blood flow to the heart muscle. This reduced blood flow can lead to various complications, including angina (chest pain), heart attack, and even death(Amsterdam et al., 2014) . The main cause of coronary artery disease is atherosclerosis, plaque buildup in the arteries. This plaque comprises cholesterol, fatty deposits, calcium, and other substances. As the plaque accumulates, it triggers an inflammatory response in the arterial walls.

This inflammation leads to the formation of atherosclerotic plaques, which gradually narrow the coronary arteries and impede blood flow to the heart muscle. As a result, the heart does not receive enough oxygen and nutrients, making it more susceptible to damage Li et al (2022). Additionally, certain risk factors contribute to the development and progression of coronary artery disease. These risk factors include high blood pressure, high cholesterol levels, smoking, diabetes, obesity, a sedentary lifestyle, and a family history of the disease. The development of coronary artery disease is primarily caused by atherosclerosis, which is the buildup of plaque in the arteries. This plaque is composed of cholesterol, fatty deposits, calcium, and other substances.

As the plaque accumulates, it narrows the coronary arteries and restricts blood flow to the heart muscle. This reduced blood flow can lead to a variety of symptoms, such as chest pain (angina), shortness of breath, fatigue, and even heart failure. The underlying cause of coronary artery disease is atherosclerosis, which is the buildup of plaque in the arteries Al-Shahrani et al (2021).

2.4 Level Of 3-D Printing For Medical Applications

The 3D printing industry has experienced significant growth recently due to the reduction in manufacturing costs of 3D printers, along with enhancements in printing precision and speed. These advancements have led to major progress in medical equipment, implant materials, and cell printing. Using a patient's imaging data from CT or MRI scans, 3D printing technology can prepare organ models, rapidly manufacture personalized scaffolds, and print directly at the defect site. This approach opens up new possibilities for creating bionic tissues or organs and addressing the donor shortage problem Yan et al (2018). There are four major levels for medical applications of 3-D printing for medical applications which is:

a) Organ models to aid preoperative planning and surgical treatment analysis.
b) Permanent non-bioactive implants.
c) Fabricating local bioactive and biodegradable scaffolds
d) Directly printing tissue and organ

2.4.1 Organ Models To Aid Preoperative Planning And Surgical Treatment Analysis

Using HeLa cells with gelatin, alginate, and fibrinogen hydrogels, researchers from China and the United States have successfully created in vitro cervical carcinoma models, enabling dramatic 3D visualization of the tumor environment. On 2D tissue culture plates, HeLa cells have a flat and elongated shape, but within the 3D hydrogel, they form spherical spheroids with smooth surfaces and close cell-cell contacts. In contrast to 2D planar cultures,

3D models can provide light on the properties of tumor cells, enabling scientists and medical professionals to more accurately identify the growth, differentiation, and dissemination of the disease Yan et al (2018).

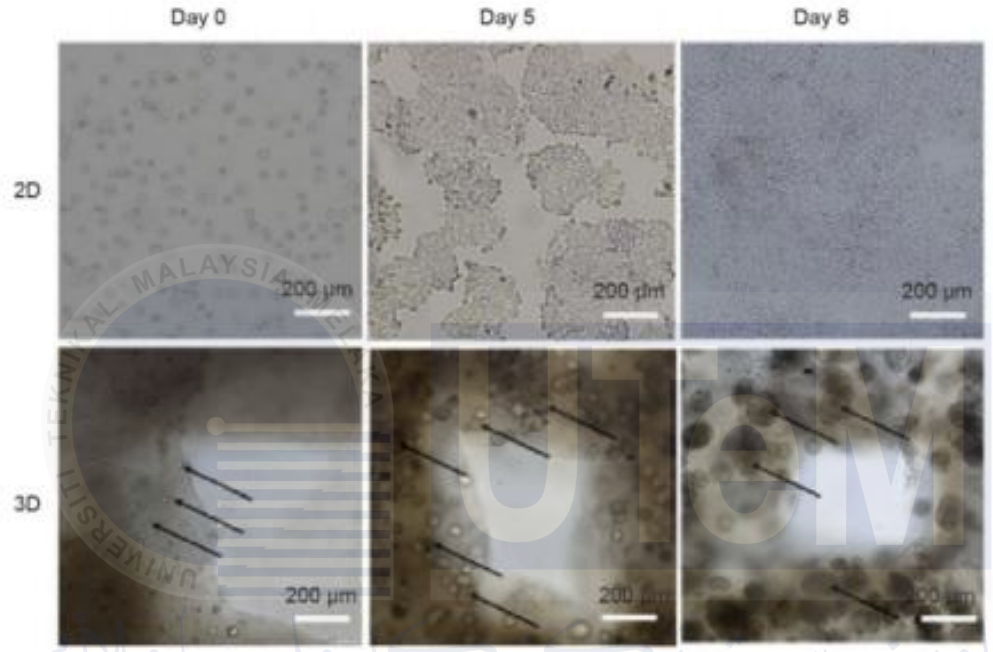


Figure 2.2 HeLa cells for different periods (Yan et al.,2018).

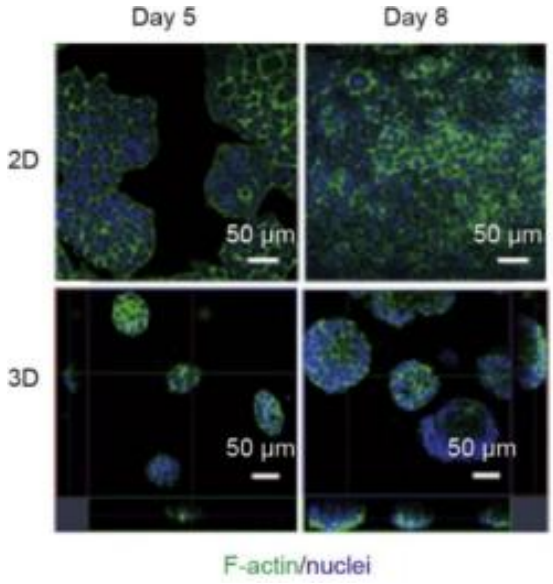


Figure 2.3 Distribution of the cytoskeleton after staining (Yan et al.,2018).

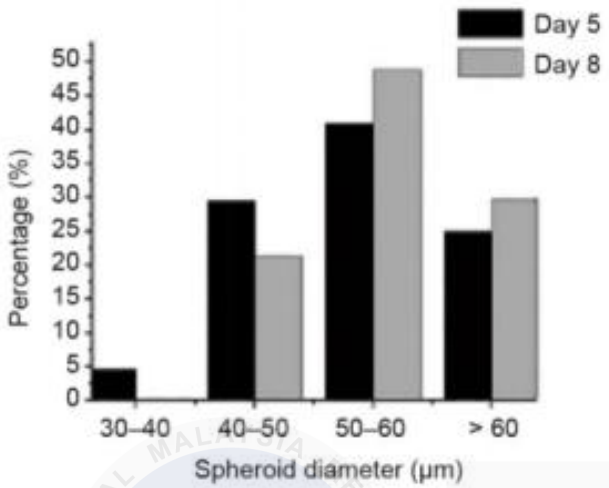


Figure 2.4 Distribution of spheroid diameter in 3D HeLa/hydrogel constructs (Yan et al.,2018).

2.4.2 Permanent Non-Bioactive Implants.

Non-degradable biomaterials are needed for permanent medical implants, which are frequently utilized in orthopedics and dentistry to ensure good biocompatibility after surgery. In contrast to conventional machining methods, 3D printing enables the individualized, on-demand manufacturing of intricate implants with superior dimensional precision and reduced production cycles. Because typical metallic implants are stiffer than bone, they frequently generate stress-shielding events that over time can damage the integrity of the bone. A new and efficient method for producing lightweight, individualized implants with adjustable stiffness is to combine topology-optimized designs with 3D printing Yan et al (2018).

Figure 2.5 CT scan and 3D echocardiography data model (Yan et al.,2018).

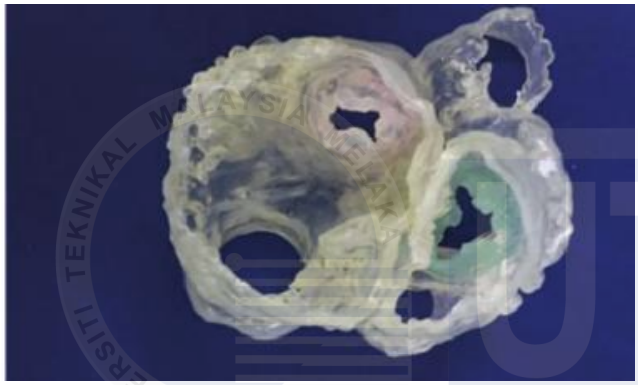


Figure 2.6 3D printed cardiac module combining various medical imaging technologies (Yan et al.,2018).

2.4.3 Fabricating Local Bioactive And Biodegradable Scaffolds

Surface modification can inhibit bacterial adhesion and long-term biofilm formation, which can lead to infections. Researchers have discovered that while host defenses and conventional antibiotics can combat infections caused by planktonic bacteria, they are ineffective against bacteria that form biofilms. Preventing the initial bacterial adhesion that leads to biofilm formation is essential for reducing the risk of infection in implants. Recent studies indicate that modifying the antibacterial properties of implant surfaces primarily through the chemical modification of biomaterials via zwitterionization and employing

special surface nanotopography or architecture, are effective strategies for controlling and preventing bacterial adhesion on implants Yan et al (2018).

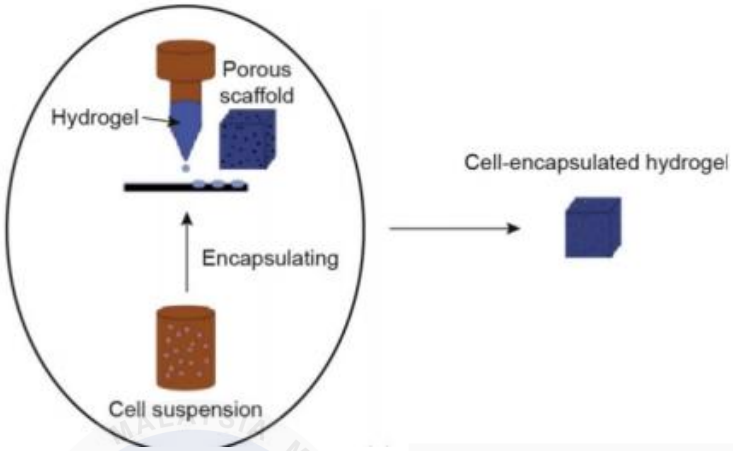


Figure 2.7 Encapsulating cells directly into gel scaffolds (Yan et al.,2018).

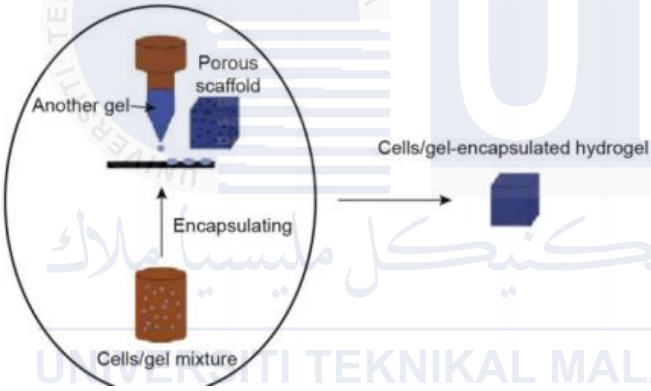


Figure 2.8 Encapsulating cells/gel mixture into 3D scaffolds (Yan et al.,2018).

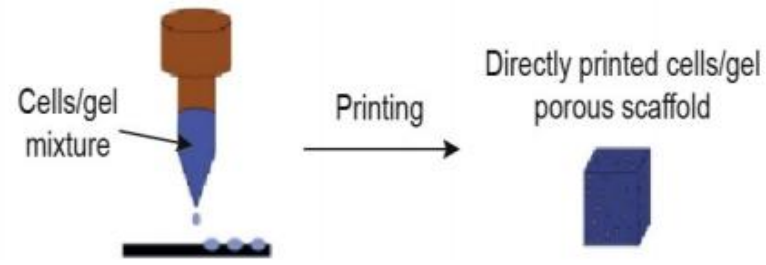


Figure 2.9 Directly printing cells/gel (Yan et al.,2018).

2.4.4 Directly Printing Tissue And Organ

Researchers from both local and foreign institutions have successfully printed tissues or organs. For example, Michael et al. (2013) used a laser-assisted bioprinting method to precisely place fibroblasts and keratinocytes in a particular 3D spatial layout to produce a completely cellularized skin replacement. This printed skin construct was inserted into a wound on the mouse's skin, leaving the surrounding skin intact for contrast. The printed skin construct was made up of keratinocytes labeled in green and fibroblasts labeled in red on top of MatriDerm®. Experiments conducted on naked mice in the dorsal skin fold chamber demonstrated that the printed cells stayed viable, kept dividing, and produced extracellular matrix (ECM). Blood vessels were also seen emerging from the margins and wound bed. Yan et al (2018) highlighted that bioprinting techniques capable of printing multiple layers of cells are essential for creating more complex tissues.

2.5 3-D Printing For Medical Purpose

Based on a Yan Q. et al. (2018) paper. Due to the lowered production costs of 3D printers as well as their increased speed and accuracy, the market for 3D printing has lately flourished, enabling significant advancements in implant materials, medical equipment, and cell printing. 3D printing technology may be used to prepare organ models, quickly produce customized scaffolds, and print directly at the problem location using patient imaging data from CT or magnetic resonance imaging. In this sense, 3D printing technology opens up new avenues for constructing artificial organs or tissue and addressing the issue of a lack of donors.

When creating a design control model for FDA review of market clearance, the

customizability of 3D-printed products adds new layers of complexity. The bespoke nature and distinct construction methods of 3D-printed medical equipment provide particular difficulties in satisfying regulatory requirements for manufacturing quality control. To guarantee a high-quality build, consistent material powder qualities and ideal printing parameters—like build orientation and laser power—must be considered and reported to the FDA. Morrison et al. (2015) describe post-printing requirements specific to 3D-printed devices, including cleaning, finishing, and sterilization.

2.5.1 Type of 3-D Printing For Medical Purposes

In addition, using the patient's unique imaging data, the combination of 3D printing and medical imaging technology may create any complicated geometric shape and patient-specific structure. Currently, popular techniques for adding materials, including biological printing, electro hydrodynamics (EHD) printing, digital light processing (DLP), selective laser sintering (SLS), stereo lithography apparatus (SLA), fused deposition modeling (FDM), and digital light processing (DLP), are all appropriate for use in medical applications Shen et al (2024).

Table 2.1 Summary of the 3D-printing process and technologies, focus on materials needed and medical applications, and comparison among the 3D-printing technologies.

