

BIOMECHANICS OF ANEURYSMS

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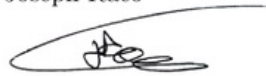


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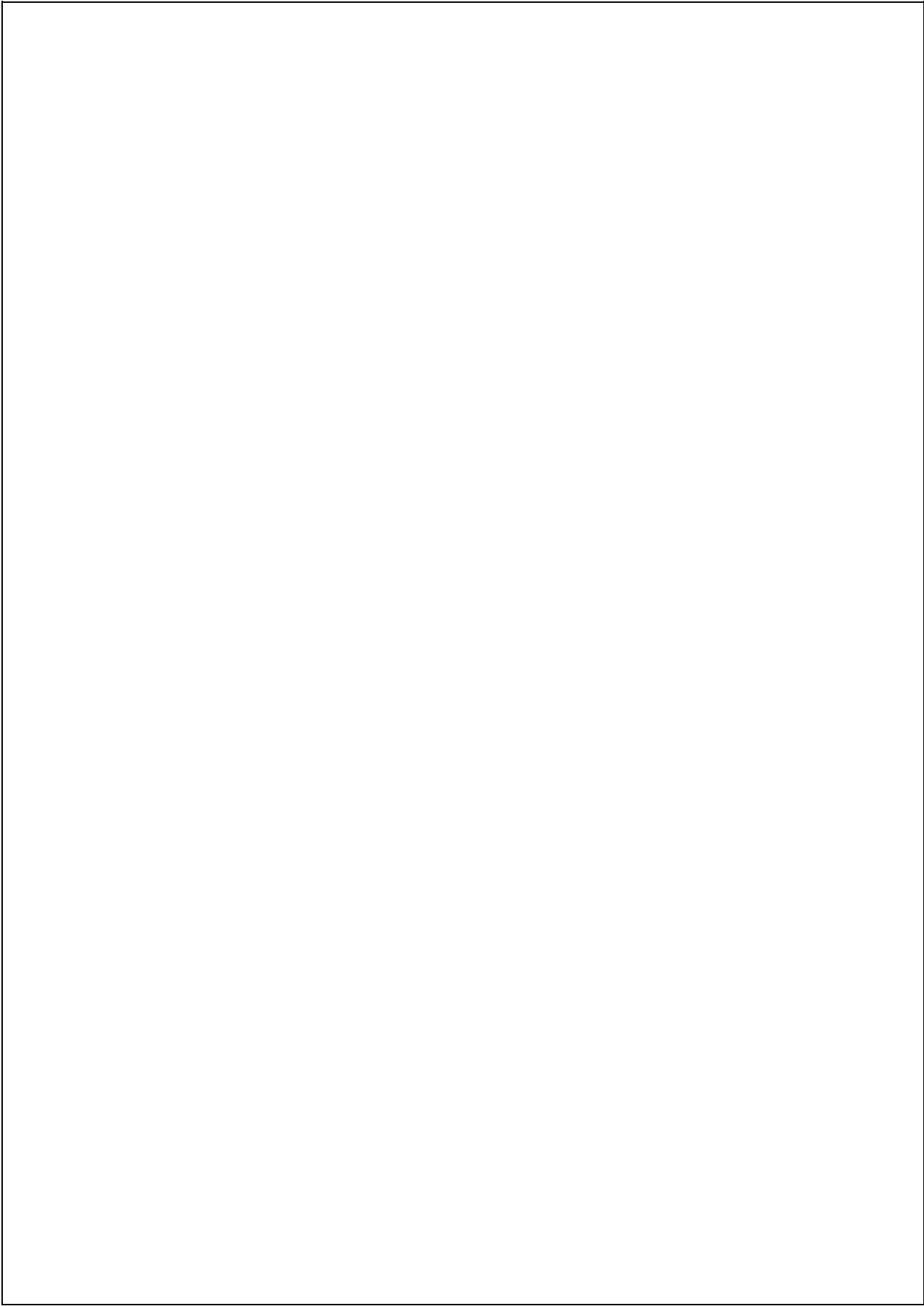
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Date: 7 November 2016



ABSTRACT

Determining the stiffness of artery walls is a difficult task due to their dynamic behavior and presence in the human body. Knowledge of artery wall stiffness would prove invaluable in predicting when an aneurysm is at high risk of rupture. Aneurysm rupture is a failure of the artery wall and hence is directly related to its mechanical properties. Medical imaging techniques such as magnetic resonance imaging (MRI) are able to provide information on a number of mechanical characteristics that are critical to aneurysm behavior. However, they cannot determine the artery wall stiffness or Young's modulus (E) which is needed to perform a failure analysis.

Multiple silicone rubber models of aneurysms will be produced, these models will vary in stiffness. The models will be placed into a flow circuit to simulate the flow of blood through them. The velocity through the models will then be measured and used to create a velocity stiffness relationship. The process will be repeated for different sized aneurysm models. The velocity stiffness relationship for each sized aneurysm will then be combined into one graph. The size of, and velocity through an aneurysm can then be used to estimate the artery wall stiffness and hence predict the risk of rupture.



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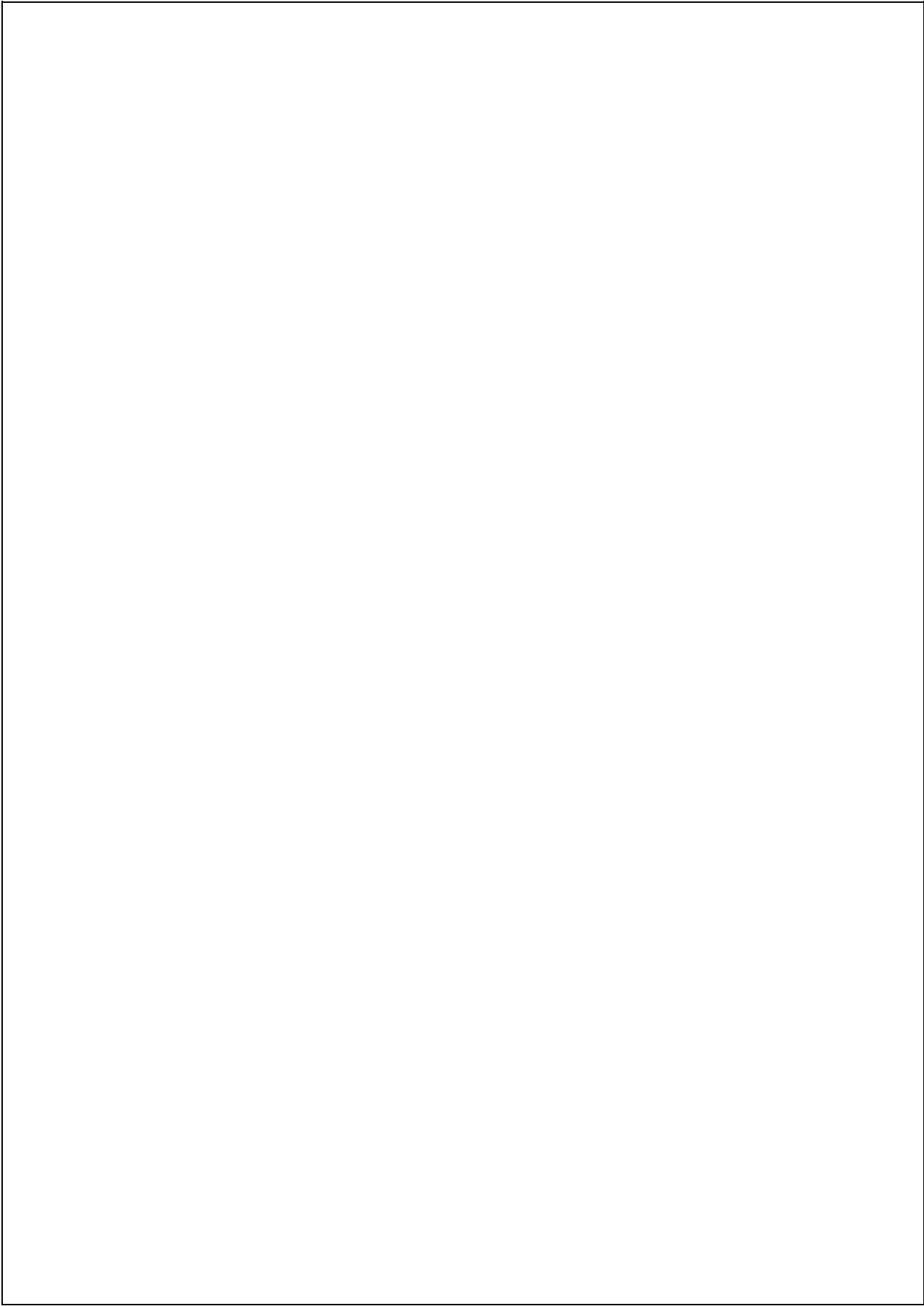
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Chapter 1

Introduction

1.1 Aneurysm

1.1.1 Definition

An aneurysm is the excessive, localised expansion of an artery wall, such that its diameter exceeds 1.5 times the adjacent healthy artery diameter [2]. This process is permanent and irreversible, taking one of two distinct geometries, see figure 1.1. Saccular aneurysms usually occur in the network of arteries that supply blood to the brain, often referred to as the Circle of Willis, while fusiform aneurysms are most often found in the abdominal aorta or the popliteal artery behind the knee [1].

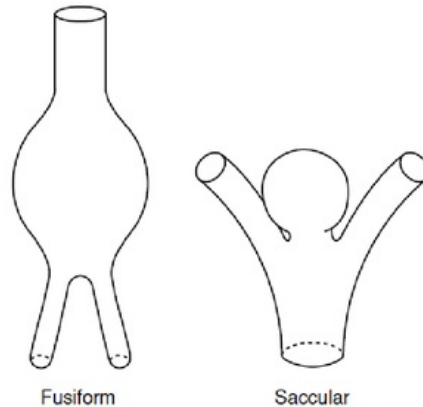


Figure 1.1: Aneurysm geometries [1].

In order to fully understand aneurysm formation and development it is essential to first understand the artery wall's ability to change its structure and composition since it is these properties of a material which determine its stiffness or elasticity. Artery walls throughout the body have varying levels of elasticity dependent on their distance to the heart and the organ that they supply blood to [1]. Furthermore they are able to temporarily change their elasticity

in response to changes in blood flow, such is the case when a person physically exerts themselves and their heart rate is increased to move blood around the body faster. The way in which this process occurs is via the endothelial cells than line the inner lumen, separating the artery wall and the blood [1]. These cells are able to detect changes in the characteristics of the blood flow and adjust the composition and structure of the artery wall to compensate. This process regulates itself to ensure the integrity of the artery wall is maintained [1].