Designation Additive Manufacturing Process	**Process Description**	**Technologies**	**Materials**	**Medical Use**	**Advantages**	**Disadvantages**
Vat photo-polymerisation	Vat polymerisation uses a vat of liquid photopolymer resin, out of which the model is constructed layer by layer	1. Stereolithography (SLA) 2. Digital Light Processing (DLP)	Photopolymer resin	1. Bone 2. Dental models 3. Dental implant guide 4. Hearing aids	1. High resolution and accuracy 2. Can generate complex parts 3. Smo other surface finish 4. Flexible printing set-up	1. Lacking in strength and durability 2. Still affected by UV light after printing 3. Not for heavy duty
Material Jettting	Material jetting creates objects in a similar method to a two-dimensional ink jet printer. Material is	Multijet Modelling(MJM)	1. Plastics 2.Polymers: polypropylene, HDPE, PS, PMMA, PC, ABS, HIPS	1. Medical models 2. Dental casts	1. High accuracy 2. Low waste material	1. Required support material 2. Limited

	jetted onto a build platform using either a continuous or drop on demand (DOD) approach			3. Dental implants guide	s 3. Multiple materials parts and colours and in one process	materials :only polymers and waxes are supported
Binder Jetting	The binder-jetting process uses two materials; a powder-based material and a binder. The binder is usually in liquid form and the build material in powder form. A print head moves horizontally along the x and y axes of the machine and deposits alternating layers of the build material and the binding material	1. Powder bed and ink jet head 3D printing(PDIH) 2. Plaster-based 3D Printing(PP)	1. Stainless steel 2. Polymers:ABS, PA,PC 3. Ceramics:Glass	Colour models especially colour coding of anatomy	1. Range of colours 2. Multiple materials supported 3. Faster 4. Different binder-powder combination for various mechanical properties	1. Not always suitable for structural parts 2. The cleaning of the 3D printing results needs time and increase the time of the procedure
Material Extrusion	Fuse deposition modelling (FDM) is a	1. Fused Deposition Modelling(F	1. Plastics 2. Polymers:ABS,	1. Medical instrument	1. Cheaper	1. Dependence of the

	common material extrusion process and is trademarked by the company Stratasys. Material is drawn through a nozzle, where it is heated and is then deposited layer by layer. The nozzle can move horizontally, and a platform moves up and down vertically after each new layer is deposited	DM) 2. Fused Filament Fabrication(FFF)	PC,AB,Nylon	s and devices 2. Rapid prototypin g exoskeleto n	process 2. Wid espread 3. AB S plastic supporte d:good structura l and easily accessib e	quality on the nozzle:bi gger radius nozzle leads to low quality 2. Low accuracy and dependa nce on the nozzle thickness 3. Low speed 4. Cont act pressure needed to increase quality
Powdere d Bed Fusion	The powdered bed fusion process includes the following commonly used printing techniques: 1. Direct Metal Laser Sintering(DM	1.Direct Metal Laser Sintering(D MLS) 2.Electron Beam Melting(EB M) 3.Selective Heat Sintering(S HS) 4.Selective Laser	Powdered based materials.Common metals and polymers used are: 1. SHS:Nylon 2. DMLS,SLS,SL M:stainless steel,titanium,alumi nium,cobalt chrome,steel	1. Model s that require lattice 2. Medic al implannts such as implants and	1. Che ap 2. Doe s not require huge area 3. Larg e range of	1. Low speed 2. Limi ted sized 3. Dep endence on powder grain

	LS) 2. Electron Beam Melting(EBM) 3. Selective Heat Sintering(SHS) 4. Selective Laser Melting(SLM) 5. Selective Laser Sintering)	Melting(SLM) 5.Selective Laser Sintering)	3. EBM:titaniu,cobalt chrome,stainless steel materials,aluminium and copper.	fixations	material options	size
Sheet Laminati on	Sheet lamination process include Ultrasonic Additive Manufacturing (UAM) and Laminated Object Manufacturing (LOM).The ultrasonic additive manufacturing process uses sheets or ribbons of metal,which are bound together using ultrasonic welding	1. Laminated Object Manufacturing(LOM) 2. Ultrasonic Consolidation(UC)	1. Paper 2. Plastic 3. Sheet metals	Orthopaedic modelling of bone surfaces	1. Speed 2. Cheap 3. Ease of materials handling	1. Dependence on paper or plastic material 2. Need of postprocessing 3. Limited material range
Direct Energy Deposition	Directed Energy Deposition(DED) covers a	Laser Metal Deposition(LMD)	1. Cobalt chrome	Limited.Commonly used to repair	1. High control	1. Limited range

	range of terminology:" Laser engineered net shaping,directed light fabrication,direct metal deposition,3D laser cladding" it is a more complex printing process commonly used to repair or add additional material to existing components		2. Titanium	existing parts and build very large parts	of grain structure 2. High quality dependent on speed 3. High accuracy dependent on accuracy 4. Fast built with rapid materail deposition 5. Fully dense parts 6. Best process for part repair	of materials 2. Poor surface quality 3. Wire process is less accurate

2.6 Designation Additive Manufacturing Process

Additive manufacturing (AM), commonly known as 3D printing, encompasses a variety of processes that create objects by adding material layer by layer based on digital models. The main categories of AM processes include Material Extrusion, where thermoplastic filament is deposited through a heated nozzle, as seen in Fused Deposition

Modeling (FDM); Vat Photopolymerization, which uses UV light to cure liquid resin, exemplified by Stereolithography (SLA); Powder Bed Fusion (PBF), where powdered material is selectively fused by a laser or electron beam, with Selective Laser Sintering (SLS) being a key technique; Material Jetting, where droplets of material are deposited and solidified, as in PolyJet printing; Binder Jetting, involving a binding agent to bond powder particles layer by layer; Sheet Lamination, which stacks and bonds sheets of material cut to shape, as in Laminated Object Manufacturing (LOM); and Directed Energy Deposition (DED), where focused energy sources melt materials as they are deposited, commonly used in metal applications. Each of these processes offers unique advantages, such as the ability to produce complex geometries, reduce material waste, and facilitate rapid prototyping and customization, driving their adoption in diverse industries from aerospace and automotive to medical and consumer products.

2.6.1 Vat Photo-Polymerization

The necessity for precise, fast, and targeted constructions that produce the right biological properties is what led to the adaptation of biomaterials for Vat Photo-

Polimerizations(VPP) 3D printing. The most recent and relevant research demonstrating the complete potential of these biomaterials in 3D printing and the medical industry is compiled in the section that follows. Every biomaterial has unique properties, uses within the medical field, and the potential to be integrated into 3D printing and medicine in the future.

Using an appropriate liquid combination of monomers and oligomers that can polymerize when exposed to light-forming thermosets, vat photopolymerization is carried out. Although there is now a push to employ longer wavelengths of light (visible up to near infrared) in order to overcome the limits of UV radiation, UV radiation is typically used for the photopolymerization process. A photoinitiator that can effectively absorb light and generate reactive species in reaction to that light is necessary for the resin mixture to form, since this will encourage the formation of polymer chains. Photopolymerization is an irreversible process since polymers cannot be transformed back into their liquid, monomeric state. To modify the finished material's characteristics and the liquid resin's behavior during the printing process, additional additives can be used in addition to monomers and photoinitiators. For instance, by lowering the depth to which light penetrates the uncured resin, a photo-absorber is frequently employed to increase the resolution of the final print.

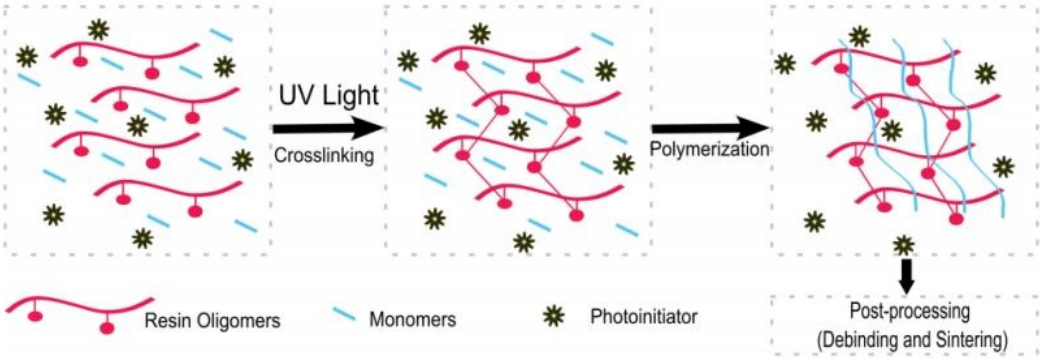


Figure 2.10 The processes of photocrosslinking and polymerization that occur before 3D printing and during 3D printing (Timifticiuc et al.,2023).

2.6.2 Material Jetting

Material jetting to make an object, 3D printing works by layer by layer selectively depositing droplets of a build substance, usually a photopolymer. A print head that resembles those found in inkjet printers moves across the build platform to start the process by ejecting tiny droplets of material. The exact placement of these droplets follows the parameters of the digital 3D model. A UV light source is used to cure or harden a coating as soon as it is deposited. Layer by layer, until the entire item is built, this process is repeated, with the build platform descending incrementally after each layer is finished. Parts with numerous materials and colors can be created by depositing multiple materials at once.

Inkjet printing is a non-contact reprographic technique in the substrate is manufactured using ink drops. This is the largest and most common inkjet printing method known as drop-on-demand (DOD). There are also two other groups: continuous-inkjet printing and electro-hydrodynamic jet printing Piłczyńska et al (2022).

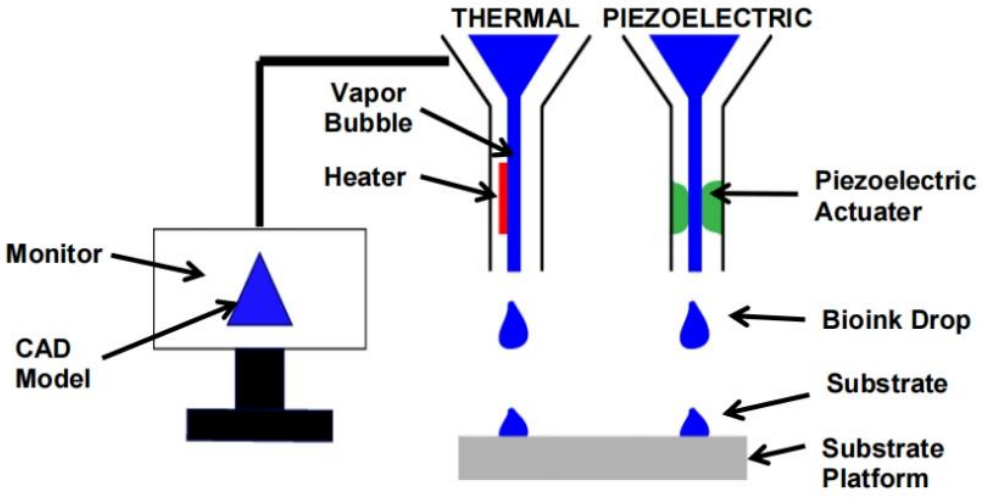


Figure 2.11 Material jetting by inkjet printing process (Piłczyńska et al.,2022).

2.6.3 Binder Jetting

Binder jetting In order to create an object using 3D printing, a liquid binding agent is selectively deposited layer by layer onto a bed of powder material. The first step in the process is to cover the construction platform with a thin coating of powder, such as metal, sand, or ceramic. Subsequently, an inkjet print head passes over this layer, precisely placing the binding agent where the digital 3D model directs. The powder particles are joined by this binder to create a solid coating. A fresh layer of powder is applied on top of the completed layer, which causes the build platform to slowly descend. Until the entire item is produced, this sequence is repeated. The bound item, sometimes referred to as the "green part," usually goes through further post-processing procedures after printing, such as curing or sintering, to enhance its strength and durability.

The basis of the BJ method is powder. As a result, the powder deposition process is essential to producing components fast and reliably. Although particles can flow similarly to

liquids, they behave in far more complicated ways. In order to consistently generate dense, flawless layers, inter-particle forces might vary with size, shape, composition, and humidity. Various methods may be needed. The deposition process is determined by the parameters of the powder flow. Standard BJ (Binder Jetting) powders (30 μm or greater) are treated in a dry condition, although with more careful process parameter adjustment, smaller particles have been effectively deposited and dispersed. Particular powder treatments could be needed. An alternative is to create agglomerates out of tiny granules. To increase packing density and consistency Ziaee et al (2019). For the smallest size ranges, the powder is frequently dissolved in a liquid

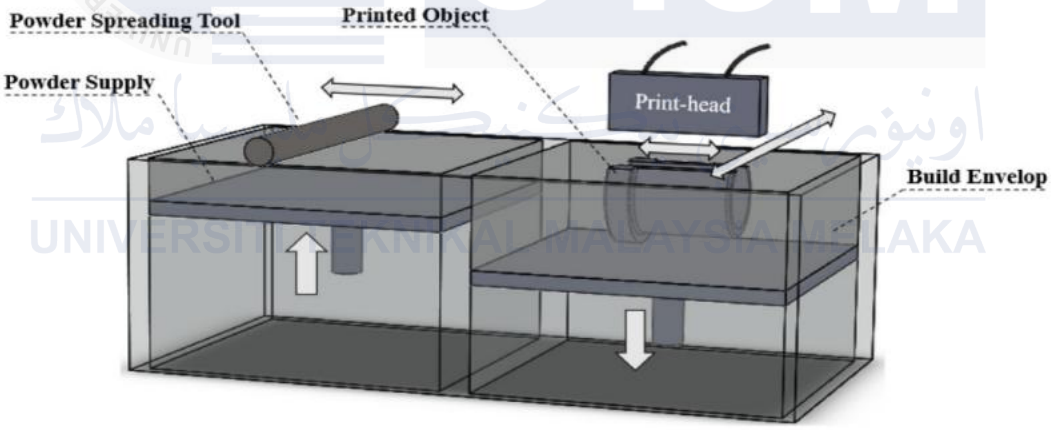


Figure 2.12 Binder jetting system schematic (Ziaee et al.,2019).

2.6.4 Material Extrusion

Material extrrusion for the process of 3D printing, sometimes referred to as fused deposition modeling (FDM), uses a heated nozzle to extrude thermoplastic filament to create objects. The filament is first fed into the heated nozzle, where it melts and is subsequently extruded onto a build platform layer by layer. The nozzle follows the route specified by the digital 3D model as it advances in both horizontal and vertical dimensions. Each layer is formed by the molten material cooling and solidifying as it is deposited by the nozzle. The build platform lowers slightly to make room for the following layer when a layer is finished, and so on until the entire item is constructed. If there are overhangs or intricate geometries in the design, support structures might be printed concurrently.