Artery stiffness is also subject to permanent changes via remodeling [1]. Remodeling is the result of long term physiological conditions such as aging, diet, lifestyle and causes the thickening or thinning of the muscular layer of an artery; in addition to changing the structure and composition of proteins which make up part of the artery wall [1].

The artery wall is a viscoelastic material, meaning it partially absorbs and partially reflects the energy of the flow passing through it [3]. When the artery wall properties change the flow passing through it may increase or decrease its velocity. This change results in the artery wall adjusting its stiffness again and consequently the velocity changes again [1]. This cycle continues indefinitely and shows that there exists a relationship between the artery wall stiffness and the velocity of the flow passing through it. Therefore it may be possible to say that for some value of blood flow there exists a distinct range of values or a single value for artery wall stiffness. If this is true then a failure analysis using only the blood flow velocity could be carried out.

1.1.2 Formation

The exact cause of this process is not known however factors such as age, diet, genetics and lifestyle are known to influence artery wall composition and behavior [1]. Changes in the artery wall can lead to degradation and perhaps initiate aneurysm formation at a weak spot. The localised nature of an aneurysm indicates that locations of relatively weak artery wall compared to the surrounding wall could be the cause behind aneurysm formation.

1.1.3 Rupture

Brown *et al.* carried out an observational study of 476 patients with aneurysms. They found that the risk of rupture is directly related to the size of an aneurysm and is more likely to rupture in females than males [4]. This study only considers aneurysms with diameters greater than 5 centimeters. It has been shown that aneurysms smaller than this can rupture [5, 6]. Therefore the size of an aneurysm does not fully predict the likelihood of rupture and additional factors must be considered.

If we were to consider the artery wall as a tube and perform a failure analysis on it, we could easily predict the risk of rupture. However there are a number of variables that must be determined before this analysis could be carried out. Knowledge of the blood flow dynamics through the aneurysm, which has been investigated extensively through experimentation [7–9] and computation fluid dynamics (CFD) [8, 10–16], can be accurately determined *in vivo*

through the use of medical imaging techniques. Artery wall stiffness in contrast is very difficult to accurately predict. This is a result of its dynamic nature, and ability to change both permanently and temporarily.

It is clear that in order to better evaluate the risk of rupture additional methods are required. If we could predict the stiffness of an aneurysm, then a failure analysis could be carried out and this information used to assess the likelihood of rupture [1]. Therefore a reliable method of predicting aneurysm wall stiffness is needed.

1.2 Background Research

1.2.1 The Cardiovascular System

All the following information in this section and its subsections was taken from the textbook Human Anatomy and Physiology by E. C. Amerman [3] unless otherwise stated.

The heart connects two circulatory systems, the pulmonary and systemic. Each system has its own pump located on the right and left sides of the heart respectively. The pulmonary circuit is responsible for pumping deoxygenated blood to the lungs where a process known as gas exchange takes place between the deoxygenated blood in the pulmonary capillaries and the air sacs in the lungs, known as alveoli. This process involves the transfer of oxygen from the alveoli into the blood and carbon dioxide from the blood into the alveoli. The oxygenated blood then leaves the lungs, returns to the heart and enters the systemic circuit. It is at this point where the oxygenated blood is pumped all over the body to the tissues, including the heart. When this blood reaches the systemic capillaries a gas exchange occurs however this time the exchange is reversed. The blood transfers oxygen to and receives carbon dioxide from the tissues while the tissues receive oxygen from and transfer carbon dioxide to the blood. After the gas exchange is completed deoxygenated blood enters the pulmonary circuit and the process is repeated. The systemic circuit has additional functions other than supplying oxygen to the body; it provides nutrients, cleans waste and delivers hormones. Furthermore, the systemic circuit works at a higher pressure than the pulmonary circuit as it has to pump blood around the entire body.

1.2.2 Computational Models

Computational Fluid Dynamics (CFD) has been used in the past to examine the fluid flow behavior and characteristics of blood as it passes through an aneurysm [8, 10–16]. These computation models have shown that there exists a central stream of fluid that expands after entering the aneurysm, with vortices between this stream and the aneurysms inner wall, see figure 1.2.

However, CFD software are commonly used to examine fluid flow through or around static objects and materials. This is not true in the case of aneurysms, which exhibit viscoelastic properties and are constantly changing their wall properties. It is because of this limitation in

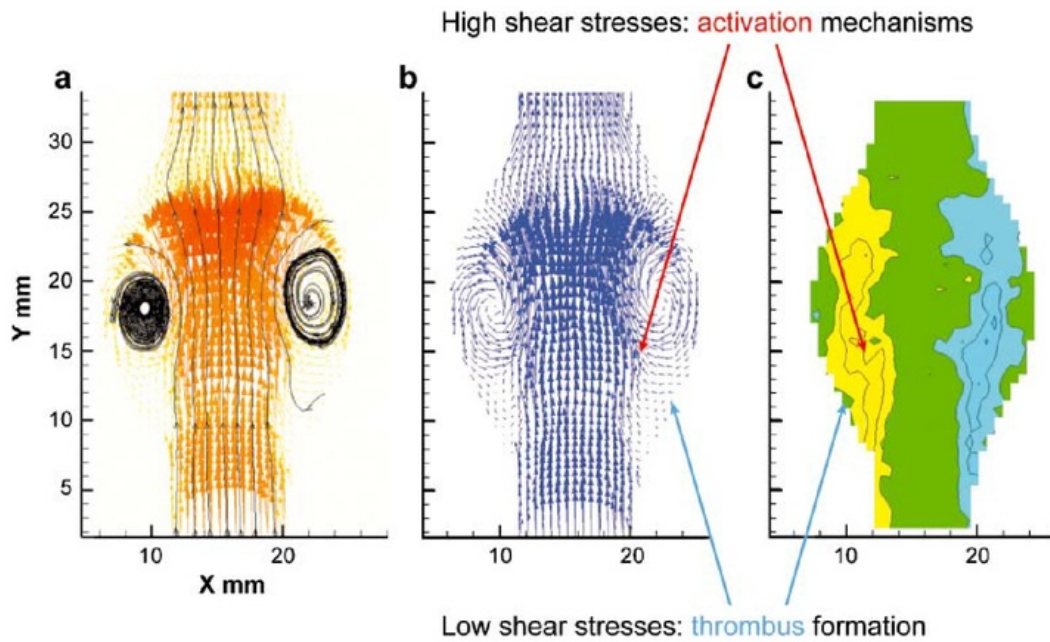


Figure 1.2: Symmetric model of an AAA fusiform aneurysm, (a) instantaneous velocity field, (b) instantaneous streamlines, and (c) shear stress field [1].

software that it is essential to perform experimental investigations, using viscoelastic materials, to observe the blood flow through an aneurysm.

1.3 Project Proposal

1.3.1 Problem Statement

Guidelines exist that attempt to evaluate the risk of aneurysm rupture. These guidelines are used when deciding to perform surgery on an aneurysm to eliminate the risk of rupture. However, it has been shown that aneurysm rupture is unpredictable due to the complex nature of the human body and these guidelines cannot predict all aneurysm ruptures.

If we reduce the problem of predicting aneurysm rupture to that of predicting aneurysm wall stiffness, we will be able to perform a failure analysis. This project will develop a method of predicting an aneurysm wall's Young's modulus, and hence predict the risk of rupture.

1.3.2 Objectives

The following objectives will need to be met if this project is to be successful in fulfilling the problem presented above.

1. Manufacture of multiple aneurysm models that are as physiological as possible.

2. Construction of a flow circuit that can be used to test how the velocity of blood changes as a result of aneurysm stiffness. The flow circuit must simulate physiological conditions.
3. Carry out an experimental investigation and record the results.

1.3.3 Approach

An experimental investigation on physiological aneurysm models in a physiological environment will be carried out in an accurate and repeatable method.

Aneurysm models will be manufactured relative to the size of an aneurysm considered high risk and which requires surgery. If we define this size to be 1 then a set of 4 aneurysms models will be created for each aneurysm size of 0, 0.25, 0.5, 0.75 and 1. Creating four models for each size will allow the aneurysm stiffness to be altered and its affect on the blood flow observed.

Each aneurysm model will be connected to the flow circuit. The velocity and behavior of the working fluid will match physiological conditions of a human being. The affect that the aneurysm model has on the velocity and behavior of the blood will then be observed for each set of 4 models. This will then be repeated for the remaining sets of models which represent the different size aneurysms.

In order to successfully meet the objectives materials and equipment will need to be selected and purchased. The methods for selecting these will involve an analysis into the requirements, presenting solutions to these requirements and then comparing them to determine the most suitable. Sourcing the selected materials and equipment will then involve internet searches into various companies and conversations via email and telephone.

The equipment and materials will be outlined below in addition to detailed requirements for the aneurysm models and the flow circuit, potential solutions for these, comparisons between the solutions and selection of the most effective solution.

1.3.4 Project Management

1.3.5 Outcomes

Produce a graph of Young's modulus against velocity for different sized aneurysms. This graph is intended to be used as an addition tool in predicting the risk of rupture by providing values for an aneurysms stiffness. This value can then be used to predict how close the aneurysm is to rupture and hence determine if treatment is required.

Task	05/09/2016 to 07/11/2016														
	Wk. 1 01/09	Wk. 2 08/08	Wk. 3 15/08	Wk. 4 22/08	Wk. 5 29/08	Wk. 6 05/09	Wk. 7 12/09	Recess 19/09	Recess 26/09	Wk. 8 03/10	Wk. 9 10/10	Wk. 10 17/10	Wk. 11 24/10	Wk. 12 31/10	Wk. 13 07/11
Research.															
Determine method of producing pulsatile flow.															
Design flow circuit, include connections, pump, connecting tubes, pulsatile flow generation, reservoir, working fluid.															
Design aneurysm mould for each sized aneurysm to suit the flow circuit design.															
Source and obtain required materials and equipment.															
Manufacture aneurysm model and determine its mechanical properties.															
Conduct experiment on the aneurysm model using the flow circuit.															
Modify the aneurysm mould and flow circuit design if necessary.															
Manufacture remaining aneurysm models and conduct experiment on each.															
Work on project report.															

Figure 1.3: Project timeline.

Chapter 2

Experimental Methods

2.1 Aneurysm Model

2.1.1 Requirements

The aneurysm model material should be an analogue to human aortic tissue and its geometry must mimic that of a typical aneurysm.

1. The model should be made from a viscoelastic material with a Young's modulus of 1.8MPa [9].
2. Uniform wall thickness of 2 millimeters.
3. Lumen diameter of 24 millimeters.
4. Oval shaped bulge.
5. Sufficient length before and after the bulge to observe the blood flow and to ensure the flow is laminar and developed.