The temperatures at which material extrusion is done range from 165°C to 300°C. The ideal processing temperature is contingent upon several factors, including the unique characteristics of the polymeric material, the hotend of the printing apparatus, the particular printing settings, and the virtual part's shape.To ensure that neither the natural reinforcing component nor the polymer utilized deteriorate, natural fiber reinforced composites (NFC) should be treated at temperatures lower than 200°C. Material extrusion functions well at these low temperatures, therefore processing NFC shouldn't provide any significant issues. Ecker and associates (2017)

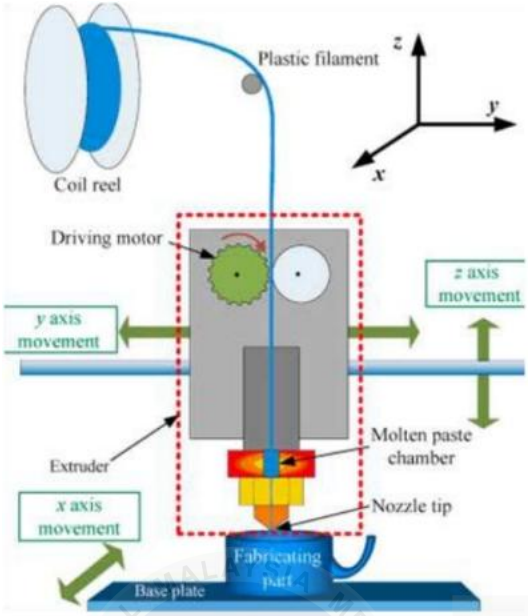


Figure 2.13 Schematic diagram of Fused Deposition Modeling (FDM) (Ecker et al.,2017)

2.6.5 Powdered Bed Fusion

Powder Bed Fusion (PBF) is an additive manufacturing technique that builds parts layer by layer using a powdered material, typically metal, polymer, or ceramic. The PBF process involves several key steps: powder spreading, selective fusing, and layer addition, which are repeated until the entire part is complete. The process begins with a thin layer of powdered material being spread across the build platform using a roller or a blade. The powder layer is usually very thin, often in the range of 20 to 100 micrometers, to ensure fine detail and precision in the finished part.Once the powder layer is spread, a high-energy heat source, such as a laser or an electron beam, scans across the powder bed, selectively fusing the powder particles together to form a solid cross-section of the part. The heat source is directed by a digital 3D model, which slices the design into individual layers. In the case of laser-based PBF, such as Selective Laser Sintering (SLS) or Direct Metal Laser Sintering (DMLS), a laser beam melts and fuses the powder particles. For electron beam-based PBF,

like Electron Beam Melting (EBM), an electron beam is used instead. The heat source's path is controlled precisely to ensure accurate melting and bonding of the particles. After a layer is fused, the build platform lowers by the thickness of one layer, and a new layer of powder is spread over the previously fused layer. This process is repeated, with each new layer being selectively fused on top of the previous one, building the part from the bottom up. The surrounding unfused powder acts as a support for overhanging structures and complex geometries, eliminating the need for additional support structures in many cases. Once the entire part is completed, it is buried within the powder bed. The next step is to carefully remove the part from the loose, unfused powder. The loose powder can typically be recycled and reused for future builds, making the process efficient and cost-effective. The extracted part, known as the "green part," often requires additional post-processing steps. These can include heat treatment, such as annealing or sintering, to relieve residual stresses and improve mechanical properties, or machining and surface finishing to achieve the desired surface quality and dimensional accuracy Singh et al (2021).

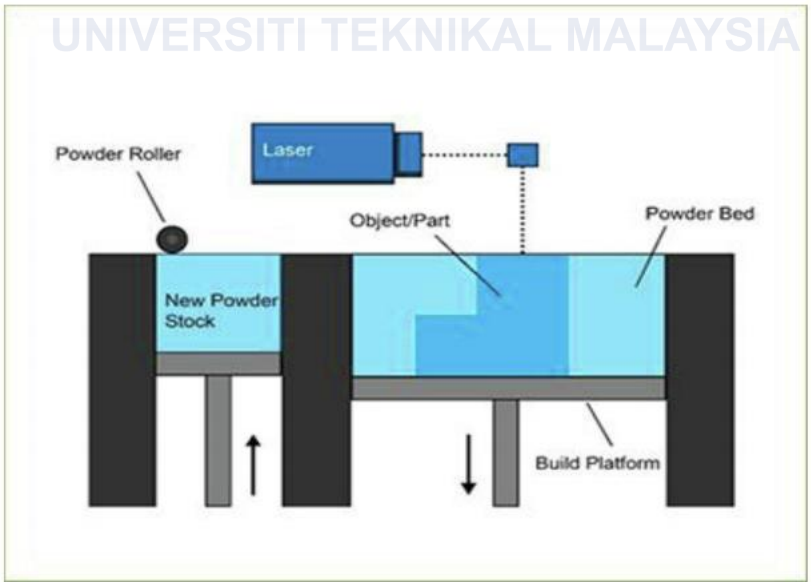


Figure 2.14 Schematic diagram for Selective Laser Melting (SLM) (Singh et al.,2021).

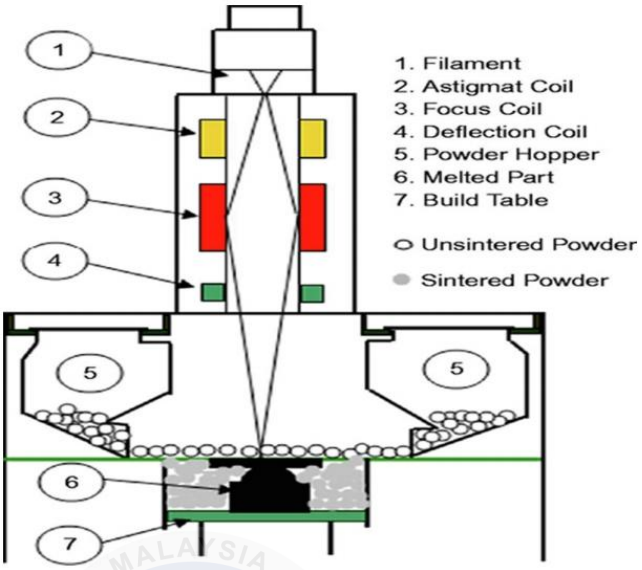


Figure 2.15 Schematic diagram for Electron Beam Melting (EBM) (Singh et al.,2021).

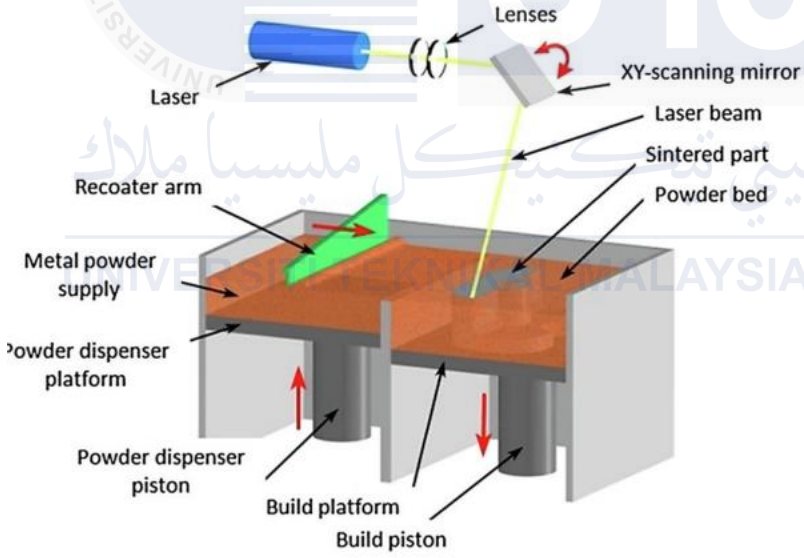


Figure 2.16 Schematic diagram for Direct Metal Laser Sintering (DMLS) (Singh et al.,2021).

2.6.6 Sheet Lamination

Sheet lamination is a distinctive 3D printing technology that builds objects by stacking and bonding sheets of material, which are then precisely cut to shape layer by layer. This method combines aspects of both additive and subtractive manufacturing processes. The following is a detailed explanation of the sheet lamination process. The process begins with the selection of sheet material, which can include paper, plastic, metal, or composite materials. Each sheet is pre-coated with an adhesive or, alternatively, an adhesive is applied during the process. The first sheet of material is placed on the build platform. A roller or other mechanism ensures that the sheet is flat and properly aligned.The bonding method varies depending on the material used. For paper and plastic sheets, a heated roller or ultrasonic welding is often employed to bond the layers together. For metal sheets, ultrasonic welding or other high-energy processes such as laser bonding are used. Ultrasonic welding involves high-frequency ultrasonic acoustic vibrations that create a solid-state weld between layers.

Once a sheet is bonded to the previous layer, a cutting mechanism, usually a laser or a blade, cuts the desired shape of the layer based on the digital 3D model. This step is where the subtractive aspect of the process comes into play. The laser or blade precisely follows the contours of the design, cutting through the sheet material to form the layer's cross-section. After cutting, any excess material that is not part of the design is removed, either manually or automatically. The build platform then lowers by the thickness of one sheet, and the next sheet of material is positioned for the next cycle of bonding and cutting. This layer-by-layer approach continues until the entire object is formed. Once the printing is complete, the object may require additional post-processing to improve its mechanical properties or surface finish. For example, the object may undergo further bonding to ensure

layer adhesion, surface smoothing to remove any rough edges from the cutting process, or additional curing if a thermosetting adhesive was used. For metal parts, post-processing might include heat treatment to enhance material properties.

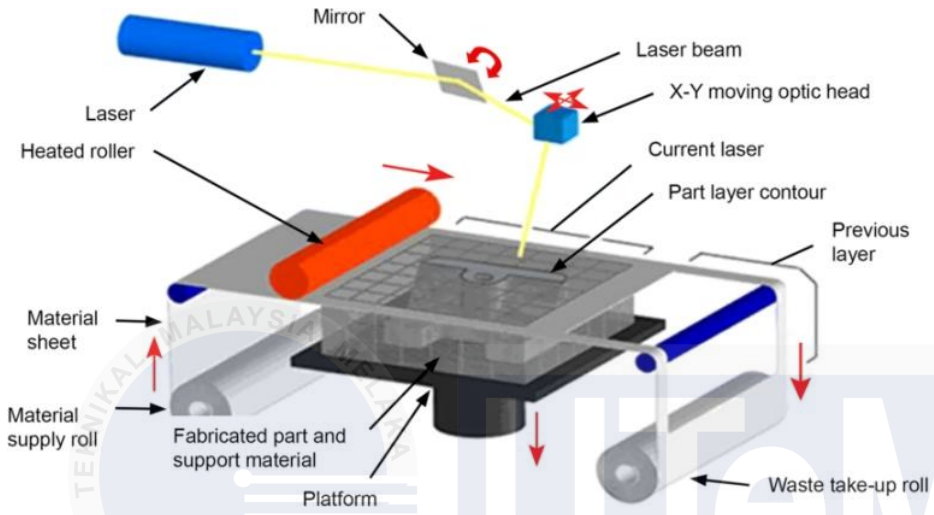


Figure 2.17 Schematic diagram for Sheet Lamination process (Mercado et al.,2020)

2.6.7 Direct Energy Deposition

Direct Energy Deposition (DED) is an advanced additive manufacturing process that involves the focused application of energy to melt materials as they are being deposited to build or repair parts layer by layer. DED is commonly used with metals, but it can also process ceramics and polymers. The process begins with a high-energy source, typically a laser, electron beam, or plasma arc, which is directed at the deposition area on the workpiece. This energy source creates a small, localized melt pool.

Material, in the form of powder or wire, is simultaneously fed into this melt pool using a nozzle. The material melts upon contact with the energy source, and as the energy source moves according to the path defined by a digital 3D model, the molten material solidifies to

form a new layer. This deposition and melting process continues, with each new layer bonding metallurgically to the previous one, creating a dense and fully formed part.

One of the key advantages of DED is its ability to add material to existing components, making it particularly valuable for repair applications. For instance, damaged parts in aerospace or heavy machinery can be restored to their original specifications by adding material only where needed. This process not only extends the life of high-value components but also reduces material waste and cost compared to manufacturing a completely new part.

DED systems are typically mounted on multi-axis robotic arms or CNC machines, which provide the precise control necessary to deposit material accurately and consistently. The ability to manipulate the nozzle and energy source in multiple directions enables the creation of complex geometries and internal features that would be difficult or impossible to achieve with traditional subtractive manufacturing techniques.

The DED process begins with preparing the digital 3D model, which is sliced into layers to generate the tool paths for the deposition head. The substrate, or base material, is cleaned and prepared to ensure proper adhesion of the deposited material. The high-energy source is then activated, creating the initial melt pool, and material feed begins. The process parameters, such as laser power, feed rate, and travel speed, are carefully controlled to achieve the desired material properties and part geometry.

As the process continues, real-time monitoring systems, such as thermal cameras and sensors, are often used to ensure quality and consistency. These systems can detect anomalies in the melt pool or deposition process, allowing for immediate adjustments to maintain the integrity of the part being produced.

After the deposition process is complete, the part may undergo post-processing steps to achieve the final specifications. These steps can include heat treatment to relieve residual stresses, machining to achieve precise dimensions and surface finishes, and inspection to ensure the part meets the required standards.

316L stainless steel powder was utilized in this DED investigation. The powder particle with a spherical form has a size range of 1 µm to 100 µm. Before starting to print, the material was warmed to 40º Celsius. In this investigation, the substrate chosen for the printing trials was stainless steel. The cast iron engine heads that were in use Zhang and associates (2021).

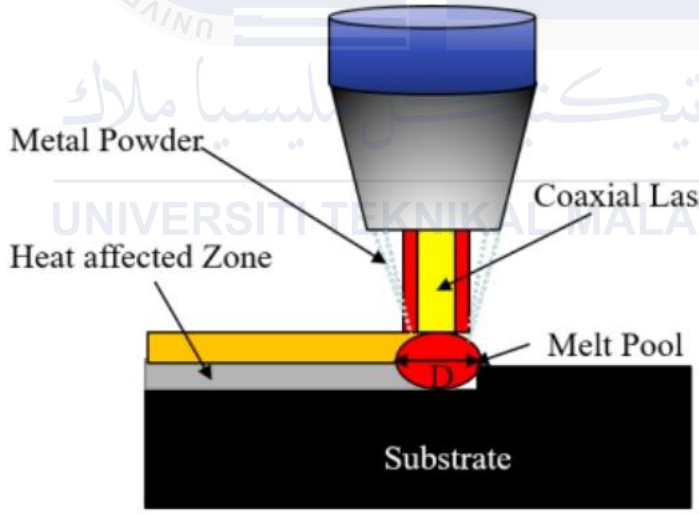


Fig. 2. A schematic diagram of the DED process

Figure 2.18 Schematic diagram for Direct Energy Deposition (Zhang et al.,2021).

2.7 Material Used In 3D Printing For Medical Purpose

The material that needs to be used for 3D printing for medical purposes needs to be polymers that have unique properties such as flexibility and anti-corrosion since it was used for arteries. The materials that can be used in 3D printing for medical purposes are Biocompatible polymers, such as Acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), and polyether ether ketone (PEEK), and Polycarbonate (PC) which are commonly used for creating patient-specific implants, prosthetics, and anatomical models due to their favorable interaction with biological tissues. Hydrogels, which can mimic the physical properties of soft tissues, are employed for printing tissue scaffolds in regenerative medicine. Metals like titanium and its alloys are essential for producing durable and strong orthopedic implants and dental prosthetics. Additionally, bio-inks, which incorporate living cells, are used in bioprinting to create complex tissue structures and potentially even organ fabrication. These materials must meet stringent biocompatibility standards and often undergo rigorous testing to ensure they are safe and effective for medical use.

Table 2.2 Comparison of different materials for the 3D Printing process and their material properties

Materials	Printing Process	Measured Properties
Acrylonitrile butadiene styrene (ABS)	Fused deposition modeling	Tensile Strength: 27–31 MPa; Layer height: 0.05–0.14 mm; Processed at 210–240 ◦C.
Polycarbonate (PC); Biomaterial blend	Fused deposition modeling	Tensile Strength: 35–65 MPa; Elastic Modulus: 2100 MPa; Nozzle Temperature: 240–270 ◦C; Orientations of 0◦ to 90◦.
Polyether ether ketone (PEEK)	Fused deposition modeling	Tensile Strength: 58–85 MPa Elastic Modulus: 3000–4100 MPa; Temperature dependent.
Polylactic acid (PLA)	Fused deposition modeling	Tensile Strength: 28–56 MPa; Elastic Modulus: 2000 MPa; Orientations of 0◦ to 90◦.