2.1.2 Materials

The model material will be made of Wacker Elastosil RT601 A/B silicon rubber from Wacker Chemicals and Xiameter PMX-200 silicone Fluid 5CS from Ingredients Plus. It has been shown that these materials closely match the mechanical properties of aortic tissue and have been used in numerous studies for creating aneurysm models [2, 9, 17]. For each aneurysm size, the set of 4 models will need to have varying stiffness values, this will be achieved by altering the mass concentration of the silicone fluid in the silicone rubber from 0 percent to 15 percent in steps of 5 percent.

The exact values of stiffness for each mixture will be unknown except for the mixture where no silicone fluid is present. Therefore in the cases where the stiffness is unknown tensile specimens will need to be manufactured and tested to determine their Young's modulus.

2.1.3 Features

Feature 1

2.2 Aneurysm Manufacture

2.2.1 Methods

3D printing will be used to create the moulds, this presents some issues as supporting elements will be required during the moulds construction. Once construction is complete the supporting elements are removed however one side of the mould will not have a smooth surface finish. Therefore during the moulds construction the supporting elements should be placed such that they come into contact with the exterior side of the mould. This will keep the interior side smooth, which is the side the model material will be against.

Regardless of the final design for the moulds the method for their construction will depend on where the supporting elements can be placed such that they do not come in contact with the interior mould surface.

Laying the mould half exterior side facing down and creating supporting elements along the entire length of the mould. This would ensure no supporting elements are in contact with the interior mould surface however a large amount of material will be required to due to the large amount of supporting elements. See figure 2.1.

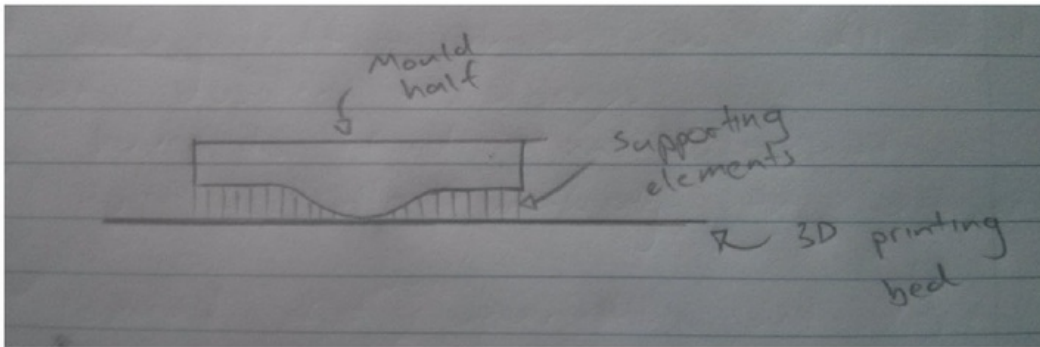


Figure 2.1: Location of supporting elements with mould half resting on its exterior during printing.

Creating both mould halves in one print with the orientation such that the mould is standing on its end. Supporting elements would then be required to support the bulge, and they would come into contact with the exterior surface and interior surface only at the bulge. The mould would then be cut to create two halves. Cutting the mould into halves has a benefit of ensuring that the mould halves connected together perfectly. See figure 2.2.

The method of creating the aneurysm models has been detailed by Corbett et. al. [9] and this method shall be followed the create the aneurysm models for this experiment.

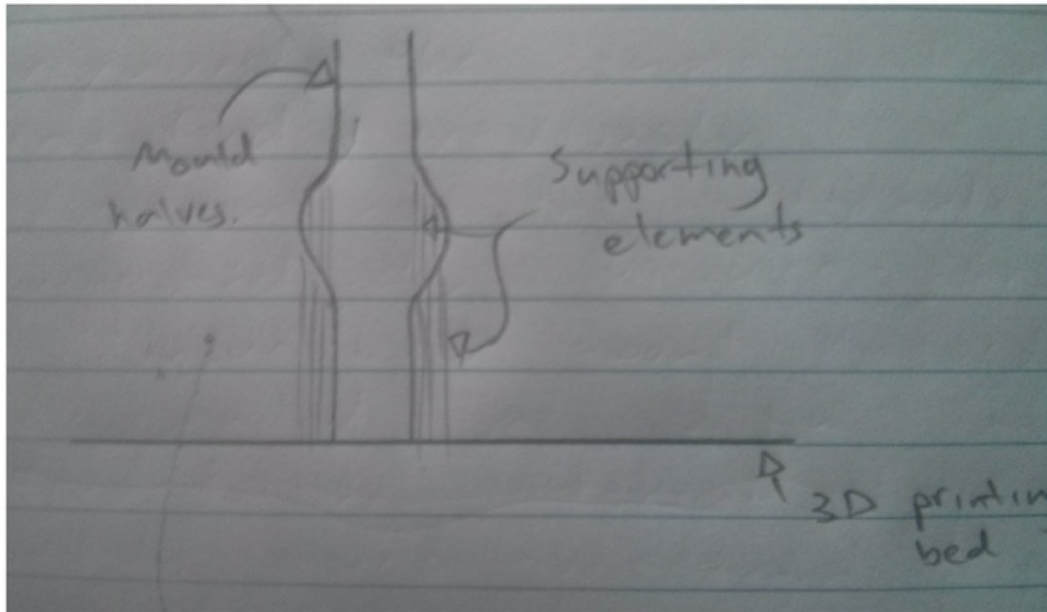


Figure 2.2: Location of supporting elements with mould standing on its end during printing.