2.7.1 Acrylonitrile butadiene styrene (ABS)

A popular thermoplastic polymer is acrylonitrile butadiene styrene (ABS), with the chemical formula (C8H8)x·(C4H6)y·(C3H3N)z. Its temperature at which glass transitions is around 220 °F (104 °C). Since ABS is amorphous, it lacks a precise melting point. Styrene and acrylonitrile are polymerized in the presence of polybutadiene to create ABS, a terpolymer. The percentages can range from 40% to 60% for styrene, 5% to 30% for butadiene, and 15% to 35% for acrylonitrile. The end product is a lengthy polybutadiene chain that is intertwined with shorter poly(styrene-co-acrylonitrile) chains UMAROVA et al (2021).

2.7.2 Polycarbonate (PC); Biomaterial Blend

It is well recognized that this substance is a strong, translucent plastic with exceptional impact, stiffness, and strength. Up to 140˚C, PC retains its stiffness, and down to −20˚C, it remains tough. There are rumors that this substance burns slowly like a polymer. For example, when mixed with a specific flame retardant, it passes multiple rigorous flammability tests. This study investigates the best printing settings for this material, concentrating on two key levers: an infill rate of 10% to 100% and a printing temperature between 270˚C and 300˚C. Bahar and associates (2022).

2.7.3 Polyether Ether Ketone (PEEK)

It features a low coefficient of friction and a good wear resistance without the need for lubrication. Owing to its durability, this material is utilized in the production of high-stakes items such compressor plate valves, pumps, electrical cable insulation, pumps, piston components, and medical implants. Applications requiring ultra-high vacuums can also use it. This material can be used in situations where a constant high temperature is required since its melting point is 343 °C. In 2019, Haleem et al (2019)

Table 2.3 Basic properties of Polyether Ether Ketone implants (Haleem et al.,2019).

S. No	Property	Description
1	Excellent biocompatibility	• PEEK material is biocompatible • It easily interacts with the human body and increases the success rate for medical applications such as replacement of prosthesis, stents, and other medical implants • Use of nano-material helps PEEK implants to perform required function concerning medical therapy that increase the performance of patient during surgery • These implants can implement in the patient body without causing deleterious changes
2	Less weight	• Implants manufactured by PEEK material have less weight as compared to other traditional material being used for the same purpose • These implants provide a natural look and feel with excellent safety and characteristics • Lightweight PEEK implants enhance comfort, safety and quality of life of the patient
3	Good mechanical properties	• PEEK implants can withstand and not deform during a load of the whole body • It provides constant function during the variation of the temperature of the body • It has high rigidity, modulus stability and chemical resistance
4	High tensile strength	• These implants have high tensile strength under the action of the load • Implants have maximum tensile strength can withstand before breaking which is beneficial for the human body • Its tensile strength is 90–100 MPa
5	Low moisture absorption	• This material has a low moisture absorption • It needs less drying time which is suitable for a medical purpose
6	High flexible	• PEEK material is capable of bent easily without breaking • Has better flexibility
7	Suitable for high vacuum or pressure applications	• Used in medical for the manufacturing of pressure or vacuum devices • It increases the performance of devices that have highly resistant to most chemicals
8	Stable high temperature	• PEEK materials stable high temperature which is beneficial for medical and engineering applications • It melts at 343 °C which have a high melting temperature as compared to most of other thermoplastics • It has good toughness, low toxicity and excellent abrasion resistance.

2.7.4 Polylactic Acid (PLA)

PLA demonstrates thermoplastic properties and is biodegradable. PLA has become an important material for bioengineering even though it has contemporary industrial uses, such as in textiles and packaging. Uses in orthopedics, cardiology, dentistry, and tissue engineering are a few examples of pertinent medical applications. PLA has the following characteristics: a flexural modulus of 5 GPa, a flexural strength of 100 MPa, an approximate tensile modulus of 3 GPa, and an approximate tensile strength of 50–70 MPa. In 2020, DeStefano et al (2020)

Table 2.4 Physical characteristics of Polylactic Acid (PLA) (DeStefano et al.,2020).

Characteristics	Unit	Amount
Molecular Weight (MW)	g/mol	66,000
Specific Gravity		1.27
Solid Density	g/cm^3	1.252
Melting Density	g/cm^3	1.073
T_g	°C	55
T_m	°C	165
Specific Heat (Cp)	J/kg °C	
190°C		2060
100°C		1955
55°C		1590
Thermal Conductivity	W/m °C	
190°C		0.195
109°C		0.197
48°C		0.111

2.8 Summary

This chapter begins with a summary of all the data from the earlier researchers' studies on the use of 3D printing in medicine, stressing the technology's revolutionary potential to transform patient care and medical treatment as well as its transformative impact across a range of healthcare applications. Research shows that 3D printing improves preoperative planning and precision in complex surgeries by enabling the quick production of patient-specific models, surgical guides, and custom implants. The technology's capacity to produce intricate anatomical replicas helps with medical education and training by giving professionals and students practical experience. Furthermore, printing tissues and organs is becoming possible thanks to developments in biocompatible materials and bioprinting methods. This has implications for organ transplantation and regenerative medicine. Clinical trials and case studies show how 3D-printed medical devices, like dental prosthetics and orthopedic implants, can improve patient outcomes by providing individualized care. The significant role that 3D printing will play in the future of medicine is highlighted by the fact that, despite current challenges with regulatory approval and scalability, ongoing research and technological innovations continue to bridge the gap between experimental applications and widespread clinical use.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter will explain the techniques and methods used to collect, select, and analyze the data on this topic. This researcher employed process flow to achieve the goals of this project. This study will be divided into four stages. The first stage is doing a simulation of the arteries using MIMIC software. After the MIMIC has simulated the arteries, the drawing file will be transferred to the desired 3D printing machine for the second stage. The third stage will involve testing the material properties of fabricated arteries such as tensile and hardness according to the ASTM standard. The collected data from the mechanical properties will then be analyzed in the final stage.

3.2 Process Flow Chart

a) Reconstruction of Left Coronary Artery (LCA) using Patient's CT-Scan data (Using MIMICS Materialize software) and 3D modeling and analysis of LCA using ANSYS 2022 (R2).
b) The developed model has been used to produce protype using 3D print techniques.

c) Analysis of LCA model for Hemodynamic parameters such as evaluation of Pressure. Velocity & WSS.

The flowchart represents a procedure with steps that are performed progressively. The flow chart can assist in understanding each phase of the process and how it is carried out. To complete the workflow, the study began with preparations of the techniques that can be used, followed by the fabrication process, the proper mechanical test methods, and the analysis of the results.

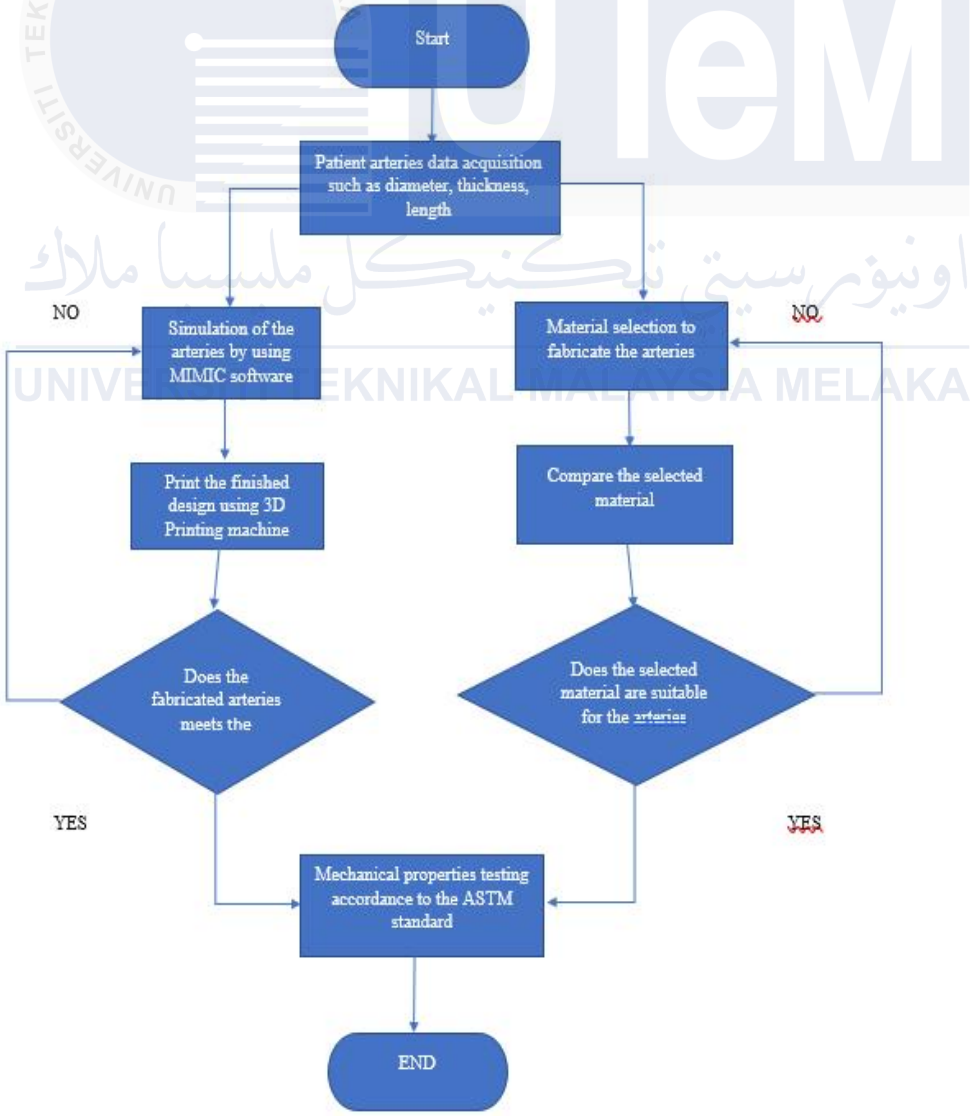


Figure 3.1 Flowchart for overall process in fabricating the artery

The first stage of the process begins with collecting the patient's arteries data such as the thickness of the arteries, diameter, and length of the arteries. This step can be done using the CT-scan machine from the radiology department at any medical institute such as a hospital and clinic. The next step required the MIMIC software to simulate the arteries so that the expected analytical results could be made from the simulation. The materials must also be researched to choose the suitable mechanical properties for the arteries. The third step involves fabricating the arteries using the 3D Printing machine. The finished fabricated arteries will then be compared with variable materials to test the requirements from the expected analytical results. Finally, the mechanical properties of the arteries will be tested according to the ASTM standard to determine whether the fabricated arteries meet the criteria. A flowchart summarizing the overall process implemented throughout this work is shown in Figure 3.1

3.3 Data Acquisition of Patient Data

The data of the left coronary artery from the patient are needed to generate an accurate simulation in the MIMIC software. The data can be gained from the MRI (Magnetic Resonance Imaging) or CT scan (Computed Tomography). CT scan is used to capture data from an inside organ and at a different density level of the human body

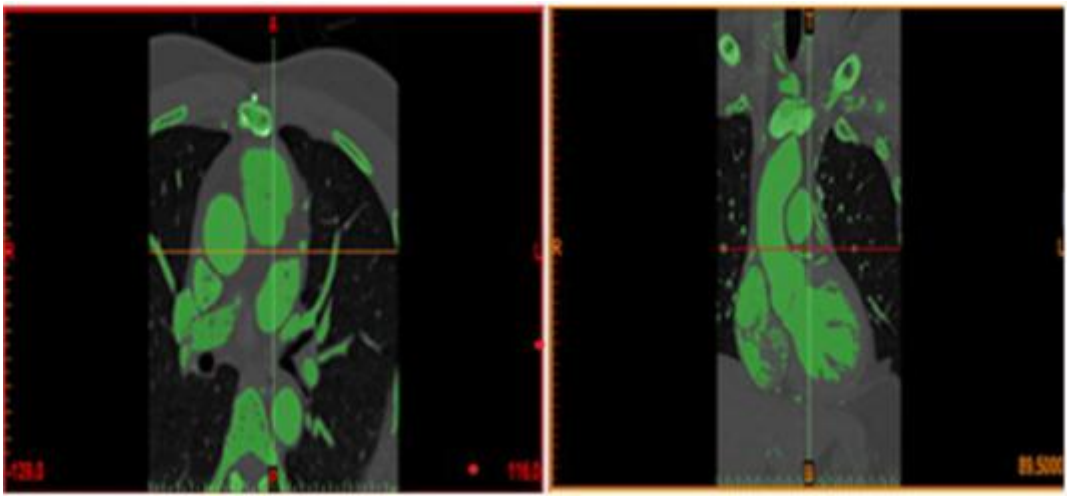


Figure 3.2 Computed tomography (CT) images (posterior and interior) and Volume rendering image with location of LCA using image processing software, MIMCS (Athani, A et,al 2023).

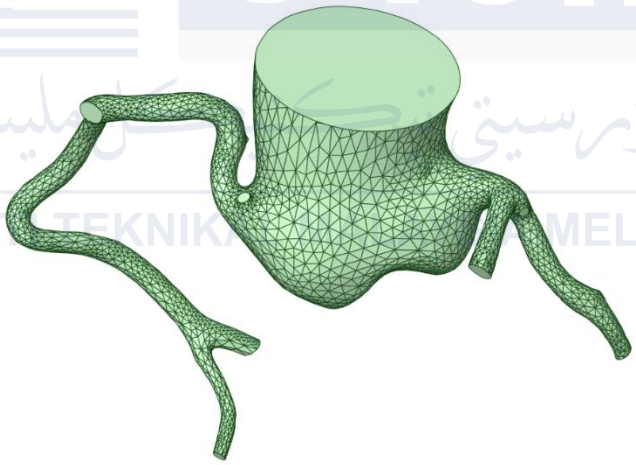


Figure 3.3 Generated image of the Left Coronary from the MIMIC software

The computed tomography (CT) images were picked up as follow; resolution time frame set to 0.6 mm, beam collimation fixed at 0.6 with a pitch of 1.4, and tube voltage maintained at 100 kVp, and the current wavering from 300 to 650 mAs. The picture replication in the critical thickness of the hub positions is at 0.6 mm, with a 0.75 mm of steady separation. In all the postures, the images consisted of more than 400 slices. The

collected images were saved in the standard DICOM format configuration as shown in Fig. 3.2 where it shows the three-dimensional main left coronary models is modified using a CT volume rendering as prescribed in previous similar studies. Fig. 3.2 shows the medical imaging process software, the MIMICS and 3-matic Research (Materialize, Belgium) and Fig.3.3 represents the final reconstructed model for discretization.

3.4 Simulation of Patient Left Coronary Artery

As discussed in the previous chapter, for the refinement of artery, it is required to use the latest specialized software such as ANSYS Workbench. Two procedures are important for artery image refinement. The first step is segmentation. DICOM (Digital Imaging and Communication in Medicine) will be imported into a 3D slicer formatted file in this part. Focused the arteries part that needs to be fabricated using region growing techniques to separate the other blood vessels from mixing. The second step for this stage is, converting the segmented 2D slices into a 3D model by using software reconstruction inside the 3D Model Creation. The STL (Standard Tessellation Language) file will be used for deeper image processing.

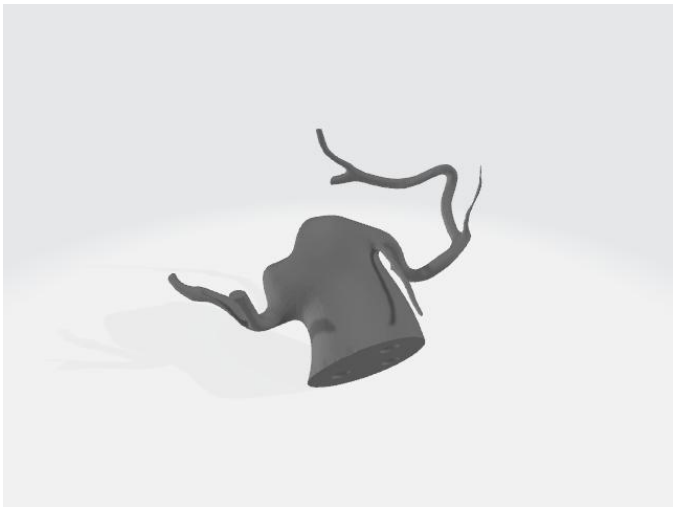


Figure 3.4 Simulation on the patient left coronary artery

3.5 Fabrication of the Model Using 3D Printing Machine

As mentioned in the previous chapter, it is important to choose the high resolution 3D printing machine to produce high-quality products at the end of the process. The suitable 3D printing machine to print high-quality arteries is FDM (Fused Deposition Modelling) printers. Plus, high-quality and suitable materials are also crucial to generate high-quality arteries. The selected material for this process is TPU (Thermo Plastic-Polyurethane) filament because of the desired material properties that are mentioned at the beginning of this chapter. After the 3D machine and type of the material had been decided, the next process was to print the model. Import the STL (Stereolithography) file into the 3D printing machine. The desired parameters such as layer height, print speed, and structure support need to be set up before the printing process begins. This step will make sure the printing quality always stay guaranteed all the time.

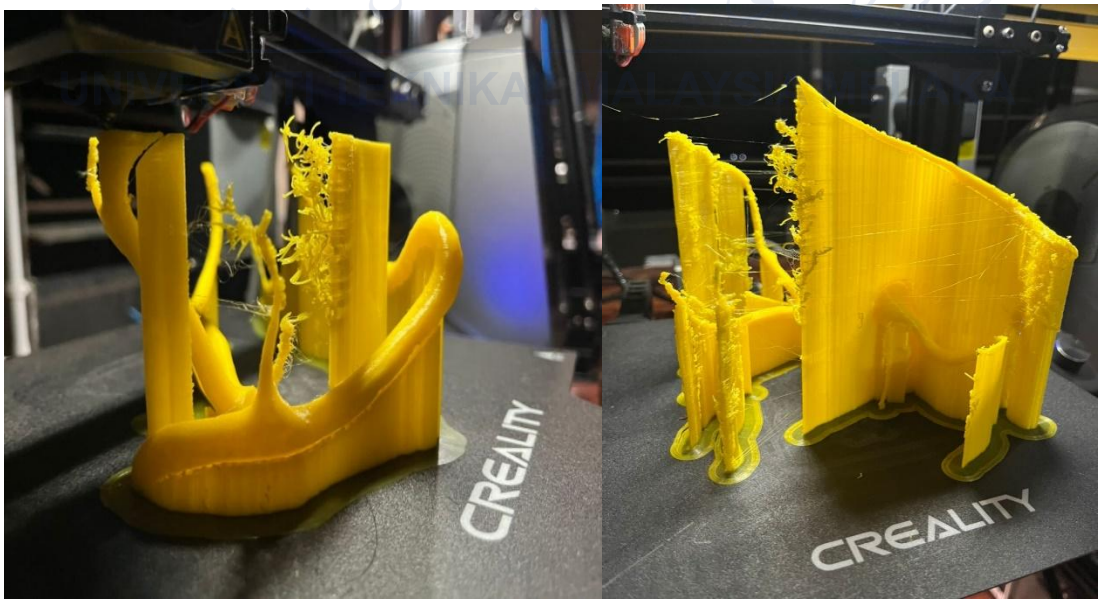


Figure 3.5 Fabrication of the left coronary artery using 3D printing machine

3.6 Post Processing Process

The post-processing process can be divided into three processes: cleaning, finishing and sterilization. This process is important to guarantee the smoothness and detail of the arteries. The first step is cleaning. This process focuses on removing the support holding the arteries and any excess material from the arteries. Then, the next step is finishing. This process used sanding and rolling techniques to increase the surface finish of the arteries. The surface finish product from the 3D printing process usually has a stacked-layer surface. Hence, sanding and rolling techniques can be used to reduce that surface. The final step is sterilization. If the model was intended for the clinical setting, then it is important to sterilize the product before it is handed to them.

Figure 3.6 3D printed Prototype of Left coronary artery

CHAPTER 4

RESULT AND DISCUSSION

4.1 Design and 3d Model

The generated STL image from the CT scan will be used to continue the blood flow analysis inside the left coronary artery. This is the first step in the blood flow analysis, which has been made using ANSYS Workbench.

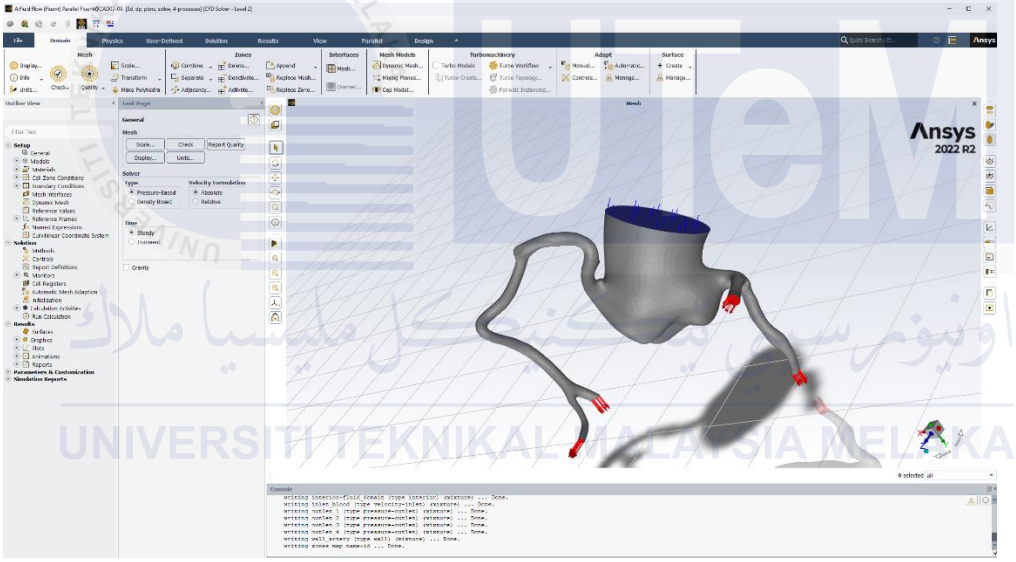


Figure 4.1 The setup for the inlet and outlet for the blood flow

4.2 Optimize Design

Researchers can now better understand the intricate hemodynamics of the human circulatory system thanks to computational fluid dynamics, which has become a crucial tool in the development of cardiovascular engineering Dur et al (2010). However, the efficient use of CFD for practical applications is severely hampered by the time-consuming nature of fixing non-watertight geometries and the patient-specific intricacy of cardiovascular illnesses. In order to overcome these problems, this study investigates the use of GPU-accelerated digital twins of the human heart, which can help cardiovascular research be conducted in a

methodical manner and lessen the need for actual patient data and the moral and financial ramifications that come with it Viola et al (2023).

4.2.1 Materials used for 3d print

The material that has been chosen is TPU (thermoplastic Polyurethane) as this material is more flexible and has a similar condition to function like the human right coronary artery. Current technology nowadays uses material that is more biocompatible for human purposes, but TPU material is also compatible for use inside the human body, but it has some degradation time.

Table 4.1 Material degradation comparison

Material	Degradation Time
TPU (Thermo Plastic-Polyurethane)	6-24 months
Collagen	5 hours
PCL (Polycaprolactone)	2-18 months
PLA (Polylactic-Acid)	6-8 months

4.3 Velocity Distribution

The right coronary artery's flow dynamics can be evaluated and regions of high shear stress or flow separation that might aid in the development of stenosis can be found by applying a range of inlet velocities to the CFD model Viola et al (2023). The CFD analysis's findings can offer important information about how well the right coronary artery is functioning, including the location of areas that might be more likely to develop blockages or other problems. Despite the study's encouraging findings, there are a few things to keep in mind. The applied velocity at the right coronary inlet in this simulation study ranges from 0

m/s to 0.4 m/s. The flow of blood within the artery during the systolic and diastolic phases serves as the basis for this applied velocity. The pressure of blood moving inside the human heart is known as the systolic process, while the pressure of the heart or human blood traveling outside the human heart is known as the diastolic process. Under typical circumstances, the pressure that normally acts on the human heart is around 120 mmHg, or 15.99 kPa.

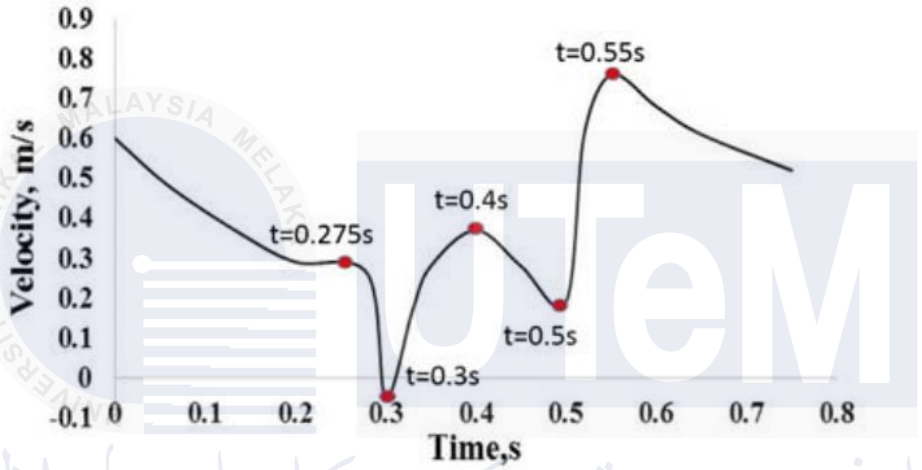
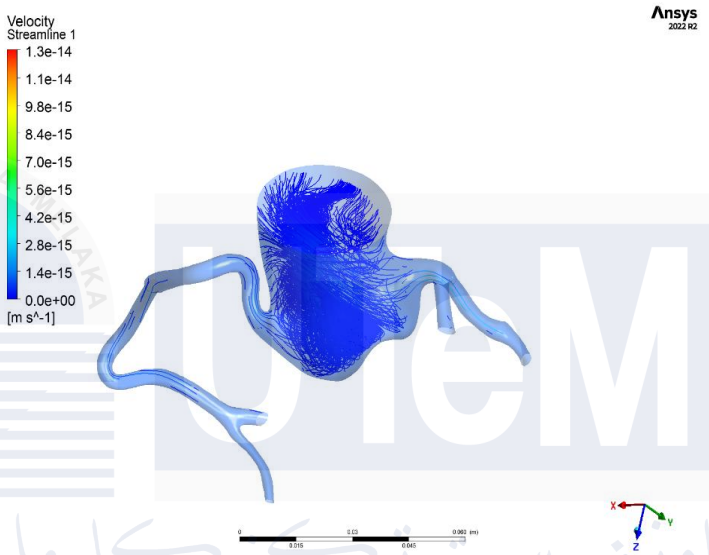
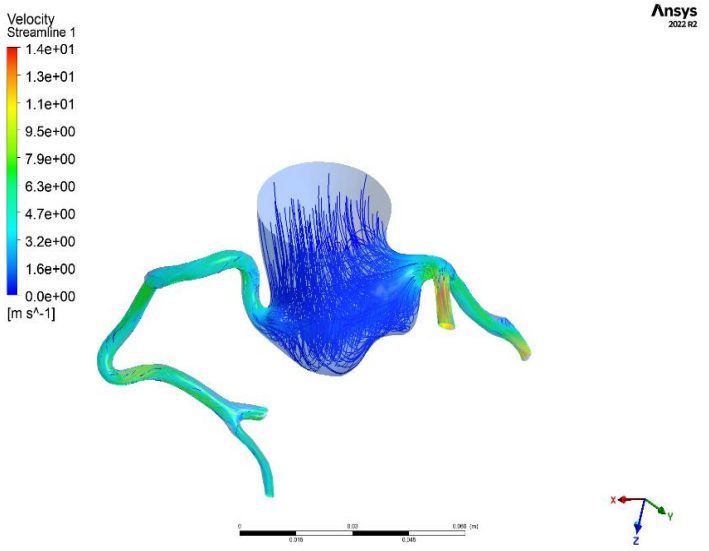
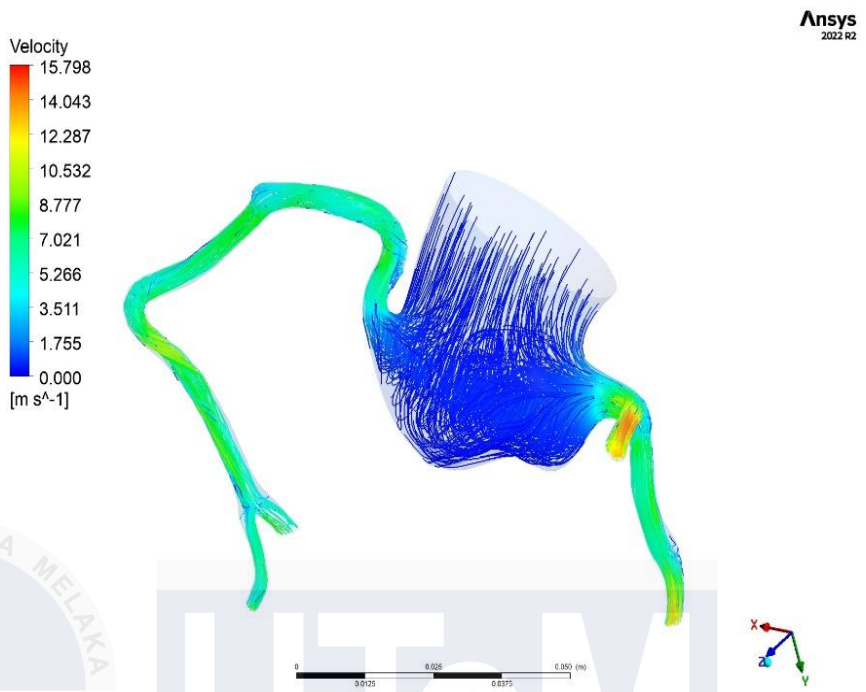
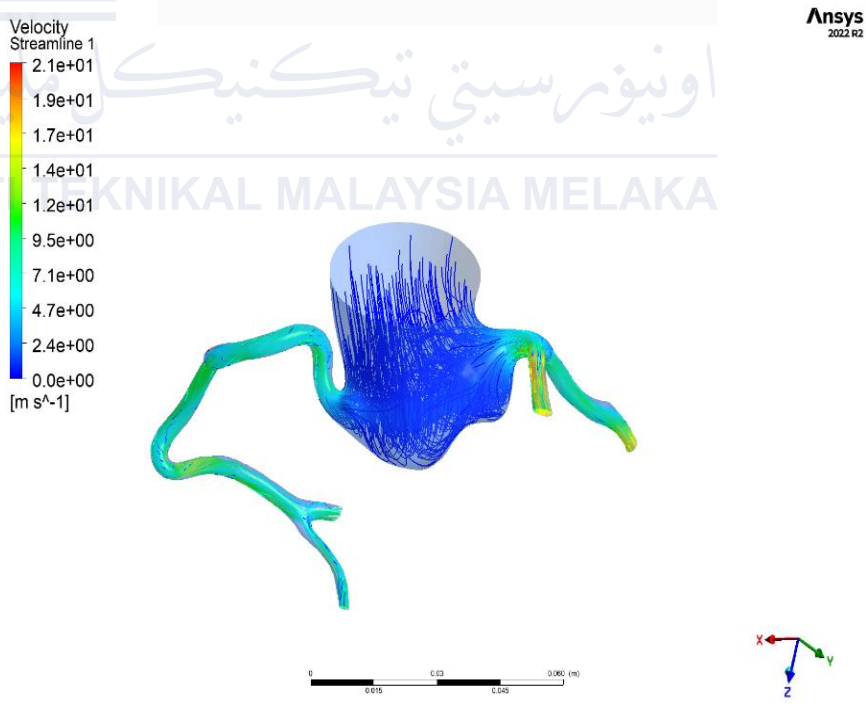
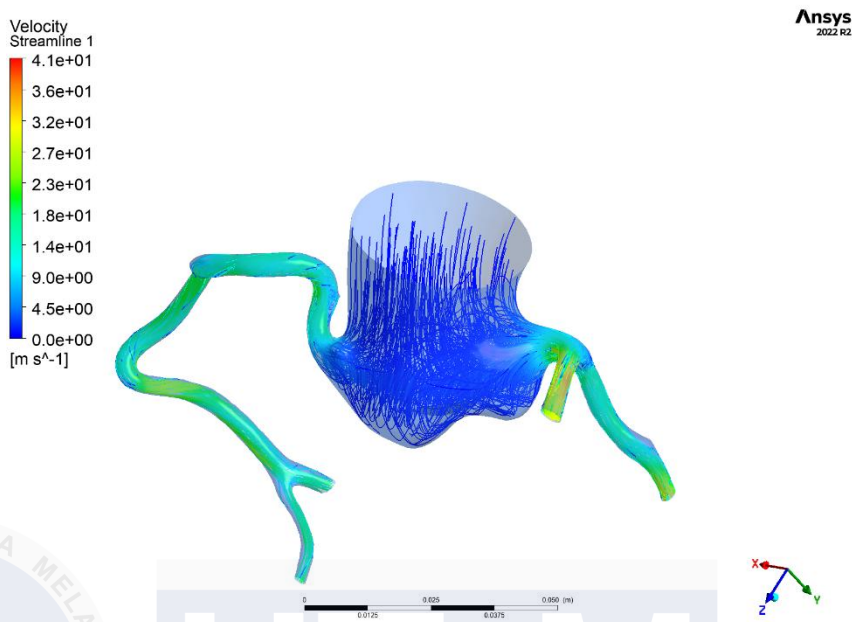