2.3 Flow Circuit

2.3.1 Requirements

The flow circuit will consist of a number of components each of which will be examined below. Several solutions for each component will be presented, including details of the components relationships. Following this, flow circuit designs will be proposed that utilise different solutions from each component.

The proposed designs should meet the following requirements in order to satisfy the project objectives.

1. Pulsatile flow that mimics that of the heart at 1 Hz or 60 beats per minute (BPM).
2. Flow visibility throughout the circuit and aneurysm model.
3. A physiological working fluid that is able to simulate blood.
4. The circuit should be able to last at least 3 years and be usable for different applications as needed in future work.
5. The circuit should not leak.
6. The fluid in the circuit should be easily drained.
7. Flow circuit components excluding the aneurysm model and pump should not have a large affect on the fluid flow so as to ensure the desired flow behavior.

The availability of components and their sizes will need to be taken into consideration. The connecting tubes and the aneurysm model should have the same inside diameter. Therefore it may be necessary to modify the aneurysm model once the equipment has been selected. 3D printed components may be used if needed.

2.3.2 Aneurysm model

The aneurysm model will need to have a temporary connection to the rest of the flow circuit. Multiple models will be tested using this circuit, they should to be easily and quickly interchangeable. If possible the connecting tubes and aneurysm model should have a flush connection along the lumen. This will ensure that the flow is not disrupted as it approaches the aneurysm. Methods of connecting the aneurysm model to the flow circuit will be detailed below.

Rigid Model Ends

While the aneurysm model is being cast in the mould, tubing could be placed such that they set into the ends of the model. This would provide a rigid, permanent connection to each end of the aneurysm model which would then be connected as if joining two tubes together with a temporary compression fitting as outline below.

This method of connecting the aneurysm model presents some problems as the aneurysm wall is only 2 millimeters thick and the tubing will not have a large surface area to bond to.

2.3.3 Connections

In order to connect the flow circuit components together, connections whether temporary or permanent will be required. The type of fitting will depend on what components are being connected.

Compression Fittings

Compressions fittings use a nylon or copper olive that wraps around a pipe like a ring. On either end of the olive is a male and female threaded connection that goes over and covers the olive. As this connection is tightened the olive is compressed against the surface of the pipe. This creates a secure fit for one of the two pipes that are being connected. Therefore it is necessary to connect the female fitting permanently to the adjoining pipe through welding. This creates a modular connection which can be removed and replaced between one pipe and the other while using only one fitting.

2.3.4 Pulsatile Flow Generator

Average peak and mean blood velocities in the ascending aorta were measured to be 66 and 11 $\frac{cm}{s}$. In the pulmonary artery, behind the knee, these velocities were measured to be 57 and 10

$\frac{cm}{s}$ [18]. An AAA is found between these two locations and therefore the average velocity an intermediate value will be chosen as the AAA average peak and mean blood velocities.

$$\begin{aligned}
 v_{AAA, \text{ average peak}} &= \frac{v_{\text{pulmonary artery, average peak}} + v_{\text{ascending aorta, average peak}}}{2} \\
 &= \frac{57 + 66}{2} \\
 &= 61.5 \frac{cm}{s} \\
 v_{AAA, \text{ mean}} &= \frac{v_{\text{pulmonary artery, mean}} + v_{\text{ascending aorta, mean}}}{2} \\
 &= \frac{10 + 11}{2} \\
 &= 10.5 \frac{cm}{s}
 \end{aligned}$$

Piston Pump

A reciprocating piston pump will generate the pulsatile flow through the use of a motor. The motor will be controled through the use of a microcontroller, arduino uno R3, a motor driver, and arduino code. The desired velocity profile will be obtained by determining a value for rotational velocity begin outputted by the motor. This can be seen in the following equations and figure 2.3.

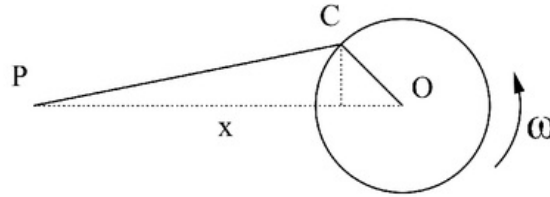


Figure 2.3: Schematic of piston and motor layout and their connections. Point O is the motor shaft, P is the piston head, and C is where they join via two rods.

Formulas and identities used below.

$$\sin^2 \theta + \cos^2 \theta = 1$$

$$2 \sin \theta \cos \theta = \sin 2\theta$$

Let $\angle \text{COP}$ be θ and $\angle \text{CPO}$ be ϕ .

$$x = r \cos \theta + l \cos \phi \quad (2.1)$$

$$r \sin \theta = l \sin \phi$$

$$r^2 \sin^2 \theta = l^2 \sin^2 \phi$$

$$r^2 \sin^2 \theta = l^2 (1 - \cos^2 \phi)$$

$$\cos \phi = \sqrt{1 - \frac{r^2 \sin^2 \theta}{l^2}} \quad (2.2)$$

Subbing equation 2.2 into 2.1 we find and letting $n = \frac{l}{r}$,

$$\begin{aligned} x &= r \cos \theta + l \sqrt{1 - \frac{\sin^2 \theta}{n^2}} \\ x &= r \left(\cos \theta + n \sqrt{1 - \frac{\sin^2 \theta}{n^2}} \right) \\ x &= r (\cos \theta + \sqrt{n^2 - \sin^2 \theta}) \end{aligned}$$