Figure 4.2 Inlet pulsatile coronary velocity profile for blood (plasma and RBC) along the time of the cardiac cycle Buradi et al (2018)

Table 4.2 Velocity Distribution Simulation

No.	Blood flow Condition (Systolic and Diastolic)	Velocity Distribution Inside the Left Coronary Artery
1	0 m/s (Early Systolic condition)	 Figure 4.3 Velocity distribution simulation for inlet velocity 0 m/s
2	0.275 m/s (End of Diastolic)	 Figure 4.4 Velocity distribution simulation for inlet velocity 0.275 m/s

3	0.3 m/s (Early Systolic Condition)	 Figure 4.5 Velocity distribution simulation for inlet velocity 0.3 m/s
4	0.4 m/s (Maximum Systolic Condition)	 Figure 4.6 Velocity distribution simulation for inlet velocity 0.4 m/s

5	0.75 m/s (Beginning of Diastolic condition)	 Figure 4.7 Velocity distribution simulation for inlet velocity 0.75 m/s

Based on the CFD analysis above, there are four condition for the velocity of the blood. The minimum value for the velocity for the blood is 0 m/s, it does not indicate that the heart is not working but it indicate that the heart is doing the contraction. During this phase, the blood inside the artery will stop moving for certain amount of time then will begin to move when the heart start pumping the blood again. On average human heart beat is 85 bpm (beat per minute). So this analysis was generated based on the average human heart beat during resting condition.

Table 4.3 Velocity Distribution Result

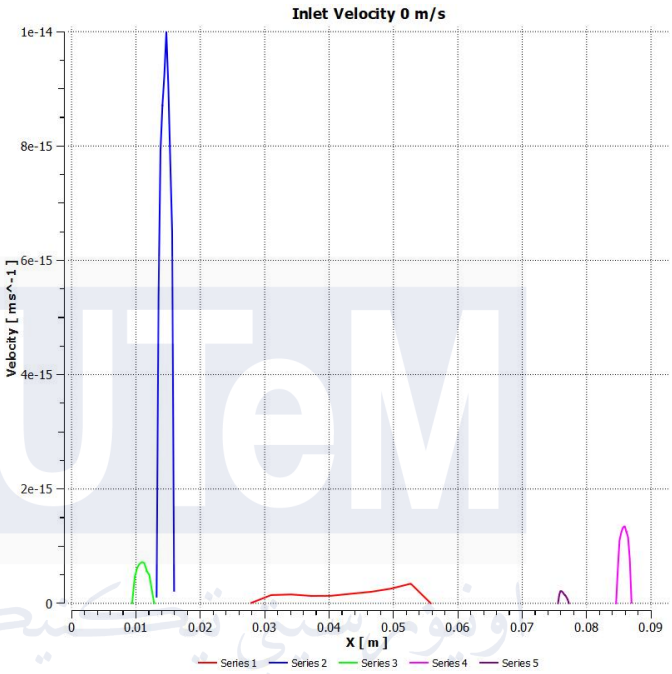
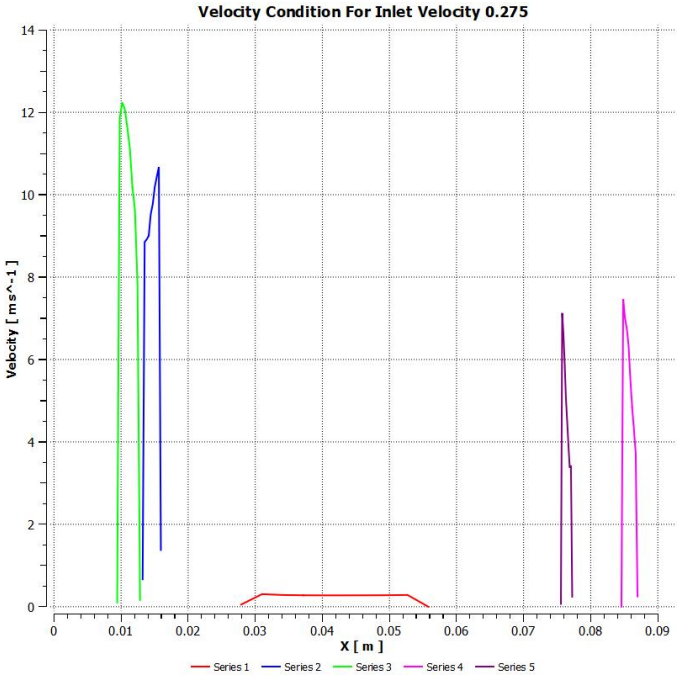
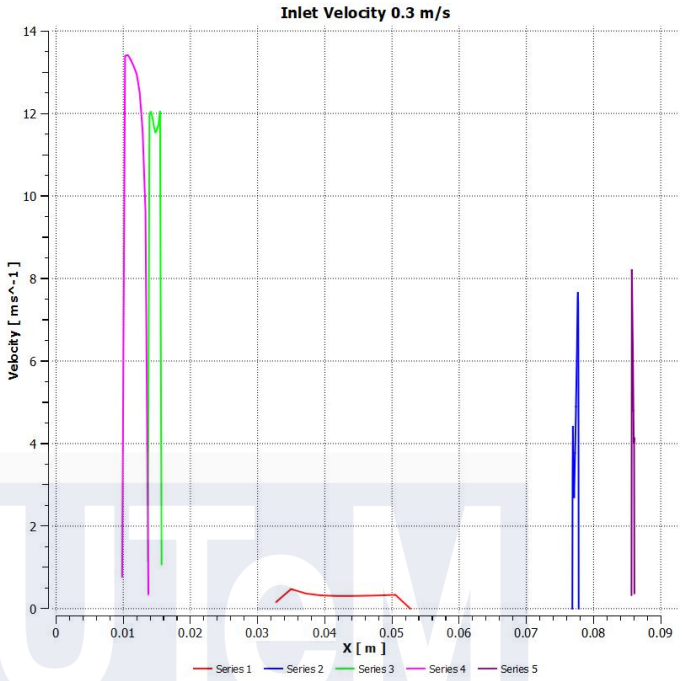
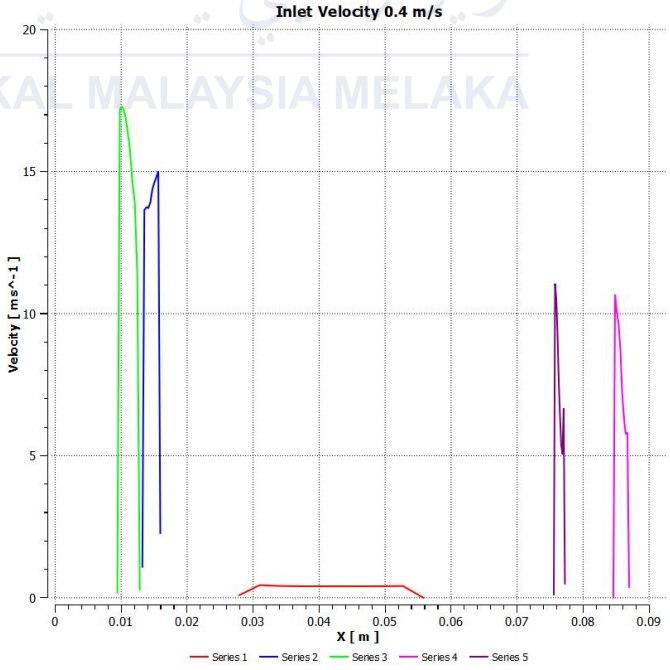
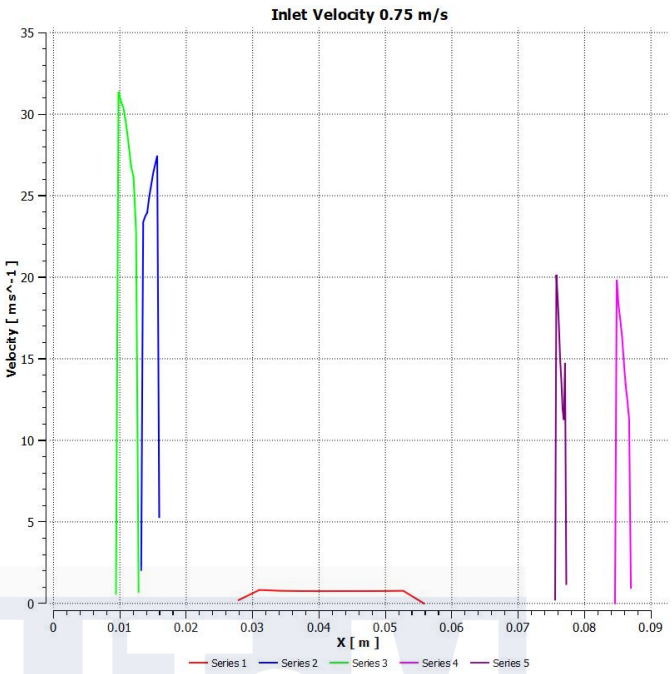
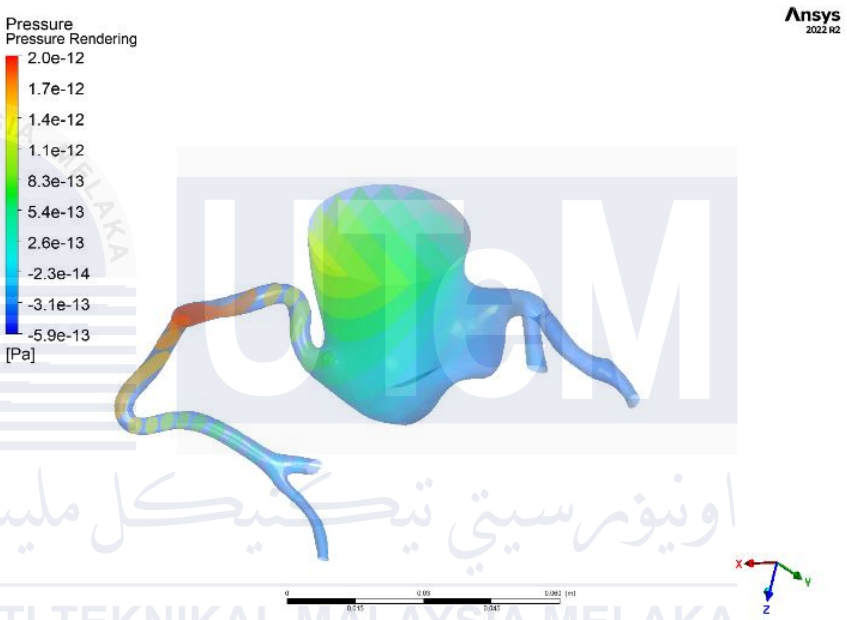
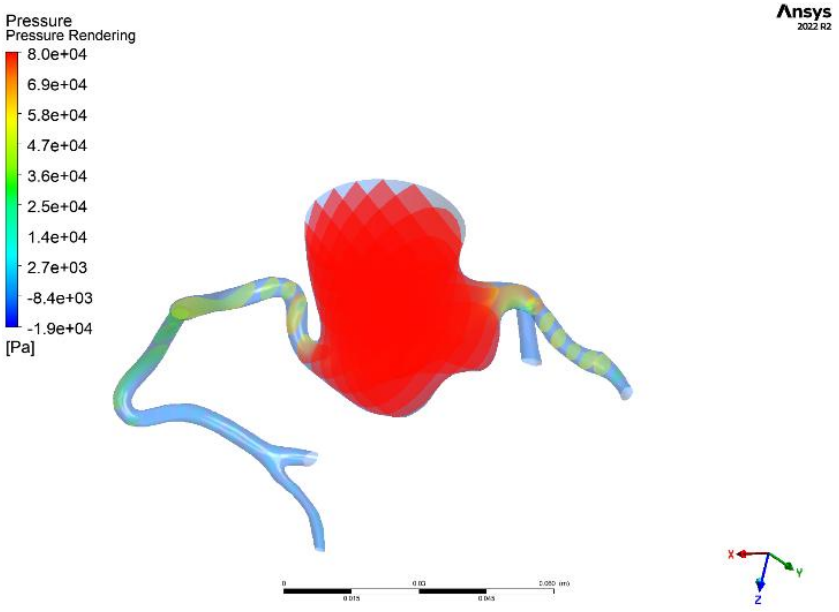
No.	Blood flow Condition (Systolic and Diastolic)	Velocity result
1	0 m/s (Early Systolic condition)	 Figure 4.8 Result analysis for inlet velocity is 0 m/s
2	0.275 m/s (End of Diastolic)	

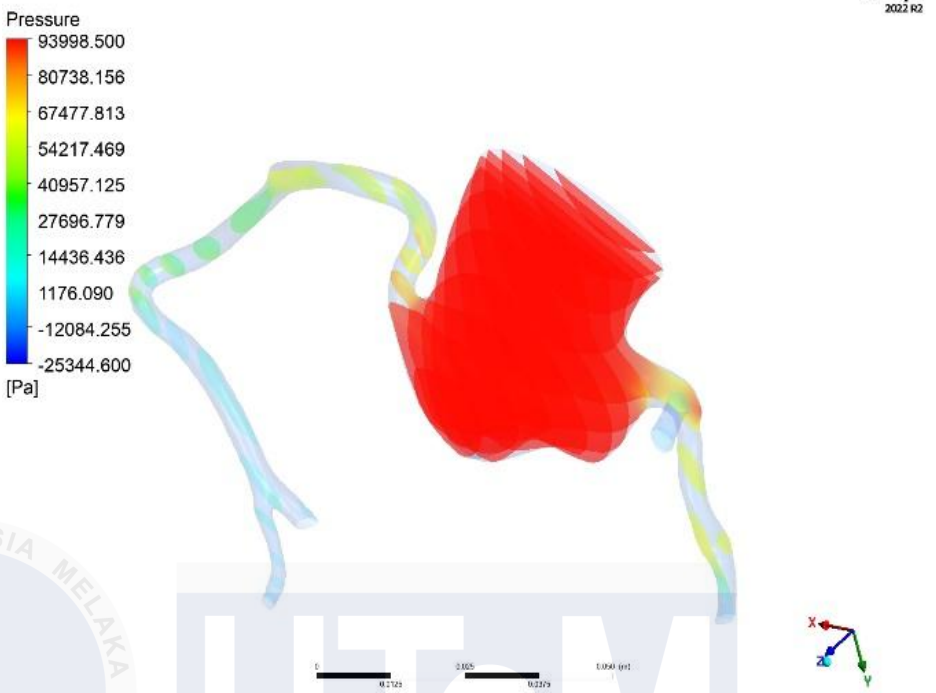
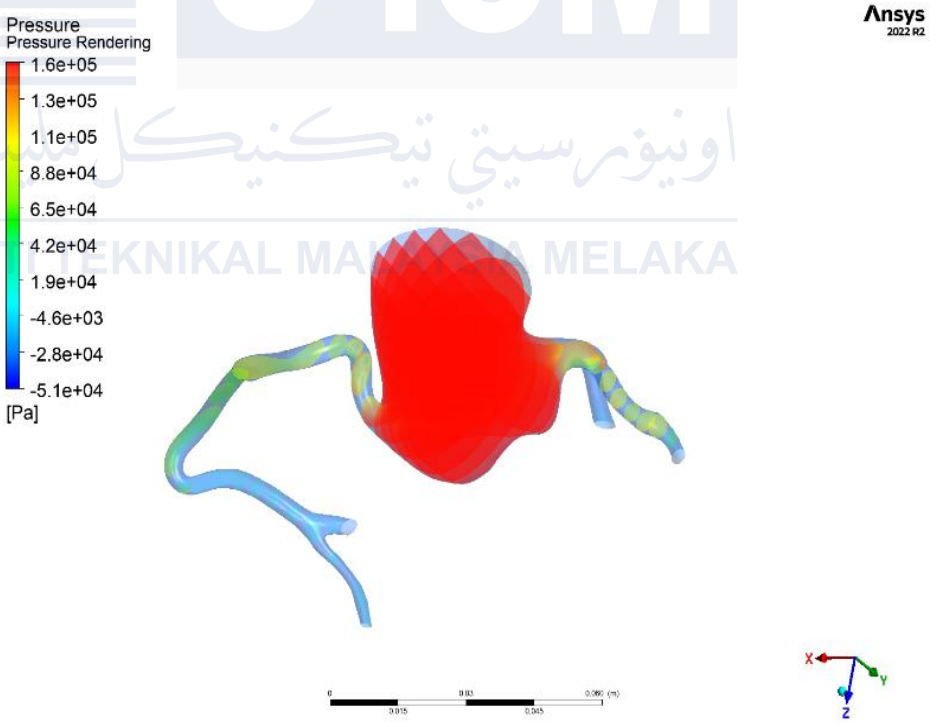
		Figure 4.9 Result analysis for inlet velocity is 0.275 m/s
3	0.3 m/s (Early Systolic Condition)	 Figure 4.10 Result analysis for inlet velocity is 0.3 m/s
4	0.4 m/s (Maximum Systolic Condition)	 Figure 4.11 Result analysis for inlet velocity is 0.4 m/s

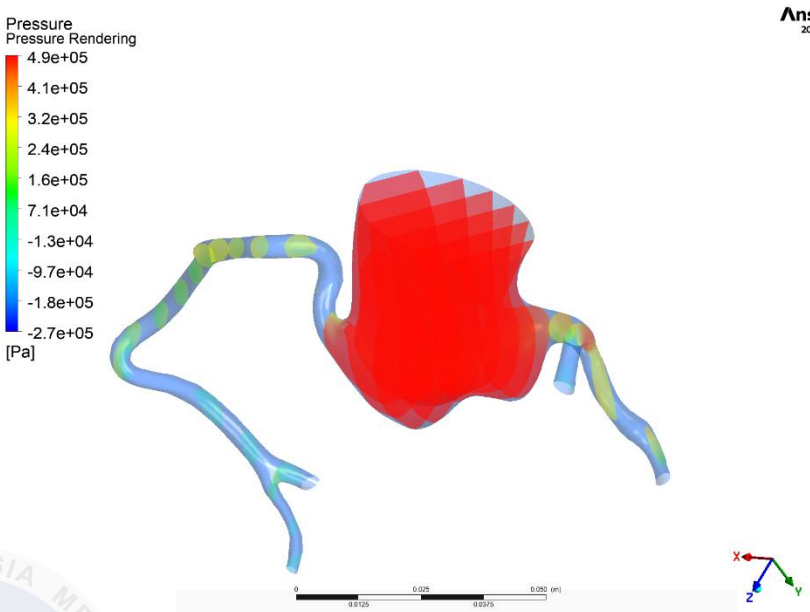
5	0.75 m/s (Beginning of Diastolic condition)	 Figure 4.12 Result analysis for inlet velocity is 0.75 m/s

4.4 Pressure Distribution of Left Coronary Artery (LCA)

Table 4.4 Pressure Distribution Simulation Result

No	Blood flow Condition (Systolic and Diastolic)	Pressure Distribution Inside Left Coronary Artery
1	0 m/s (Early Systolic condition)	 Figure 4.13 Pressure distribution for inlet velocity 0 m/s
2	0.275 m/s (End of Diastolic)	 Figure 4.14 Pressure distribution for inlet velocity 0.275 m/s

3	0.3 m/s (Early Systolic Condition)	 Figure 4.15 Pressure distribution for inlet velocity 0.3 m/s
4	0.4 m/s (Maximum Systolic Condition)	 Figure 4.16 Pressure distribution for inlet velocity 0.4 m/s

5	0.75 m/s (Beginning of Diastolic condition)	 Figure 4.17 Pressure distribution for inlet velocity 0.75 m/s

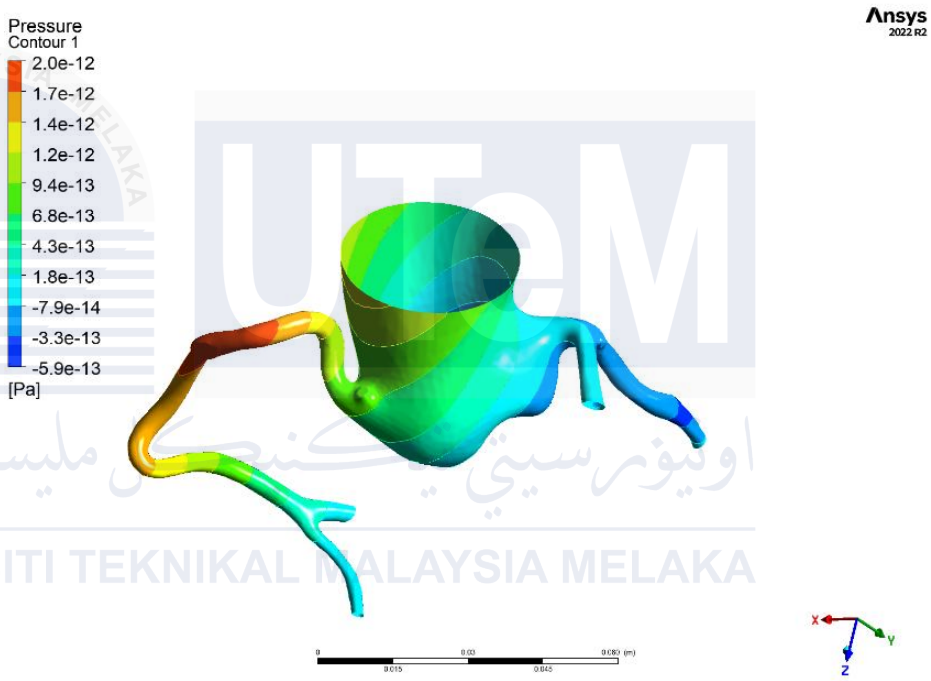
Another important aspect of the cardiovascular system's general health is the distribution of pressure inside the left coronary artery. The medical team can learn a lot about the left coronary artery's function and possible vulnerability to the development of stenosis or other obstructive disorders by examining the pressure gradients and locating areas of high or low pressure.

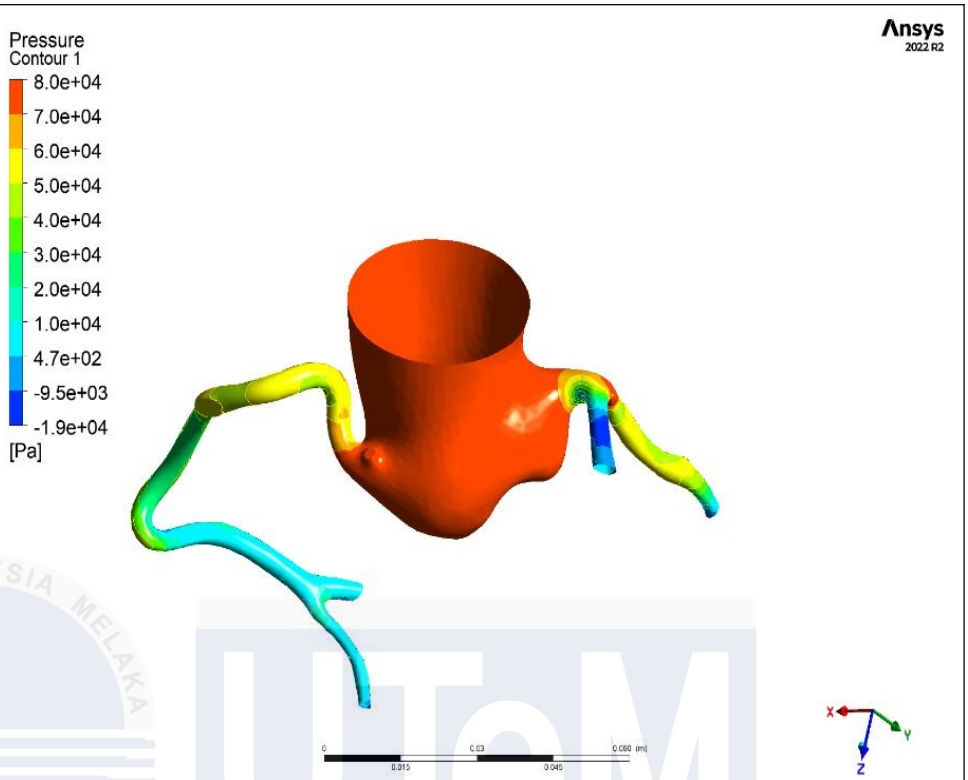
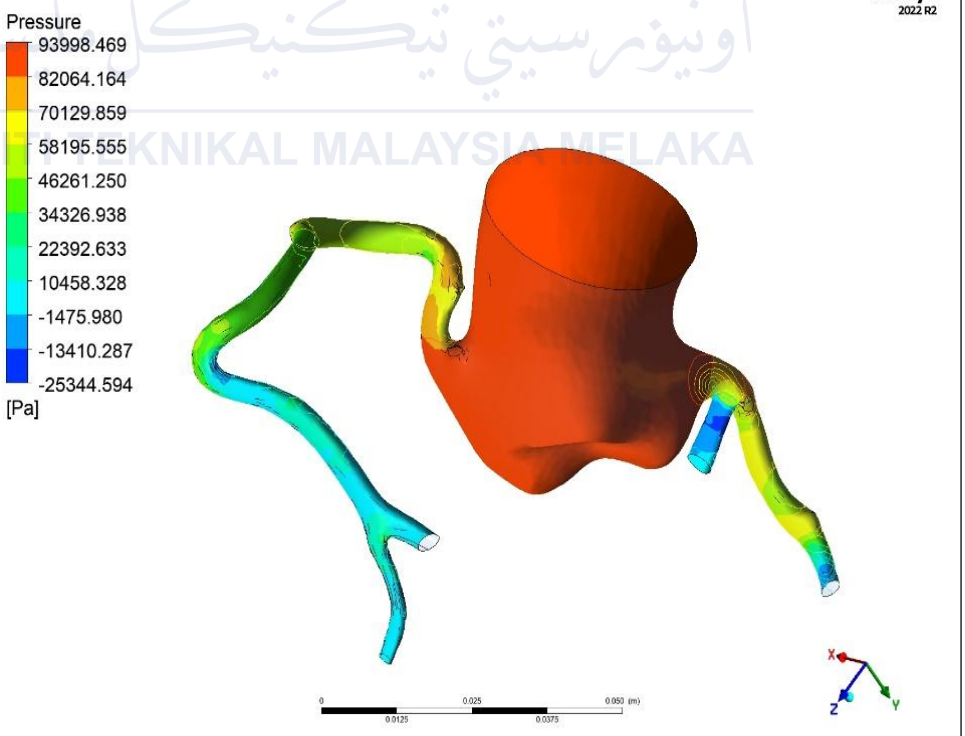
The overall function and robustness of the left coronary artery can then be enhanced by using this information to guide the design optimization process. Additionally, the pressure analysis can be used to guide the choice of the best course of treatment by evaluating the effects of possible procedures, such as bypass surgery or stent implantation (Fujiwara et al., 1978).