In order to determine the piston head velocity we differentiate x , that is, we find the rate of change of distance between the piston head and the stationary motor. 4

$$\begin{aligned} \dot{x} = \frac{dx}{dt} = v &= r(-\sin \theta \omega + \frac{1}{2}(n^2 - \sin^2 \theta)^{\frac{1}{2}} \times -(2\omega \sin \theta \cos \theta)) \\ &= -r\omega \left(\sin \theta + \frac{2 \sin \theta \cos \theta}{2\sqrt{n^2 - \sin^2 \theta}} \right) \\ &= -r\omega \left(\sin \theta + \frac{\sin 2\theta}{2\sqrt{n^2 - \sin^2 \theta}} \right) \end{aligned}$$

We know the desired piston velocity (v) that we want, and we need to determine omega (ω).

$$\omega = -\frac{v}{-r\omega \left(\sin \theta + \frac{\sin 2\theta}{2\sqrt{n^2 - \sin^2 \theta}} \right)} \quad (2.3)$$

Valves

One way check valves and control valves will be used to control the flow of fluid through the system. The check valves will ensure the fluid is pumped in the desired direction and that it is not able to move in the opposite direction during the piston head retraction.

2.3.5 Connecting Tubes

Rigid tubing will be used as the fluid flow through them could cause them to move if they were flexible, creating disruptions. Furthermore these tubes will be transparent to allow the fluid

flow to be easily observed.

2.3.6 Reservoir

The reservoir should be sized such that sufficient fluid is available to supply the operating flow circuit. The reservoir should not deplete itself fully. The water that leaves the reservoir will be returned via the return tubing to ensure that the fluid level remains constant. This level can be adjusted without any affect on the flow circuit; since the reservoir will be located vertically above the rest of the system along with the return tubing. In order to prepare the circuit fluid will be added to the reservoir and allowed to flow through the circuit via the use of a control valve. Once the flow circuit is filled with water and contains no air the control valve can be closed until the experiment is ready to commence.

The flow circuit can hold a large amount of volume (V) and this will significantly add to the mass (m) of the system.

$$\begin{aligned}
 V &= \frac{\pi}{4} \times d^2 \times l \\
 &= \frac{\pi}{4} \times 0.024^2 m^2 \times 2.4m \\
 &= 1.085 \times 10^{-3} m^3 \\
 &= 1.085L
 \end{aligned} \tag{2.4}$$

$$\begin{aligned}
 m &= \rho \times V \\
 &= 1060 \frac{kg}{m^3} \times 1.085 \times 10^{-3} m^3 \\
 &= 1.151kg
 \end{aligned} \tag{2.5}$$

The values from equations 2.4 and 2.5 provide information that will be used to size the reservoir and the system is adequately supported. The reservoir supplying fluid to the system and holding fluid from the return tube should have a capacity greater than 1.085 liters.

Furthermore a second reservoir will be located at the lowest vertical point of the flow circuit to drain the fluid when the experiment is complete. It will operated via an additional control valve that once opened will allow the fluid to leave the system. The fluid can then be stored for later use or disposed of responsibly.

2.3.7 Supports

All the elements of the flow circuit will require supports so they remain in the desired position and do not move during operation. This will be achieved through the use of a back board to which all flow circuit elements will be secured. The backboard should be maneuverable by a single person and should become compact for transport or storage.

2.3.8 Working Fluid

A similar experiment was done by Asbury *et al.* where a mixture of bone charcoal powder and tap water, at a ratio of several grams to 21 was used as the working fluid [13]. The viscosity of this mixture, $0.010 \text{ cm}^2/\text{sec}$, was measured to be roughly one third of blood, $0.033 \text{ cm}^2/\text{sec}$.

2.3.9 Component List and Costs

Table 2.1: Flow circuit components and their costs.

Item Name	Item Description	Supplier	Cost Including Shipping [\$]	Quantity	Total Cost [\$]
Xiameter PMX-200 Silicone Fluid 5CS 500 g	Aneurysm model material	Ingredients Plus	55.00	1	55
Ambersil 400 ml Mould Release Agent	Silicone release agent	RS Components	18.92	1	18.92
Arduino Uno R3	Microcontroller	Core Electronics	38.99	1	38.99

Chapter 3

Results

3.1 Results

3.1.1 Flow Circuit Design

The flow circuit design in fig 3.1 consists of the aneurysm model in teal, two one way check valves in brown and one control valve. These valves allow the flow circuit to be controlled and when under the influence of the pump, cycle fluid throughout the system from bottom of the reservoir, through the aneurysm and back to the top of the reservoir.

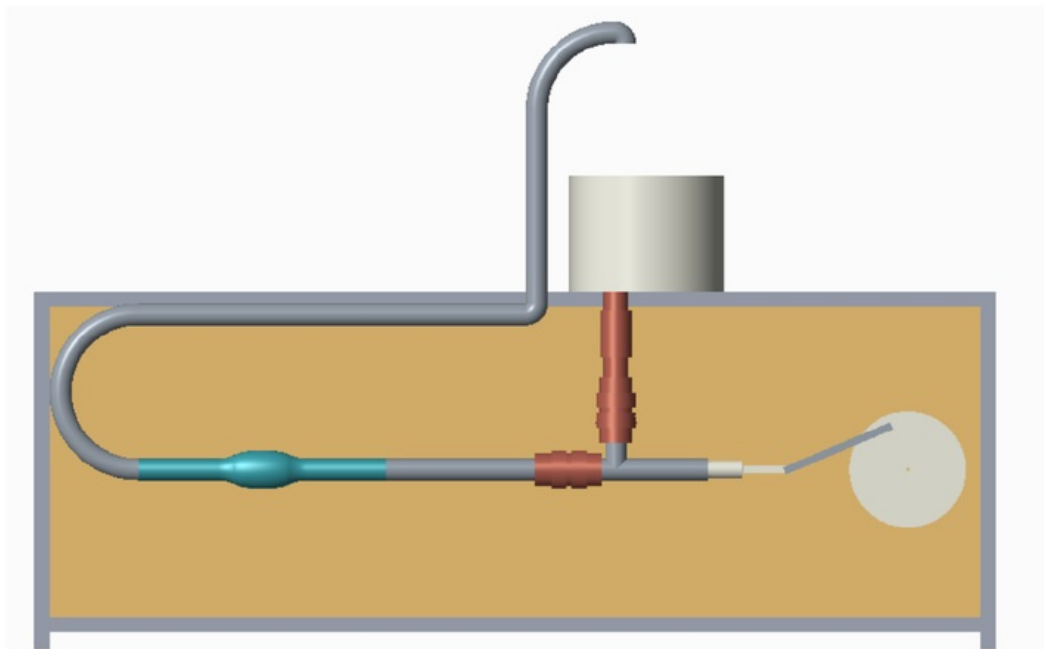


Figure 3.1: Flow circuit design, containing the aneurysm model seen in teal, connecting tubes, the inlet and outlet reservoirs, and a connection for a pump.

3.1.2 Mould Half Design

Figure 3.2 shows the design for the mould half. Two mould halves will be bolted together to contain the casting fluid while it is allowed to set.

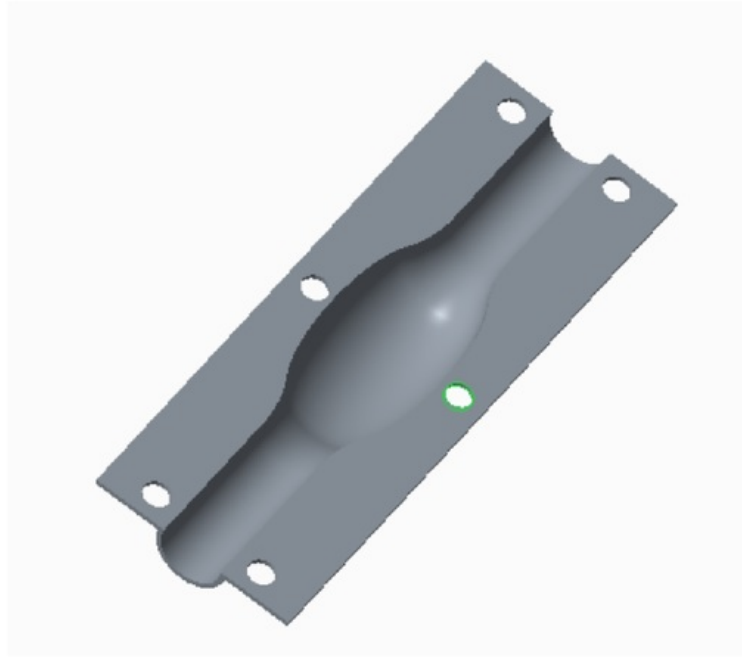


Figure 3.2: Mould half design

Chapter 4

Discussion

4.1 Discussion

The design of the flow circuit has not been tested or proven to work. Therefore testing must be performed to ensure it is able to produce pulsatile flow and the flow moves throughout the system as desired. Creating a flow circuit has proven difficult due to component availability and budget.

Similarly creating the aneurysm models for use in the flow circuit has not yet been completed due to 3D printing limitations. These include the heated bed of the 3D printer that heats the model as it constructed. The heat from the bed travels up the model and once the model exceeds a height range, the model starts to warp as the top of the model (the part furthest away from the heated bed) is allowed to cool and therefore does not bond well with the remaining model construction. The printers ability to make uniform circle shapes requires that the circular shape be drawn on a plane parallel to that of the printer bed. If this is done, supporting structures would be placed along the surface of the mould that needs to be smooth for the casting process. Therefore additional work would need to be performed on the printed moulds, such as sanding to smooth the surface.

The mould materials have been obtained via the companies Wacker Chemicals and Ingredients Plus, moulds are still needed to complete the manufacture of the models.

Chapter 5

Conclusions and Future Work

5.1 Future Work

This topic has not been completed and requires additional work to complete. The flow circuit and aneurysm models still need to be created and then data needs to be obtained, followed by the presentation of this data.

This project has only focused on AAA's. Aneurysms can be found all over the body and have varying mechanical properties, furthermore saccular aneurysms were not considered. This work should be repeated for these types of aneurysms, in order to develop additional graphs for predicting stiffness for a given aneurysm.

5.2 Conclusions

Knowledge of aneurysms is constantly evolving and current research is providing new information into their formation and rupture. It is critical that this research is continued as it helps in our understanding of the human body and quantifies the risk of aneurysm rupture, saving lives.



Chapter 6

Abbreviations

AAA	Abdominal Aortic Aneurysm
MRI	Magnetic Resonance Imaging
CAD	Computer Aided Design
CFD	Computation Fluid Dynamics
BPM	Beats Per Minute
PVC	Polyvinyl Chloride

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