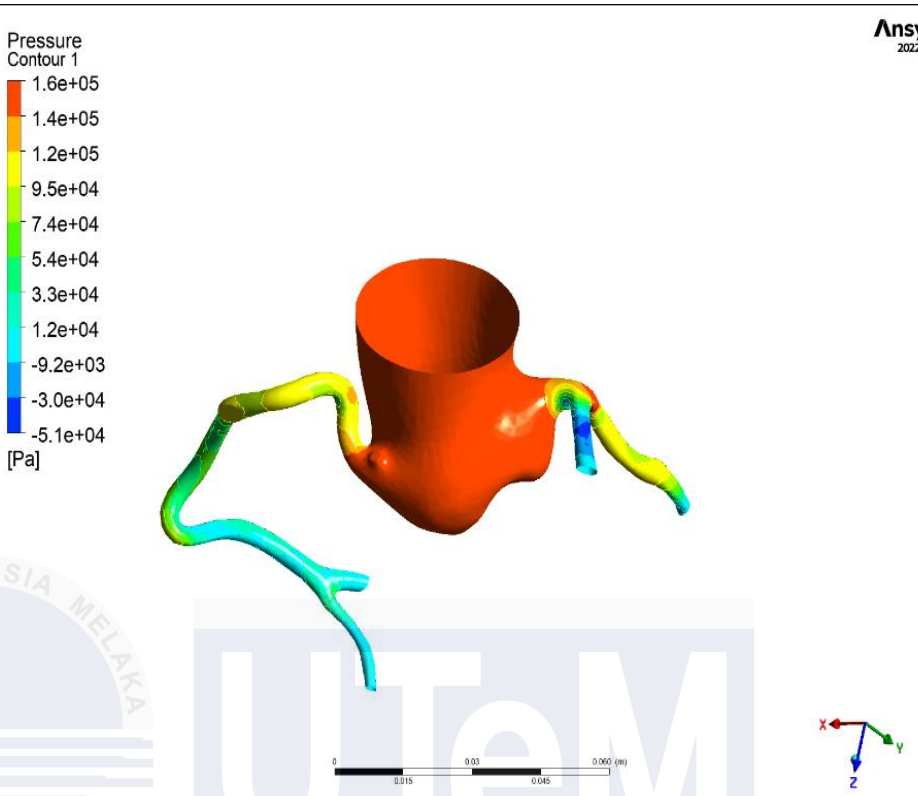
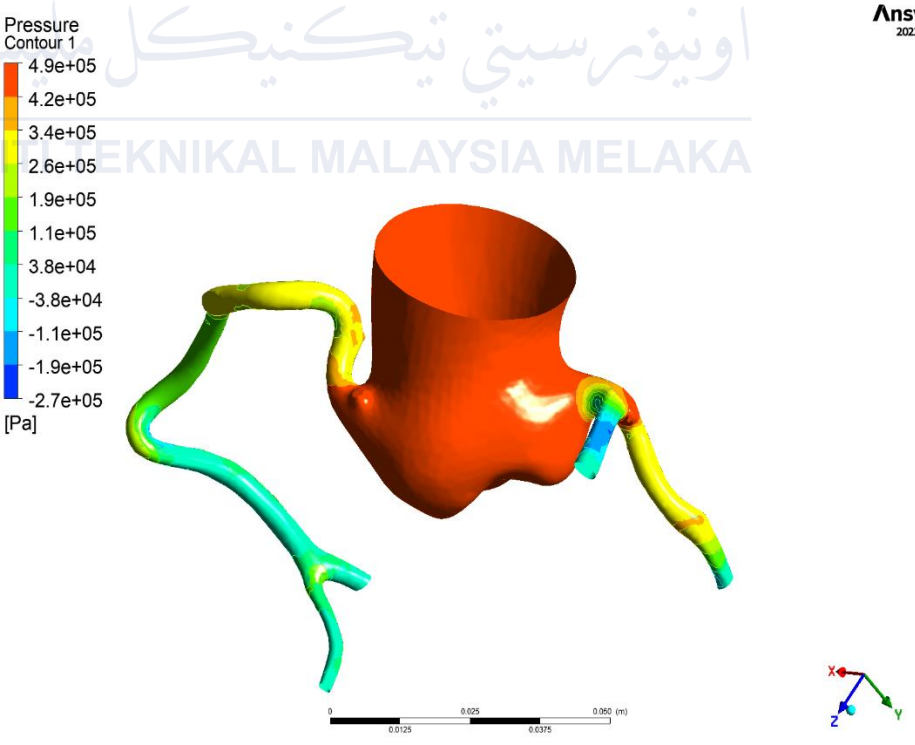
This study has shown the potential of optimizing the design of the right coronary artery utilizing ANSYS Workbench CFD software and GPU-accelerated digital twins of the human heart. Researchers and medical practitioners can better comprehend the intricate hemodynamics involved in cardiovascular illness by utilizing these cutting-edge computational techniques, which will ultimately enhance patient outcomes and treatment approaches. (Rampidis and others, 2022).

4.5 WSS Distribution of Left Coronary Artery (LCA)

Table 4.5 WSS Distribution Simulation Result

No	Blood flow Condition (Systolic and Diastolic)	Wall Shear Distribution Simulation Result on Left Coronary Artery
1	0 m/s (Early Systolic condition)	 Figure 4.18 WSS simulation for inlet velocity 0 m/s

2	0.275 m/s (End of Diastolic)	 Figure 4.19 WSS simulation for inlet velocity 0.275 m/s
3	0.3 m/s (Early Systolic Condition)	 Figure 4.20 WSS simulation for inlet velocity 0.3 m/s

4	0.4 m/s (Maximum Systolic Condition)	 Figure 4.21 WSS simulation for inlet velocity 0.4 m/s
5	0.75 m/s (Beginning of Diastolic condition)	 Figure 4.22 WSS simulation for inlet velocity 0.75 m/s

The left coronary artery's wall shear stress is a crucial consideration in the design optimization process, in addition to the pressure analysis. Atherosclerosis and other vascular disorders can be significantly influenced by wall shear stress, which is the frictional force that the blood's flow exerts on the arterial wall.

The medical team can determine which areas of the left coronary artery may be more susceptible to plaque accumulation or other obstructive problems by examining the distribution of wall shear stress inside the artery. With the aim of lowering the wall shear stress in these high-risk regions and enhancing the general health and functionality of the left coronary artery, this data can then be utilized to direct the design optimization process.

The medical team in charge of the care and treatment of cardiovascular patients can benefit greatly from the conclusions drawn from this thorough examination of the right and left coronary arteries, including the pressure distribution and wall shear stress.

4.6 Result Summary

The left coronary artery's flow dynamics are complicated and can vary greatly based on many variables, including the inlet velocity, vessel geometry, and the existence of stenosis or other obstructive conditions, according to the results of the CFD analysis performed using ANSYS Workbench. The medical team can create focused therapies to enhance the left coronary artery's overall performance by identifying areas with excessive wall shear stress or pressure gradients.

However it's crucial to remember that the CFD study has some drawbacks, like the simplified geometry and boundary conditions, which might not accurately depict theIn conclusion, this work has shown how the design of the left and right coronary arteries can be optimized by utilizing ANSYS Workbench CFD software and GPU-accelerated digital twins. To optimize the design of the left coronary arteries, ANSYS Workbench CFD software and digital twins of the human heart were utilized, along with the uncertainty in the material characteristics and physiological parameters employed in the simulations. The medical team can create more effective treatment plans for their patients and gain a more thorough picture of their overall cardiovascular health by integrating the findings from the analysis of left coronary arteries.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The great potential of using cutting-edge computational tools, such ANSYS Workbench CFD software and GPU-accelerated digital twins, to optimize left coronary artery architecture has been brought to light by this work. The medical team can gain important insights by performing in-depth analyses of the pressure distribution, wall shear stress, and other vital hemodynamic parameters within the coronary vessels. This will help them identify areas that are susceptible to obstructive conditions and create focused interventions to enhance cardiovascular health in general.

Although the study's findings are encouraging, it's critical to recognize the limits of the CFD research, including the simplification of the geometry and boundary conditions, the unpredictability of the material characteristics and physiological factors employed in the simulations, and others. For the design optimization process to become even more accurate and reliable in the future, it will be essential to keep improving these computer models and adding more precise, patient-specific data.

The medical community can make great strides toward the creation of individualized, precision-based treatments for cardiovascular diseases by utilizing the power of cutting-edge computational tools and encouraging close cooperation between researchers, clinicians, and manufacturers of medical devices. This will ultimately improve patient outcomes and the quality of life for those who are impacted by these crippling conditions.

5.2 Recommendations

The following suggestions for further research are put forth in light of the study's findings, including the inclusion of more thorough patient-specific data: Future research should concentrate on adding more precise patient-specific data, such as high-resolution medical imaging, patient-specific material qualities, and physiological factors, to enhance the precision and dependability of the CFD simulations.

Integration with clinical decision-making: As computational tools improve in accuracy and dependability, it is essential to incorporate them into clinical decision-making. This way, the insights gained from CFD analysis can be utilized to inform treatment choices and track patients' long-term results.

Investigation of advanced optimization techniques: To further improve the left coronary artery's architecture and handle the trade-offs between different hemodynamic parameters, researchers should investigate more complex optimization algorithms and methodologies, such as multi-objective optimization.

Experimental study validation of computational models: Although CFD analysis offers insightful information, in order to guarantee the accuracy of the results, it is crucial to verify the computational models using in-vitro or in-vivo tests.

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APPENDICES

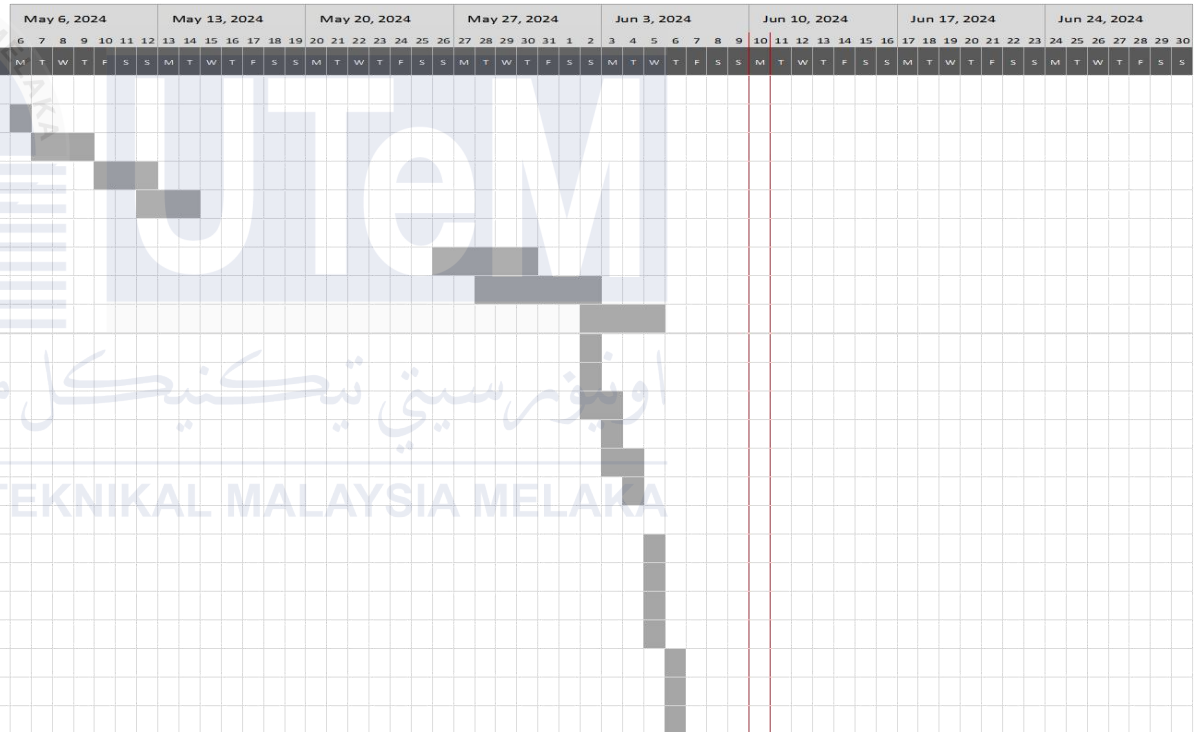
APPENDIX A Project Gantt Chart

THREE-DIMENSIONAL MODELLING AND 3D PRINTING OF ACTUAL PATIENTS ARTERY USING CT-SCAN IMAGES

Muhammad Nur Akma Afiq Bin Awang Hamat
B092110433

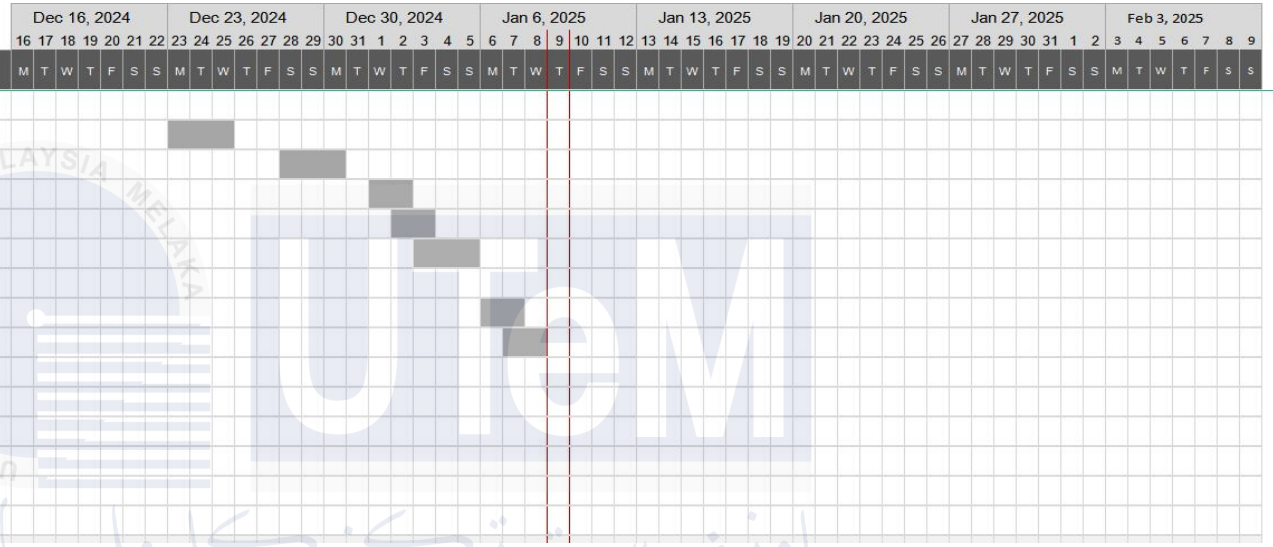
Project Start: Sun, 5/5/2024
Display Week: 1

TASK	ASSIGNED TO	PROGRESS	START	END
Chapter 1(Introduction)				
Background	Name	100%	5/5/24	5/6/24
Problem Statement		100%	5/7/24	5/9/24
Research Objective		100%	5/10/24	5/12/24
Scope Of Research		100%	5/12/24	5/14/24
Chapter 2(Literature Review)				
Introduction		100%	5/26/24	5/30/24
Coronary Artery		100%	5/28/24	6/2/24
3-D For Medical Purpose		100%	6/2/24	6/5/24
Coronary Artery Disease		100%	6/2/24	6/2/24
Level Of 3-D Printing For Medical Applications		100%	6/2/24	6/2/24
3-D Printing For Medical Purpose		100%	6/2/24	6/3/24
Designation Additive Manufacturing Process		100%	6/3/24	6/3/24
Material Used In 3D Printing For Medical Purpose		100%	6/3/24	6/4/24
Summary		100%	6/4/24	6/4/24
Chapter 3 Methodology				
Introduction		100%	6/5/24	6/5/24
Process Flow Chart		100%	6/5/24	6/5/24
Data Acquisition of Patient Data		100%	6/5/24	6/5/24
Simulation of Patient Artery		100%	6/5/24	6/5/24
Fabrication of The Model Using 3D Printing Machine		100%	6/6/24	6/6/24
Post Processing Process		100%	6/6/24	6/6/24
Material Properties Testing		100%	6/6/24	6/6/24



Project Start:	Sun, 5/5/2024
Today:	Thu, 1/9/2025
Display Week:	33

TASK	ASSIGNED TO	PROGRESS	START	END
Chapter 4				
Introduction		100%	12/23/24	12/25/24
Design Analyzing		100%	12/28/24	12/30/24
Optimize Design		100%	1/1/25	1/2/25
Analysis Of The Left Coronai		100%	1/2/25	1/3/25
Result Summary		100%	1/3/25	1/5/25
Conclusions And Recommendations				
Conclusions		100%	1/6/25	1/7/25
Recommendations		100%	1/7/25	1/8/25



APPENDIX B Turnitin Report

Combined C1-C4(V3).docx

ORIGINALITY REPORT

27%	19%	19%	17%
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

PRIMARY SOURCES

C4-C5 Akma.docx

ORIGINALITY REPORT

3%	2%	2%	1%
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS