Optimization of the in-vitro model equipment for future heart-valve studies

BACHELOR'S PROJECT - REPORT

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Spring semester 2014

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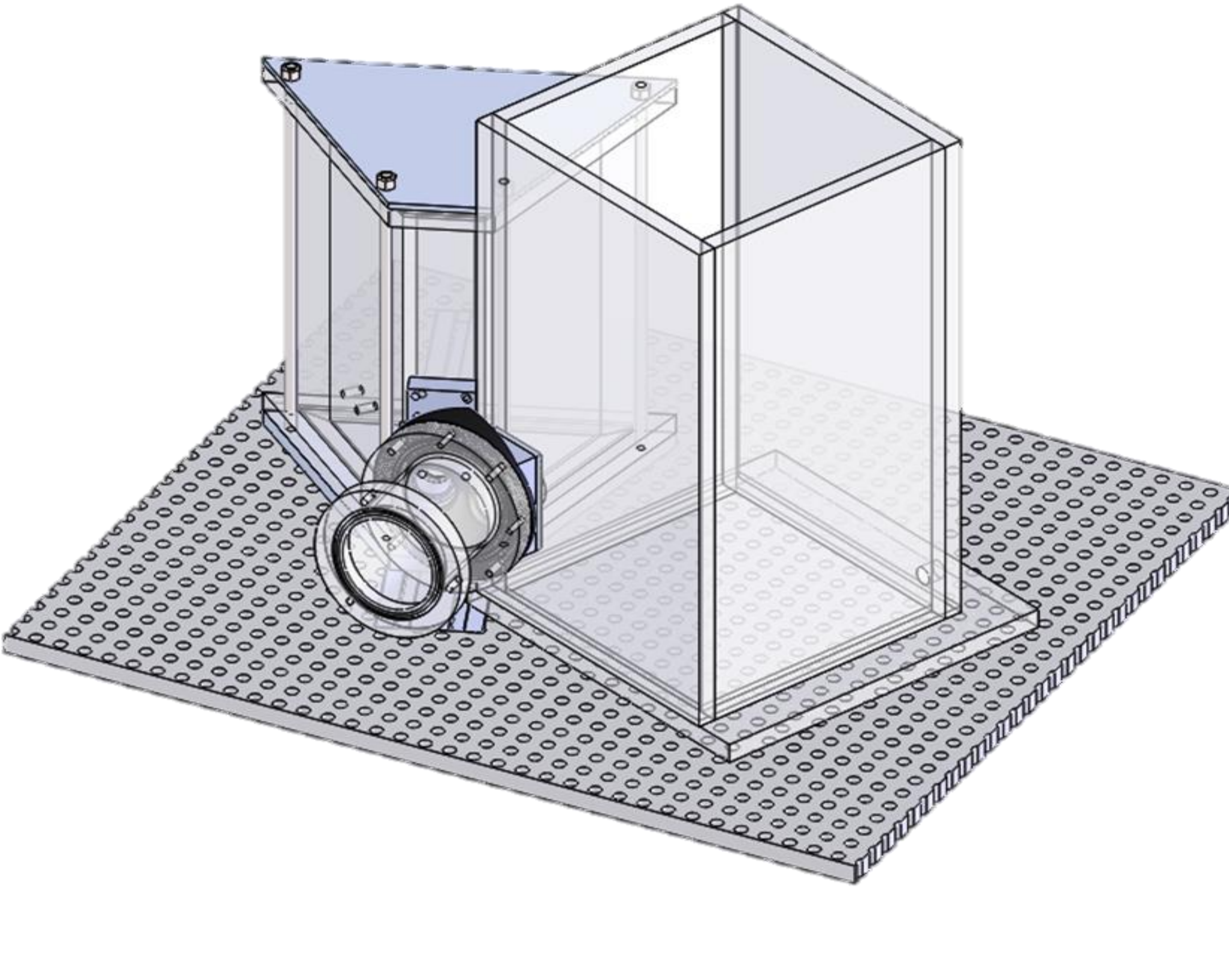

ABSTRACT

The aim of this project was to optimize an in-vitro model designed for heart valve studies by achieving more lifelike pressure curves together with reducing the undesirable noise in the chambers.

Based on the experience collected from previous designs a new model was designed and constructed. Several tests were made with in order to verify if the optimizations had a positive impact on the pressure curves and on the collected data.

Moving the chambers to the same level, increase the size of both – atrium and the compliance chamber – and installing a silicone bag in the ventricle chamber to increase the compliance in the model are the principal changes made in the model. Moreover, a more durable model for the future studies was desired.

The tests' results have showed that the new model still does have a large amount of noise on the pressure curves. Furthermore, the silicone bag does not have a significant impact on the data collected. Regarding the durability of the model, it has been possible to find a solution to the problems in the existing model.

The conclusion for the project is that a more durable model is possible to achieve. Damping factors are required to take into consideration in order to reach the proper damping in the model, and consequently reduce the noise. The silicone bag's materials and shape are able to accomplish the functions as expected in the model. However, it is not possible to draw any conclusions relating to the pressure curves therefore it is not easy to say if the bag's impact has an effect or not in the in-vitro model.

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TITLE PAGE

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FOREWORD

This report has been done by Ana Ochotorena Portales, an international mechanical engineering student from Spain in an Erasmus program.

During the project process the following people has been related providing help and support:

- *Peter Johansen* – Associate professor, PhD at Aarhus University in the Department of Engineering
- *Anders Hvilsted* – Associate Professor at Aarhus University School of Engineering
- *Tommy Kragh Bechsgaard* – PhD student at Aarhus University
- *Cave team*
- *Dalgas Avenue's Workshop*
- *Katrinebjerg's Workshop*
- *M7BACH14 group*

READING GUIDELINE

This project is divided in two parts. The report section is where the main descriptions, explanations and results obtained are presented. An appendix section is furthermore submitted where more detailed explanations, graphs, drawings and calculations are attached.

Along the report script are noted some references that guide the reader into the appendix sections for further information or more detailed calculations. There are also some references which lead into webpages, books or persons related with the corresponding item. All the graphs, tables and equations are also referenced; those which include an [A.O.P.] acronym are done by the author. Note that this project is a part of the entire new in-vitro model design which was done beside the M7BACH14 group; some sections are therefore referenced to them.

Furthermore at the beginning of the report is a background description where some extra information related with the topic studied is explained.

1- INTRODUCTION

1.1. General description

[1] In vitro models are being widely used to study mechanical properties of bio-prosthetic heart valves. In order to ensure valid results from these studies it is imperative that the model simulates lifelike conditions. In previous studies made with the in vitro model distal noise has been recorded on the pressure curve as seen in figure 1. Deviations will occur in in vitro models compared to in vivo testing; this distal noise is an example of a deviation. The in vitro system is made of acrylic material which is rigid compared to human heart tissue, in order to simulate elasticity; the in vitro model has a compliance chamber that can simulate the elasticity of the heart. However the compliance chamber might not deliver sufficient elasticity to the entire model. The model will be altered in order to obtain more accurate conditions. Lifelike readings of flow and aortic pressure are necessary.

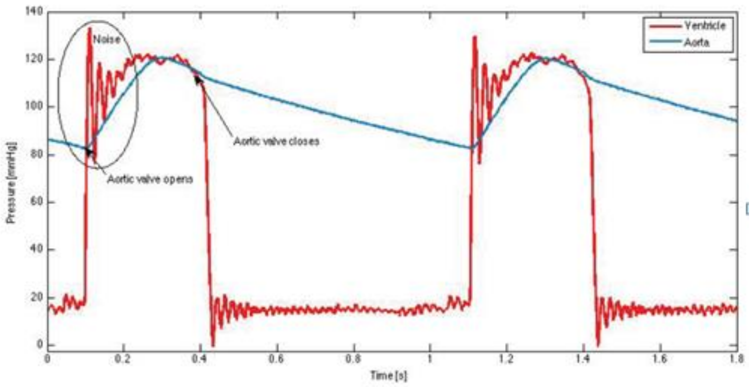

Figure 1 - Raw pressure data from "The effect of Sinus of Valsalva on TAVI valves" [2]

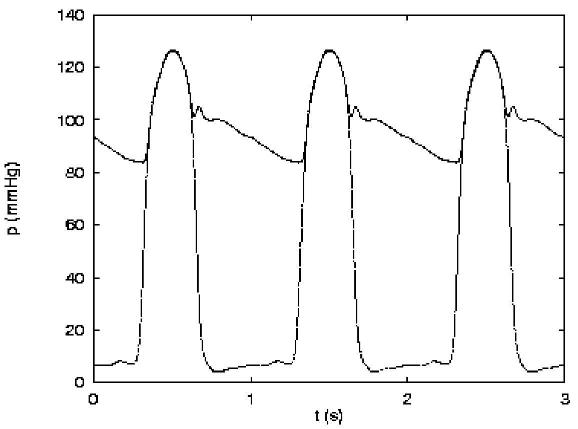

Figure 2 - Normal pressure curve [3]

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[1] The general description is done towards to the M7BACH14 so as to the project's aim is the same but divided the tasks into two groups (M7BACH14 and MIBAC4)
[2] Photo from "The effect of Sinus of Valsalva on TAVI valves" report
[3] Photo from "The effect of Sinus of Valsalva on TAVI valves" report

1.2. Project specification

[4] The project will conducted by two bachelor groups at IHA, group 14 and international bachelor group number 4. Group number 4 will be focused mainly on optimizing the compliance chamber and the aortic root. Meanwhile, group number 14 will be focused on re-dimensioning the atrium and ventricle chamber.

Hypothesis

1. More lifelike conditions can be created by redesigning the model, and more compliance is added.
2. By investigating different type of assembly connections, a more durable model can be made.
3. By moving the pressure sensors and the flow meter closer to the valve more realistic pressure readings can be obtained.

Methods for adding compliance and stabilize flow

A more laminar flow can be obtained if the chambers are repositioned. A more laminar flow might reduce the amount of wave energy that is being reflected on the walls of the model. In the heart this energy would be absorbed by the soft heart wall tissue. Repositioning the chambers means that the chambers will have to be re-dimensioned and redesigned without corrupting the lifelike properties already existing in the model.

The distal noise was worse the higher the CO was. This implies that the atrium chamber is not able to stabilize sufficiently. A bigger atrium chamber is therefore needed.

Adding compliance to the ventricular chamber might reduce the fluctuations on the pressure readings. Compliance can be added by installing a silicon bag in the ventricle chamber. A silicon bag therefore needs to be constructed.

By making the compliance chamber bigger it is possible to simulate more elasticity in the model which might reduce fluctuations on pressure readings.

Methods for increasing model's durability and longevity

The current material, acrylic, is very brittle. The model often has cracks and tears as a result of this. Therefore different materials will be evaluated in order to reduce damages in the model.

Cracks and tears appears most frequently in the compliance chamber's screw connections, alternative ways of connecting the walls of the chambers will therefore be evaluated.

[4] The project specification is done towards to the M7BACH14 so as to the project's aim is the same but the tasks have been divided into the two groups (M7BACH14 and MIBAC4)

Method for obtaining realistic pressure and flow readings

In the current model aortic pressure is being recorded in the ventricle chamber and in the compliance chamber and the flow is measured in a tube between these chambers. It is inaccurate to measure aortic pressure and flow at these locations; therefore the pressure sensors and flow meter should be located at the aortic root, closer to the valve section. The aortic root should be longer in order to install the flow meter. A longer aortic root also makes it possible to use the ultrasound transducer.

Note that the location of the pressure sensor might cause fluctuation of readings.

Verification of flow and compliance

The efficiency of the different methods for obtaining more lifelike results needs to be tested. Each improvement step will be tested separately in order to reveal which one has had the largest effect.

Verification of models durability

The choice of material will be based on different theoretical criteria.

To make sure that the compliance chamber connections can endure the load, different connections will be tested, by subjecting them to high pressure. The sturdiest connection will be chosen for the model.

Project boundaries

From the hypotheses, a definition of the project includes the following;

1. Redesign of the model thus more physiological pressure and flow conditions can be established
2. Testing the model under different conditions and test the following;
    - Compliance and resistance adjustment
    - Pressure curves
    - Flow Conditions
3. Visual access to the test segment (heart) for future ARAMIS studies

Criteria for success

A Success project will mean that it has been possible to;

- Construct an In Vitro model on the basis of past experience, where there are no cracks and significant leaks.
- Maintain the physiological conditions had been achieved in existing model
- Reduce noise on the pressure curves / Finding the cause of them.
- Construct a model where the analytical equipment ARAMIS can be used.

2- BACKGROUND

2.1. Heart [5] [6] [7] [8]

The heart is a muscular organ about the size of a closed fist and works as the body's circulatory pump. It is located in the middle of the thoracic cavity, between the lungs, above the diaphragm, ahead the vertebral column and behind the sternum. Its weight is around 275 [g] in men and 250 [g] in women.

The heart wall is made of three layers: endocardium, myocardium and pericardium. Each part will be therefore lightly explained below.

- *Endocardium*: It is formed by an epithelial lining that is continuous with the endothelium of the blood vessels inside. It is the layer that lines the inside of the heart and it is very smooth.
- *Myocardium*: Most voluminous layer formed by cardiac muscle tissue. It is the muscular middle of the heart wall that contains the cardiac muscle tissue.
- *Pericardium*: It completely surrounds the heart. The visceral layer of the pericardium is the *epicardium* layer, which is the first layer of the heart wall. It is a thin layer that helps to lubricate and protect the outside of the heart.

The heart consists in two cavities which are not communicated between each other: the right side and the left side. The right side is the pump for the pulmonary circulation. It receives all the oxygen-poor blood returning from the systemic circulation, specifically from three veins: superior cava, inferior cava and coronary sinus. On the other hand, the left side of the heart is the pump for the systemic circulation. It receives oxygen-rich blood from the lungs, by the pulmonary veins and afterwards it will be ejected into the aorta. From the aorta the blood streams through arteries, capillaries, where the exchange of nutrients and gases occurs.

Each side has other two cavities, the one above is called atrium and the one below is called ventricle, between them there is located a valve. The heart has therefore four valves that will been explained below.

- *Tricuspid valve*: It is located on the right dorsal side heart, between the right atrium and ventricle. The main goal of this valve is to prevent back flow of the blood in the right atrium when the right ventricle is getting contracted.
- *Mitral valve*: It is located in the left dorsal side heart, between the left atrium and ventricle. The main goal of this valve is to prevent back flow of the blood in the left atrium when ventricular systole. During diastole this valve opens filling the ventricle with blood. Diastole ends with atrial contraction, which ejects the final blood.

[5] Sobotta – Atlas de anatomía humana (Órganos internos)
[6] http://www.juntadeandalucia.es/averroes/~29701428/salud/circu.htm
[7] http://salud.doctissimo.es/atlas-del-cuerpo-humano/aparato-circulatorio/
[8] http://www.reparacionvalvularmitral.org/content/view/27/

- *Pulmonary valve*: It is located on the right dorsal side heart, between the right ventricle and the pulmonary artery (it entrust with the transport of the blood to the lungs to pick up oxygen). It opens in ventricular systole, when its pressure rises above the pressure in the pulmonary artery. At the end of ventricular systole, when the pressure in the ventricle falls, the pulmonary valve closes.
- *Aortic valve*: It is located between the left ventricle and the aorta. It manages the transport of the blood to the rest of the body. During ventricle systole, when the pressure in the left ventricle rises above the pressure in the aorta, the valve opens, allowing the blood to exit the ventricle into the aorta which distributes it into the rest of the body. When ventricular systole ends, the pressure in the left ventricle decreases, so the aortic pressure forces the valve to close.

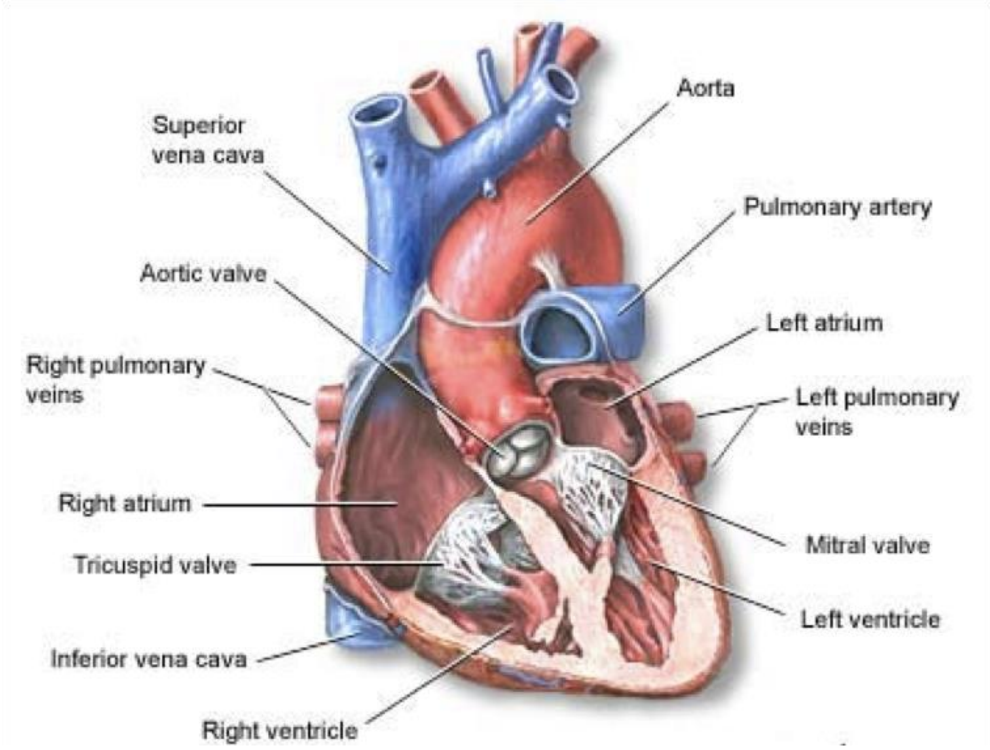

Figure 3 - Parts of the heart [9]

[9] http://www.studyblue.com/notes/note/n/cardiovascular-system/deck/1189322

2.2. Blood[10]

Blood is mostly liquid. It is composed by plasma and three kinds of elements or cells: red blood cells, white blood cells and platelets.

- Plasma: Is the liquid part of blood, it is salty (salt concentration 0.9%) and yellowish. In it float other elements, food and waste substances. The plasma contains proteins that help clot, and carry substances to improve other functions.

- Blood cells: *Red blood cells* (erythrocytes or red blood cells, which carry oxygen to the tissues), *white cells* (leukocytes, the have the function of defence against infections) and *platelets* (they are small cells that help to clot).

2.3. Cardiac cycle[11] [12] [13]

The heart function is a coordinated contraction and expansion movements, simultaneously with the contraction of the atria the enlarged ventricles and vice versa occurs. The relaxation period (or dilation) is called *diastole* where the heart is filled with blood and the period of contraction called *systole*, in which the heart sends blood into the arteries. Flow passing through the heart is controlled by pressure difference in each cavity; certainly the flow goes from areas of higher pressure to areas of lower pressure.

Following will be described the heart's movements, notice that it has been divided in successive and uninterrupted stages: First the atria are distended, so they are being filled in. Then the atria contract and the atrioventricular valves open, is when the blood gets into the ventricles that are undisturbed or dilated, filling them. When the ventricles are filled, they contract and push the blood into the arteries. Nonetheless, as the in-vitro model is performing the left side of the heart these movements' description will be therefore explained.

After the blood has passed through the lungs, where it has been recharged with oxygen and got rid itself of carbon dioxide, it is returned into the left atrium through the pulmonary veins. During diastole the mitral valve is opened and the blood in atrium goes into the ventricle, the diastole finish with atria systole when it contracts in order to forward the rest of the blood into the left ventricle to fulfil it before its contraction. When the powerful ventricle contracts the mitral valve closes preventing backflow. While ventricle systole, the ventricle reaches the aorta pressure and the aortic valve opens, therefore blood is forced into the aorta which distributes it into the rest of the body apart from the lungs.

[10] http://www.juntadeandalucia.es/averroes/~29701428/salud/circu.htm
[11] http://www.cvphysiology.com/Heart%20Disease/HD002.htm
[12] https://www.inkling.com/read/medical-physiology-boron-boulpaep-2nd/chapter-22/the-cardiac-cycle
[13] The Heart and Cardiac Output (Chapter 1) – 2004 Nursecom Educational Technologies

The cardiac cycle is divided in three phases: atrial systole, ventricular systole and relaxation or diastole. The explanation of each phase is explained below.

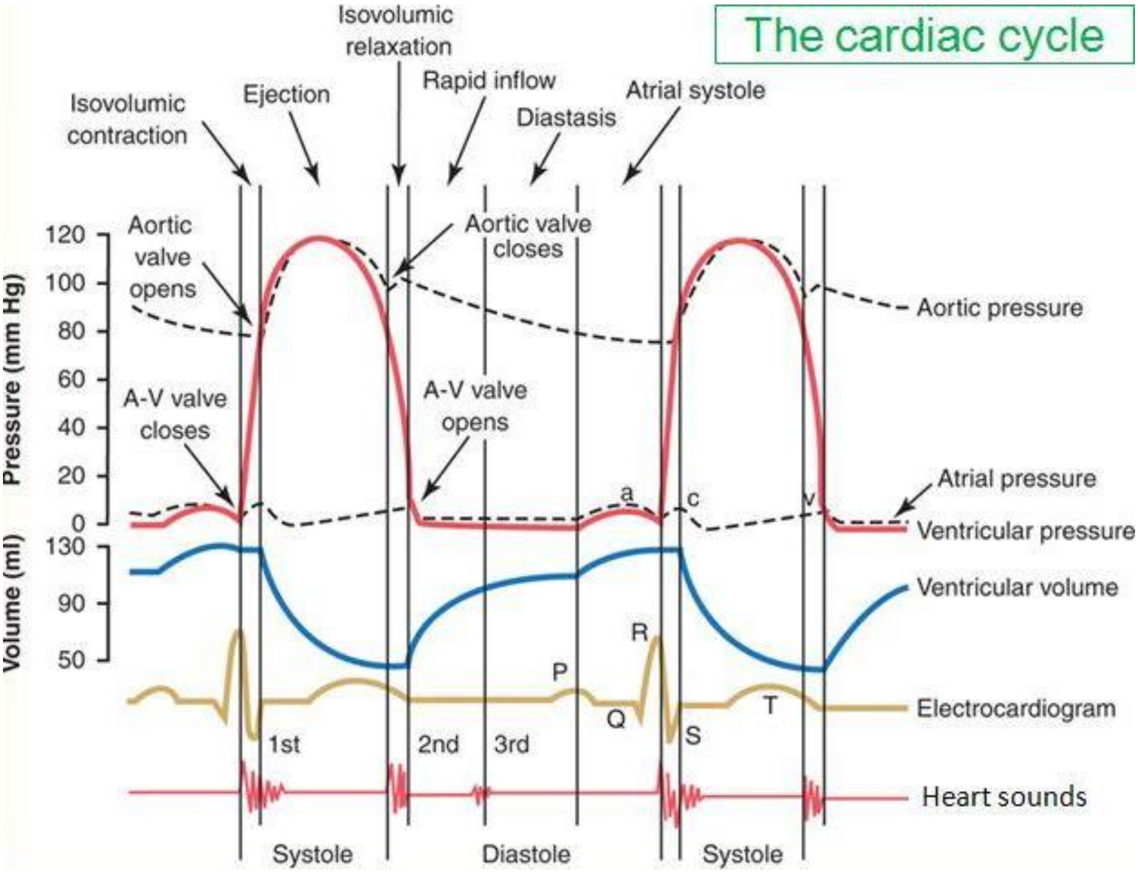

Figure 4 - Phases of the cardiac cycle [14]

The cardiac cycle is the period of time that an entire systole and diastole is completed. The complete process lasts about 0.8 [s] and the systole lasts about 0.3 [s].

In the atrial systole, the atriums are contracted and the blood gets into the ventricles that are kept in diastole. Mitral and tricuspid valve are opened, meanwhile aortic and pulmonary valves keep closed. During this phase the atriums are smaller, thereby it is only possible to refill around a 25% of the ventricles. In the ventricular the ventricles get contracted in order to introduce blood in the aorta and lungs. Due to the pressure differences, the aortic and pulmonary valves open however, mitral and tricuspid close. During the relaxation, the four cavities (the two atriums and the two ventricles) maintain in diastole and blood flows into the heart through the veins. In this stage, the ventricles fill around 75% of its capacity (the other 25% will be filled after the atrial systole). Mitral and tricuspid valve, are opened, meanwhile aortic and pulmonary valve are closed.

[14] http://www.studyblue.com/notes/note/n/cardiac-cycle-quiz/deck/5860939

One of the aims of the project is achieving a more lifelike ventricle and aortic pressure curves. This means that the obtained graphs should be similar to the one seen in figure 4. The ventricle pressure curve has a maximum peak around 120 [mmHg], increasing with a large slope in isovolumetric contraction and decreasing rapidly while isovolumetric relaxation. When systole stage starts the aortic pressure has a value around 80 [mmHg] and rises with the ventricle pressure until the ejection. At the end of systole it detach from the ventricle pressure decreasing slowly. After systolic contraction it is seen a sudden pressure drop due to flow back in the arteries while the valve is closing, this phenomenon is called “dicrotic notch”

Some concepts according to the cardiac cycle

In this section some concepts related to the cardiac cycle are going to be explained.

1- Heart rate, HR: It is defined by the number of cycles per minute. The typical values are 60/80 for a normal person and 40/55 for an athletic person.
2- Stroke volume, VS: It is the amount of blood ejected by the heart in one beat. Its units are [L/beat]
3- Cardiac output, CO: It is the blood flow ejected by the heart per minute. Its units are [L/min]. For its calculation it is needed the value of stroke volume, SV. An average resting cardiac output is 5 [L/min]. The following equation describes the calculation for the cardiac output:

$$CO = VS \; x \; FC$$

Equation 1 - Cardiac output calculation

4- Blood pressure: It is the force exerted by the blood against the inner walls of blood vessels; it is greater during systole than during diastole. The typical value is around 12/8, what it means 120 [mmHg] at systole – 80 [mmHg] at diastole

2.4. Diseases

[15] [16] [17] [18] The heart valves normally open to let the blood flow through the heart and then close to prevent backflow. If one of these valves becomes diseased or damaged, this can affect the flow blood in two ways: Regurgitation or stenosis.

Regurgitation

This phenomenon happens when one of the valves does not close properly, allowing the blood to flow backward, in the opposite direction. This situation reduces the capacity of the heart to eject the blood into the rest of the body, so with each heartbeat more blood than usual is in the left ventricle which makes it work hard. That situation increases the flow back pressure in the heart and lungs.

Stenosis

This phenomenon shows when one of the valves does not open fully, obstructing the blood flow. Hence, the opening of the aorta narrows. Two common varieties of aortic stenosis are: degenerative aortic stenosis and bicuspid aortic stenosis. As a consequence of the stenosis, the left ventricle must generate a higher pressure with each contraction to efficiently move blood forward into the aorta, namely, the heart has to pump blood harder. Consequently, at the beginning, the left ventricle walls get thicker in order to generate higher pressure. Later on, the heart dilates and its walls become thinner, deteriorating the systolic function and making difficult the ability to pump blood.

[15] http://www.medtronic.es/su-salud/enfermedad-cardiaca/index.htm
[16] Servicio Aragonés de salud (Temario específico)
[17] http://www.papworthhospital.nhs.uk/docs/leaflets/PI43_Transcatheter_Aortic_Valve.pdf
[18] http://www.heart.org/idc/groups/heart-public/@wcm/@hcm/documents/downloadable/ucm_307677.pdf

2.5. Overall about the different kind of valves[19] [20] [21] [22]

The prosthetic heart valves are artificial elements especially designed to replace human damaged valves. They consist in an opened part through which the blood is going to flow, and an occluder mechanism that ensures the opening and closing of the hole.

In a general understanding, there are two kinds of valves. The mechanical valves, wherein construction it is not included the biological material, and the biological valves made of flexible leaflets from animals or humans.

Mechanical valves (Open heart surgery)

Before the current mechanical valves' structure there has been developed other models such us 'ball valves'. They were first designed by Starr-Edwards, which consist of a silicone ball seated in a sewing ring when closed and moved forward into the cage when open. The original design has suffered several modifications but the basic design remains similar to the original. However, nowadays it only exits the Starr-Edwards model and no longer the rest, due to troubles related to high rate of thromboembolism and prosthetic dysfunction.

Another kind of valve is called 'disc valves', first designed by Bjork-Shiley in order to increase the opening angle of the prosthetic valve. His model is no longer manufactured due to high number of accidents; this model however exists in other brands.

The current model is called bi-leaflet valves. It was introduced by St. Jude Medical in 1977 and it has been being used until nowadays. One of its main characteristic is that the flow is central, which means a more similar hemodynamic compared to the physiology. This kind of valves, are fairly different from the previous ones since they have two semi-circular leaflets connected by a butterfly hinge. This concept of connection creates three areas of flow, one central and two peripheral ones. Its opening angle is 85º performing an almost parallel position of the bi-leaflets compared to the blood flow. A nearly laminar, central and minimum steady flow is achieved. The ring is metallic and the leaflets are made of carbon graphite impregnated in tungsten covered by pyrolite carbon, which reduces the thrombogenic capacity. This model has shown an excellent durability and low rate of thromboembolic events. However closing noise is possible to be listened and it involves the requirement of anticoagulant treatment. St. Jude Medical's valves and similar ones produced by other manufacturers are nowadays the most commonly implanted type of mechanical prosthesis.

[19] http://med.unne.edu.ar/revista/revista137/valvulas.htm
[20] http://www.ncbi.nlm.nih.gov/pmc/articles/PMC1767148/
[21] http://med.unne.edu.ar/revista/revista137/valvulas.htm
[22] http://www.heart.org/HEARTORG/Conditions/More/HeartValveProblemsandDisease/Types-of-Replacement-Heart-Valves_UCM_451175_Article.jsp

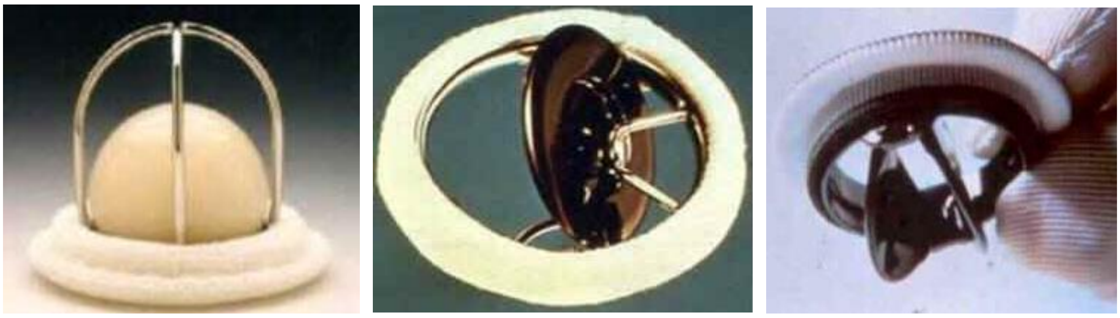

Figure 5 - Different kinds of valves, ball valves, disc valves and bi-leaflet valves [23]

Biological valves (Open heart surgery)

With the idea to obtain a more physiological valve, less thrombogenic and without anticoagulant treatment required, biological tissues were developed.
There is a widespread variety of biological valves, depending on its origin and its mounting. Different kinds of valves have been performed: autologous valves, autograft valves, homograft valves or allograft and heterograft valves or xenograft valves. Central flow developed is achieved for all the biological valves. In the following paragraphs are going to be slightly explained each of them.

An autologous valve is formed from the patient's own tissue such as pericardium. The procedure was challenging and the valves had very restricted durability. For this reason this method has no longer been used. More recently frame mounted valves constructed from the patient's pericardium have been developed.

An autograft valve is a valve moved from one position to another. This procedure involves replacing the patient's diseased aortic valve with their own pulmonary valve. The surgery requires a double valve replacement increasing the surgical risk. Some problems have been appreciated later on related to failure of the pulmonary homograft which may require a second surgery.

A homograft or allograft valve is a valve transplanted from a human donor (human cadavers, usually). There are three available techniques which are been used. This method is a tentative technique for young people due to anticoagulant treatment is not required. However, the surgery to implant this kind of valve is complex and there is a low availability of homograft.

A heterograft or xenograft valve is the valve transplanted from another species or manufactured from tissue. Porcine valves are treated to make it acceptable for the recipient. They are usually mounted on stents, rigid or flexible, attached to a sewing ring. Nonetheless, more recently stentless valves have become available even though they are more difficult to be implanted.

[23] http://med.unne.edu.ar/revista/revista137/valvulas.htm

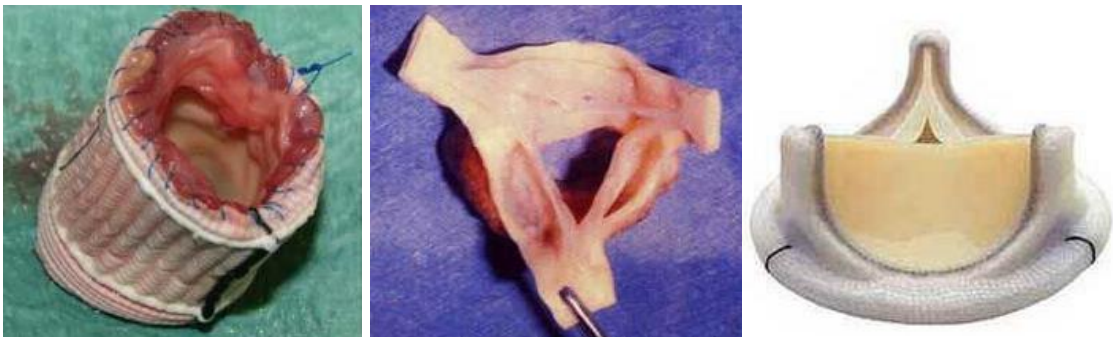

Figure 6 - Autologous valve, Heterograft valve and Homograft valve [24]

TAVI (Transcatheter Aortic Valve Implantation) [25] [26]

For those patients with a high risk for an open heart surgery required for mechanical and biological valves implantation, a worthy alternative is a transcatheter aortic valve implantation (TAVI) or transcatheter aortic valve replacement (TAVR).

TAVI is a recently procedure performed using the Edwards Sapien Transcatheter Heart Valve (THV). This kind of valve consists of a flexible metal frame, called stent, which secures the device on its position inside the human own valve. This device has attached three leaflets inside to direct the flow. This valves are made of biological material, usually cow's or pig's pericardial tissue.

The technique needed for TAVI valve implantation is minimally invasive; the valve replacement is settled using a balloon catheter without removing the old damaged valve. It can be inserted through very small openings in the body and can be performed by two different approaches: transfemoral approach (entering through the vein in the groin, through femoral artery) and transapical approach (entering from between two ribs, doing a small cut on the left side of the chest so as to get to the apex of the heart).

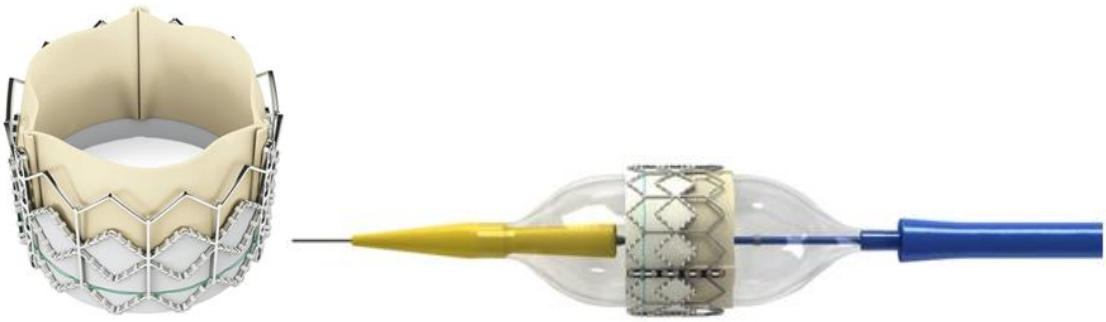

Figure 7 - TAVI valve and Balloon catheter with TAVI valve [27]

[24] http://med.unne.edu.ar/revista/revista137/valvulas.htm
[25] http://www.papworthhospital.nhs.uk/docs/leaflets/PI43_Transcatheter_Aortic_Valve.pdf
[26] http://www.nuhcs.com.sg/patients-and-visitors/our-services/cardiology/transcatheter-aortic-valve-implantation-tavi.html
[27] http://www.medgadget.com/2010/09/transcatheter_aorticvalve_implantation_tavi_reduces_mortality_rate_compared_to_standard_therapy.html

3- PREVIOUS IN VITRO MODEL – DESCRIPTION

[28] It is a "flop loop" simulating the left side of the heart which consists in eight different parts. In the following paragraphs is a list of the different parts of the current model provided in the laboratory, and subsequently the explanation for each all.

3.1. List of the parts of the current model:

1- Pump
2- Mechanical mitral valve
3- Left ventricle chamber
4- Biological aortic valve
5- Aortic root
6- Compliance chamber
7- Left atrium chamber

Figure 8 - Old Cave model (A.O.P.)

[28] This information has been achieved by the Cave team and previous reports. Note "The effect of Sinus of Valsalva on TAVI valves" report

3.2. Description of each part of the current model:

The in vitro system is based on a piston pump attached to the ventricle chamber. The pump can be adjusted into the desired heart rate and stroke volume; it is possible therefore to control the cardiac output. It also produces four different contraction types that can be achieved by adjusting the waveform of the pump's signal.

The ventricle chamber represents the left ventricle of the heart. It is made of 15 [mm] thick acrylic plates glued together. The top plate is screwed in with the atrium chamber by the usage of nylon screws and sealed with a silicone ring in order to improve the connection. It has a volume of 2 [L] and it has two entrances: one for the pump and another for the atrium chamber. It also has an exit connected to the aortic root.

The aortic root represents the ascending part of the aorta. Inside it, it is mounted the biological aortic valve which consists in a treated valve made of organic tissue, normally from pigs[29]. The chamber made of acrylic and it is mounted between two flanges, which are fixed to the ventricle and compliance chamber by four nylon screws. To minimize the leaking in the connection, O-Rings have been positioned between the flanges and the aortic root and they will be compressed to ensure minimal outflow.

The compliance chamber is not a physical part of a heart. By adding compliance in the model it is possible to simulate the elasticity of the biological material in the body. The chamber is made of 15 [mm] acrylic plates glued together. The top plate is screwed in with nylon screws and sealed with silicone seal to minimize the leakage ensuring the air to remain inside the chamber. It has a volume of 1.8 [L] and it has two entrances: one for the aortic root and one for pressurized air and it has one exit to drive the water into the atrium.

The connection between the compliance chamber and the atrium chamber is by a silicone tube. This tube is 300 [mm] long and it has an inner diameter of 12 [mm]. Around it, it is positioned an ultrasonic flower meter to measure the mean flow (cardiac output). A peripheral resistance is mounted on the tube in order to produce atrial resistance. It is manually adjusted by thumbscrew.

The atrium of the heart is connected to the ventricle chamber by the mitral valve which consists in a mechanical valve sewed to a silicone seal. This chamber is mounted on top of it, linked with nylon screws. Thereby it requires less fluid to produce the right hydrostatic pressure in the ventricle chamber. In the model, it is the only chamber opened to the atmosphere; therefore it is possible to fill it easily and quickly. Usually the pressure is around 10-15 [mmHg]. It is made of 15 [mm] thick acrylic plates glued together reaching a volume of 1.3 [L]. Additionally, it has one entrance for the compliance chamber and it has one exit for the ventricle chamber.

[29] The test valves are provided by the Hôpital Européen Georges-Pompidou and the University Paris Descartes. These valves are home-made according to the properties than the commercial TAVI valves have.

3.3. ARAMIS

The vi-vitro model is also used for ARAMIS measurements. The images captured by using a high speed camera are uploaded to the ARAMIS software in order to calculate the strain by pattern recognition. Before those calculations, a calibration by using calibration plates is required.

In order to be able to use this program and do the calibration properly, some dimensions are required in the model such us angle or distance. It is therefore needed to take them into account when designing the new model. Moreover, it is important to ensure the parallelism between the cameras and the valve that is going to be analysed. The main characteristic the cameras require for a precise capture is a certain angle. Consequently, the length of the back plate of the compliance chamber should ensure the achievement of those angles.

A proper luminosity is required for accurate recordings, it is thus a factor to be aware of.

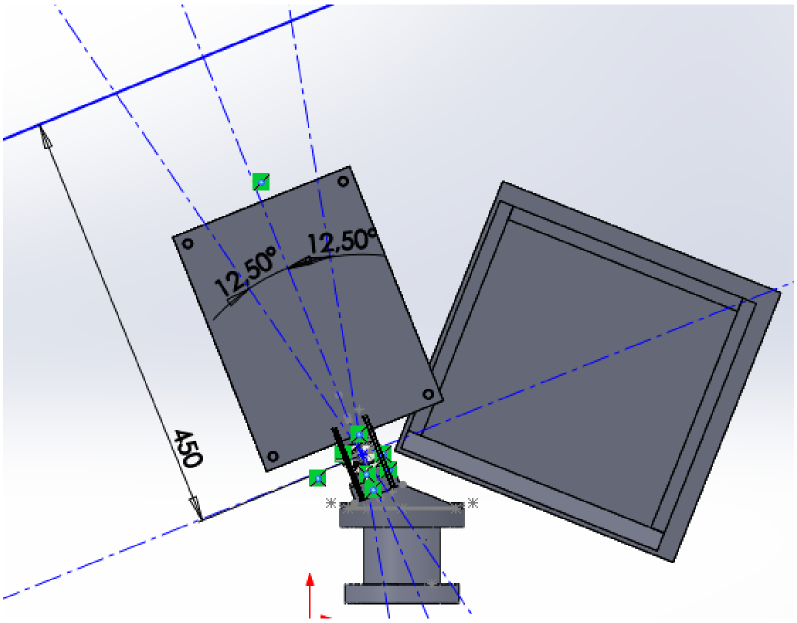

Figure 9 - Required angles for the ARAMIS analysis [30]

[30] Photo from M7BACH (Sandra) SolidWorks assembly

3.4. Discussion of the current in-vitro model

Due to some inaccurate circumstances seen in the previous in-vitro model, a new design was required. In the following section is going to be explained the concerns in order to provide an explanation of the reasons for this new model creation.

Flow in the previous in-vitro model performs not steady, thus a lot of wave energy is reflected on the walls of the model. For that reason, a larger size of the atrium was suggested as a possible solution. Furthermore, that atrium increment may reduce the distal noise that has been appreciated. This noise rises with the cardiac output.

Regarding the pressure readings, some fluctuations have been perceived and for that reason, addition of more compliance was required, as a possible solution to improve them. This compliance will be added not only in the compliance chamber but also in the ventricle chamber by using a silicone bag.

In addition, some troubles related with materials, such as cracks or tears around the screws sections are a concern in the previous in-vitro model. Consequently, an improvement in materials and connections is required due to the material's fragility. Some inaccurate connections in the model prompt leakage especially between the chambers. This problem may provide errors in measurements and is a non-desirable aesthetic design.

In the current model, the measurements of the flow and pressure have been done in an inaccurate area, so a replacement of the position is therefore necessary.

These problems have been appreciated by some partners who were working with the model in previous projects and also by the people who normally working with it. A list with requirements that have to be fulfilled and concerns has been provided as a help guide[31].

[31] This list is attached in the appendix section 2

4- UPDATES IN THE IN VITRO MODEL

The previous in-vitro model has to be improved due to the troubles and concerns explained in the previous section. The new design is based on the preceding in-vitro model with a new distribution of the chambers in order to achieve a more physiological distribution. In the following paragraphs are presented the explanation of each part, the designing process, the improvements and requirements to be fulfilled.

4.1. Compliance chamber

The compliance chamber is used to simulate the body's elasticity. Compressed air is supplied inside the deposit in order to add compliance.

4.1.1. Requirements

[32] This chamber has to fulfil some requirements given by the coordinator and the cave-group members. Following these requirements, better results are expected in the pressure curves.

Avoiding as maximum as possible the screw connections in the chamber is a requirement to be satisfied. Screws connections lead into cracks as it has been seen in the previous model. It is also required to increase the volume of compressed air inside the chamber. In the requirement's document, 3-4 [L] of air above the aortic root is requested. However, this state was finally rejected as long as the available air volume section increase compared to the old model. Guide straws for Millar catheters are also needed in the chamber.

4.1.2. Versions of the new compliance chamber

Two versions of compliance chamber have been performed. Initially a square model was designed; nonetheless a trapezoidal shape design was considered due to space necessities.

Square compliance chamber

This chamber has been done by avoiding screw connection between the walls. Metal plates in the upper and lower part of the deposit and glue connection in the polycarbonate walls have been used to entirely close it. In addition, some recesses have also been made in order to improve the connection between side walls and top and bottom plates. In order to avoid air leakage in the top plate, the model has been sealed by fulfilling the recess with a silicone ring. By the fact, as threaded holes in the plastic have been avoided in the chamber, cracks in the top plate are not presented.

The volume of the chamber is 3.4 [L] – 1.5 [L] of water and 1.9 [L] of air –. The water level must to be above the aortic root hole in order to avoid back flow air inside the aortic root which may damage the valve.

[32] These requirements are explained with more detail in the appendix section number 2

One of the chamber's corners had to be cut due to space problems with the atrium chamber in the assembly, but it does not affect the volume inside the deposit since this corner is only in the top and bottom plates. The atrium has been designed with a large size in order to fulfil the required pressure and the ventricle module has the smallest angle possible to reduce the entire assembly area. On the other side, the aortic root is desired to be as much centred as possible with the compliance chamber leading into space troubles while assembly.

The deposit has been designed with some inlets and outlets. In the top plate there is the inlet used for introducing compressed air and it is also attached an outlet to insert a pressure gauge. In the front wall there is the hole to connect the aortic root and in the back plate there is an inlet to attach the tube that connects this deposit with the atrium chamber. Finally in the left side there are the guide straws to insert the Millar catheters used to measure pressure.

Finally, the aortic root has been connected to the deposit by a screw connection which has been improved using QuickSerts®[33] . In order to reduce the leakage in the connection a silicone ring[34] has been used.

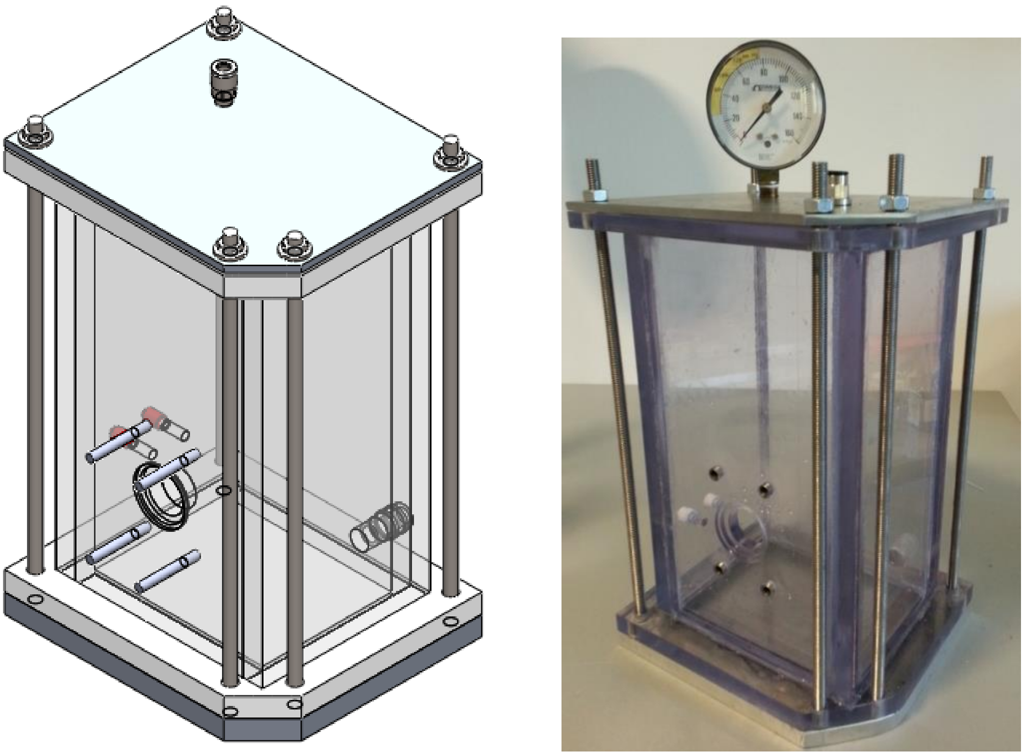

Figure 10 - Square compliance chamber (A.O.P.)

[35]Before achieving the final model, some other ones were gone through. The main changes between the first models and the final one are the size and the connection with the aortic root. In previous designs the aortic root was attached by an O-ring connection but not the final one which has been done by a silicone ring connection. Furthermore, the previous models

[33] More about QuickSerts® connection can be found further in this report - section 5.3.3.
[34] More detailed explanation is shown in this report - section 6.3.
[35] More information about the steps followed in the design process and the images are attached in the appendix – section 3

were larger; however it was finally decided to be built smaller, achieving a lower volume inside, as there was no need though. In order to accomplish the aim about avoiding leakage in the top plate, a silicone ring was made in the recess in order to seal better the connection between it and the rest of the side plates in the chamber.

Trapezoidal compliance chamber

The volume of the chamber is 4.2 [L] – 1.9 [L] of water and 2.3 [L] of air –.

The in-vitro model is also used to analyse biological valves which have length is smaller. The chambers therefore have to be closer each other. As the assembly between the chambers is not easy due to lack of space, a new model was desired. A deposit with a trapezoidal shape was considered in order to let the chambers be nearer.

Furthermore, better flow leading is expected. This item will be tested to prove its behaviour in flow leading.

[36]The way to design this model was the same as the square chamber and also the same materials have been used. The main characteristic of this model is the trapezoidal shape. Minimizing the front width and finding an accurate angle between the front and side wall is possible to give more room to assembly the rest of the elements in the model.

Note that the height for the Millar catheters position was increased in this design compared to the square model in order to locate them aligned with the aortic root. This location will avoid pressure drops.

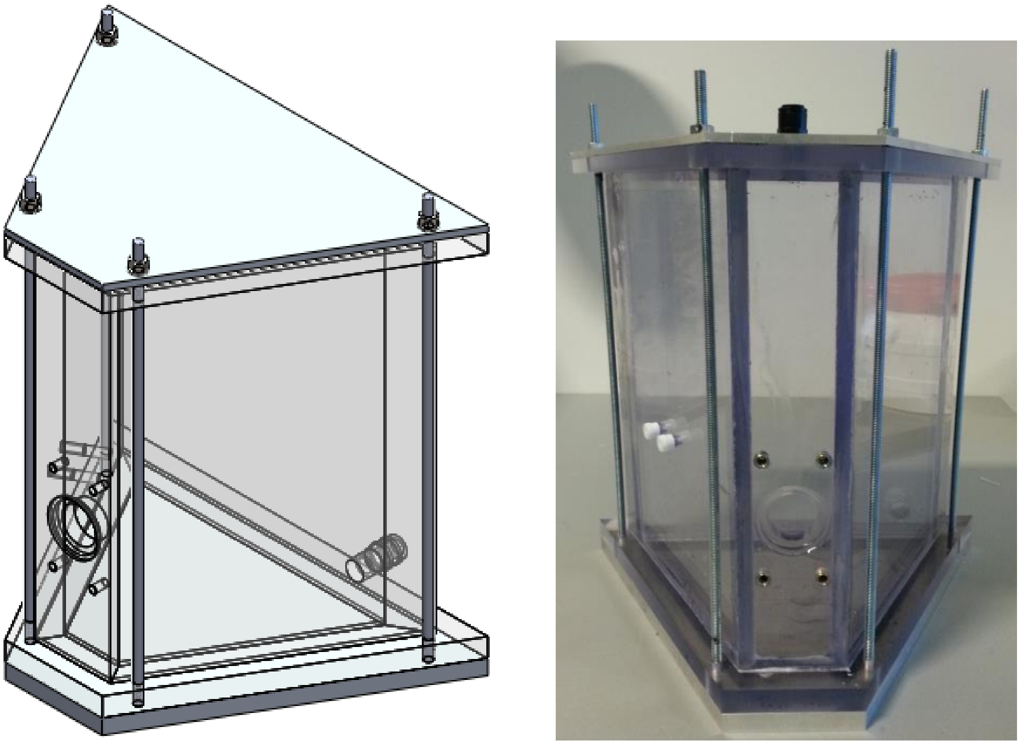

Figure 11 - Trapezoidal compliance chamber (A.O.P.)

[36] More information about the steps followed in the design process and the images are attached in the appendix – section 3

4.1.3. Pressure calculations inside the chamber

Pressure inside the compliance chamber was desired to be calculated. By using Bernoulli equation the water pressure can be achieved taking into account the water height and the compressed air inside the chamber. Subsequently, the forces that the screws in the top plate are supporting will be calculated. This calculation is made to ensure the chamber connections to be able to support this pressure without breakage. The previous model and the new model will be therefore analysed and compared, even though the closing mode has been changed due to material troubles explained in other sections.

[37]The Bernoulli equation for inviscid, steady and incompressible flow is the one bellow.

$$\frac{1}{2}\rho v^2 + p(r) + g\rho z = cte$$

Equation 2 - Bernoulli equation [38]

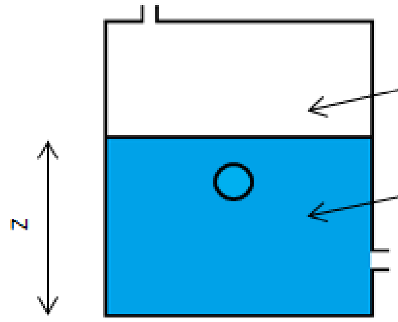

Figure 12 - Simplified compliance chamber (A.O.P.)

The water must be a bit above the aortic root in order to avoid back flow of the air, otherwise the air can damage the valve. The amount of water is few enough to neglect its influence[39], so to calculate the force that the screws are supporting it is going to be supposed only compressed air inside the chamber. The pressure in the top plate of the chamber taking account the water is 121 [kPa], and the compressed air is about 120 [kPa]. So the difference is enough small to be ignored.

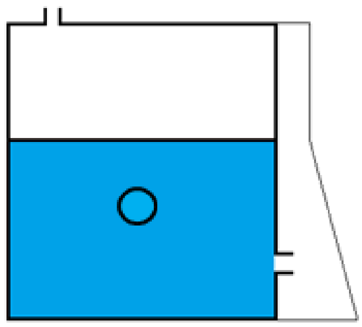

Figure 13 - Pressure distribution in the chamber (A.O.P.)

[37] Theory to achieve this equation is attached in the appendix – section 8
[38] Basics of fluid mechanics, Notes from Uffe Vestergaard Poulsen (Assistant professor – Department of Engineering – Sustainable Energy Systems)
[39] All the calculations are attached in the appendix – section 9

4.1.4. Calculation of forces and stress in the screws

Theoretical

[40] By calculating the forces in the top and side plates of the chamber, the following values were achieved. This force calculation was done by taking into account the constant pressure due to the compressed air of 120 [kPa] and using the equation that relates pressure and area to reach the force. Note that the pressure is perpendicular to area, and then the value was split into the number of screws since the compliance chamber can be seen as symmetrical. The area used in the total plate area normal to pressure.

$$P\ [Pa] = \frac{F[N]}{A[m^2]}$$

Equation 3 Pressure equation

For the top plate in the old compliance chamber, the forces values achieved are shown in the graph below.

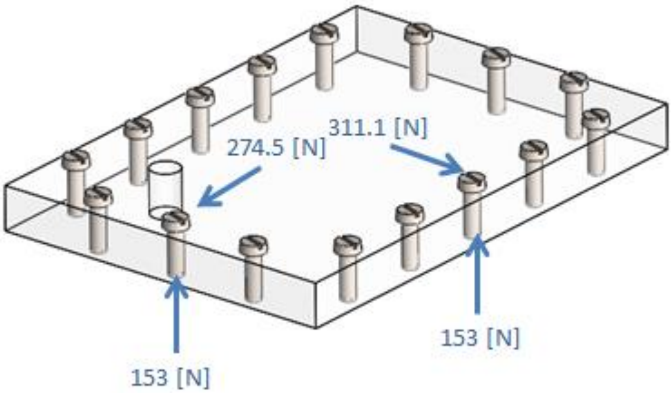

Figure 14 - Forces values in the top plate (old compliance chamber) (A.O.P.)

For the top plate in the new compliance chamber, the forces values achieved are shown in the graph below.

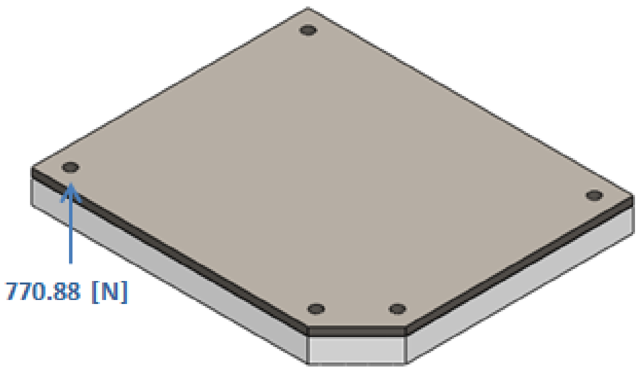

Figure 15 - Forces values in the top plate (new compliance chamber) (A.O.P.)

[40] All the detailed calculations are attached in the appendix section 11

Knowing the force values is possible to calculate the stress that the screws are suffering. In order to do this calculation it has being used the following equation that relates the force and the cross sectional area reaching hence the stress value. Note that the screw area is the one perpendicular to the force.

$$\sigma\ [MPa] = \frac{F[N]}{A[mm^2]}$$

Equation 4 - Stress equation

For the top plate in the compliance chamber, the stress values are shown in the figure below.

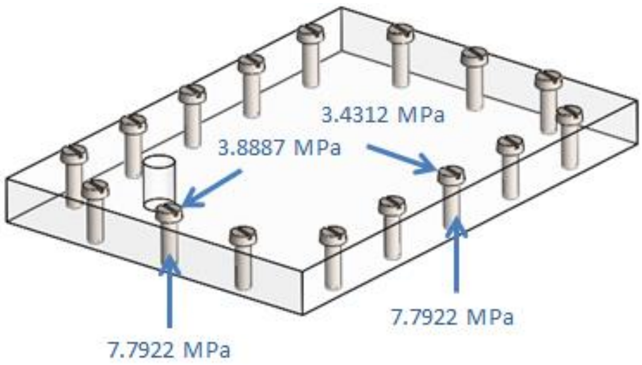

Figure 16 - Stress values in the top plate (old compliance chamber) (A.O.P.)

For the top plate in the new compliance chamber, the stress values are shown in the figure below.

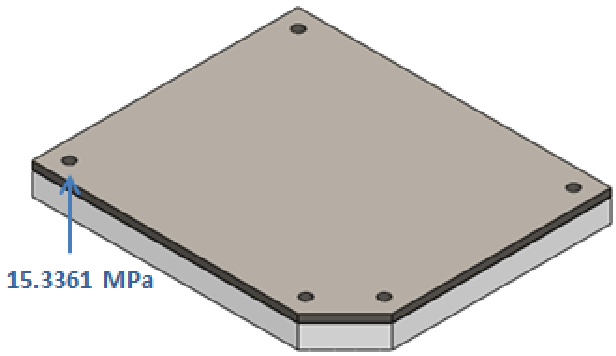

Figure 17 - Stress values in the top plate (old compliance chamber) (A.O.P.)

SolidWorks simulation

[41] The values achieved in the previous section by theoretical calculations were compared with a static SolidWorks simulation. In these simulations was possible to seen not only the Von Misses stress in the screws but also the displacement for the plates, letting also know if the pressure is an influence for these cracks seen in the plates before.

[41] More detailed results are shown in the appendix section 12

For these simulations it has been assumed symmetry and it was analysed the pressure influence for each wall isolated from the entire chamber. The conclusion for the pressure influence in the breakage was positive, due to the values of stress and displacement are bigger enough to cause some troubles in the connections. Although there are other reasons for the breakage in the screws explained in other sections more detailed, such as moisture absorption by the nylon screws and the threaded holes.

More simulations were done in order to find the most accurate ones such as comparing the results with threaded and non-threaded holes. More values such as strain were reached as well.

[42] More accurate simulations using advanced fixtures in SolidWorks have been done, taking into account the glue connection between the walls and the analysed one. Threaded holes were substituted however by clearance holes for the simulations because it is not possible to achieve realistic results with them in SolidWorks. Even though, it is known that in each thread of a bolted joint there is a stress concentration.

Conclusion of the results

Below it has been summarized in a table all the results – the theoretical calculations and the SolidWorks results – for the top plate in both models (old and new).

			Maximum Stress [MPa]	**Maximum Displacement [mm]**	**Maximum strain [-]**
Old model	**SolidWorks' Simulation**	**Threaded hole**	18.9110	0.05008	0.006173
		Clearance hole	6.7945	0.05008	0.001381
	Theoretical calculations		7.7922	-	-
New model	**SolidWorks' Simulation**	**Clearance hole**	26.932	0.02005	0.0001665
	Theoretical calculations		15.336	-	

Table 1 - Stress and Displacement comparison in the top wall (A.O.P.)

Summarizing, the new model will reach more stress value in the threaded holes due to the reduction of the number of screws and the increase of size; nonetheless the material has been improved so the results for the cracking mode due to pressure are expected better. The yield point for the acrylic is 45 [MPa] and the yield point for steel is around 235 [MPa], therefore even though the stress in the new chamber is bigger, the stress value is further from the yield point. In addition to this, the holes in the polycarbonate are clearance holes so there is no viable way to crack them due to pressure, moisture absorption or other agents that have been studied.

[42] More detailed explanation about these simulations in M7BACH14 – "Otimering af In Vitro model til fremtidige hjerteklap studier", 2014 – appendix section 17

4.1.5. Forces inside the compliance chamber

In the initial testing period the square compliance chamber has been used. During this period it has been seen that the back plate of square compliance chamber is not able to support the internal force, cracking when the amount of air increases inside the chamber. This problem is due to various items; firstly the glue connection is not able to support the compressed air, this can be caused by the glue used – epoxy and acrylate may not be the most accurate glue to be used in polycarbonate – new glue name was therefore use it as a glue improvement. Furthermore, the pump acts direct to the compliance chamber increasing the force that it has to support.

In order to avoid glue connection problems the same chamber has been designed in acrylic in order to fasten it with acrylate glue since it has been seen in previous models that acrylate works correctly on this material.

The force that the back plate of this chamber is supporting while the air is increasing has been calculated in order to see how much it increases with the height of air, causing the breakage of the glue connection. For this calculation has been assumed that the compressed air is constant and has a value of 1.2 [bar] (This value may be lower due to loses in the tube from the compressor to the chamber – to identify this value a pressure gauge is required). The clamp in the tube that connects the compliance and the atrium chamber is supposed completely opened therefore there is no influence due to the pump movement. [43] The forces results depending on the percentage of air and water can be seen below.

air [%]	water [%]	Force air [N]	Force water [N]	Sum of forces [N]
0	100	0	43.77	43.77
10	90	408.72	35.45	444.17
20	80	817.44	28.01	845.45
30	70	1226.16	21.45	1247.61
40	60	1634.88	15.76	1650.64
50	50	2043.6	10.94	2054.54
60	40	2452.32	7.00	2459.32
70	30	2861.04	3.94	2864.98
80	20	3269.76	1.75	3271.51
90	10	3678.48	0.44	3678.92
100	0	4087.2	0.00	4087.20

Table 2 - Forces depending on the [%] of air and water (A.O.P.)

[43] More detailed calculation are attached in the appendix – section 10

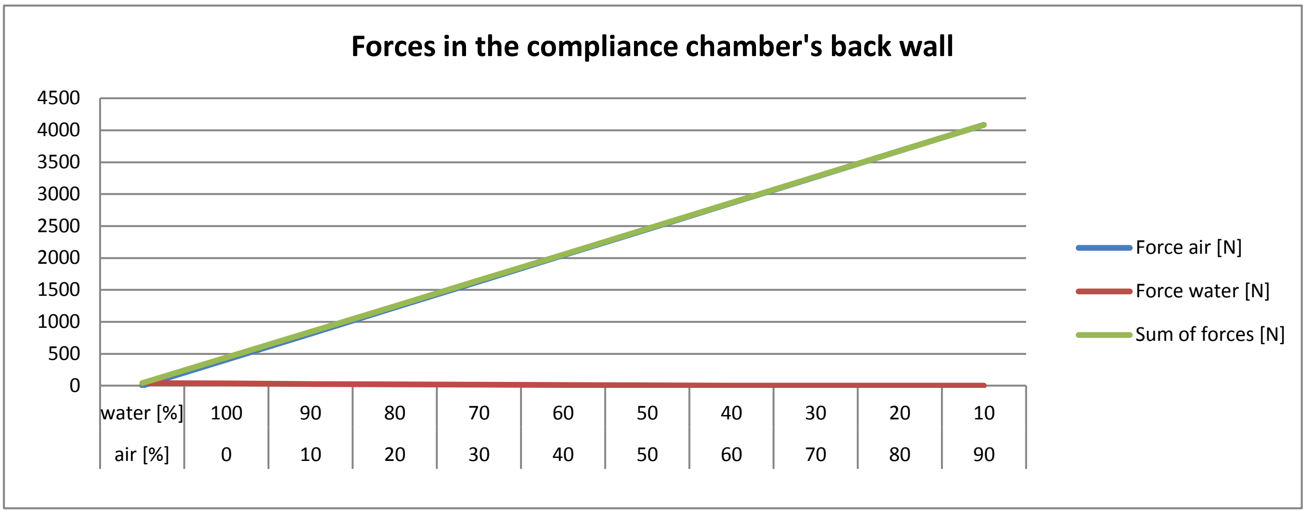

Figure 18 - Forces depending on the [%] of air and water (A.O.P.)

When the sum of forces creates a shear stress higher than the one that the glue connection can support [44] the connection breaks. Note that during the tests it has been seen that the connection breaks when the air percentage is close to the aortic root section height. In addition the clamp to produce atrial resistance was closed and the pump acting.

[44] How to calculate the shear stress in the connection is shown in appendix – section 10

4.2. Aortic root

The aortic root represents the ascending part of the aorta where the aortic valve is positioned. The aortic root in the model is integrated by the acrylic aortic root (with blocked or intact sinus of Valsalva), where the TAVI valve is positioned, and the fittings to connect the acrylic root with the chambers (ventricle and compliance chamber).

4.2.1. Requirements

[45] The aortic root design has to fulfil some requirements given by the coordinator and the cave-group members. Following these requirements better results are expected in the pressure graphs and in flow measurements.

In this paragraph are going to be briefly commented. One of the requirements was to change the position of the Millar catheters sensors in order to achieve more accurate readings. There was also required room in order to locate an ultrasound transcatheter close to the aortic valve and there was also desired to be able to measure flow in this section. In addition, avoid water leakage was also a requirement to be carried out.

4.2.2. Versions of the fittings

For the aortic root design, the main problem to focus in was the fittings in order to connect them with the chambers avoiding water leakage.

In order to fulfil these requirements, two models of fittings were designed: one recommended for pressure readings and other to have enough room to position the flow sensor (also possible to measure pressure, but due to length is non-recommendable in order to avoid larger pressure drops).

Both models are designed in POM material due to its good properties[46]. Each fitting is connected to its correspondence chamber by four M6 bolts inserted in the chamber's walls by using quicksert to reduce the cracks' possibility. Between the fitting and the wall a silicone ring is positioned to minimize leakage. Within the two fittings is located the acrylic aortic root, to connect both fittings four M5 threaded rods are used. To insert the aortic root among the fittings, two O-rings are used (one is direct sewed towards the aortic valve).

Fittings for pressure measurements

The position of the Millar catheters in the previous model was in the chambers (ventricle and compliance chambers); however they were desired to be closer to the TAVI valve to achieve more accurate pressure results, avoiding the pressure drops due to cross section between the aortic root's section and the chambers' sections. For that reason, the Millar catheters' new position is in the top surface of the fittings. In this new position the cross section where the catheters are positioned is the same as the place where the aortic valve is.

[45] These requirements are explained with more detail in the appendix section 2
[46] More information about materials selection in the report – section 7

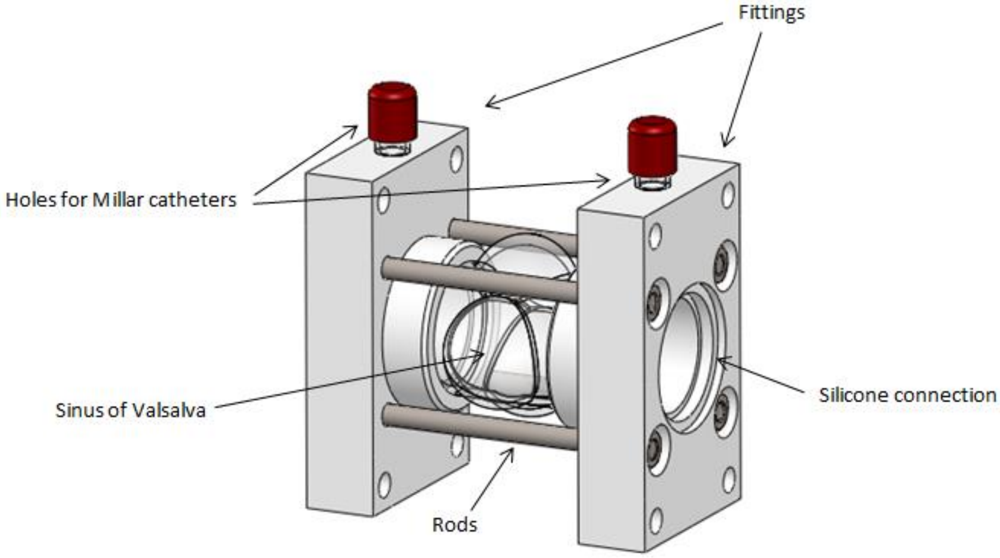

Figure 19 - Assembly of the aortic root (SolidWorks) (A.O.P.)

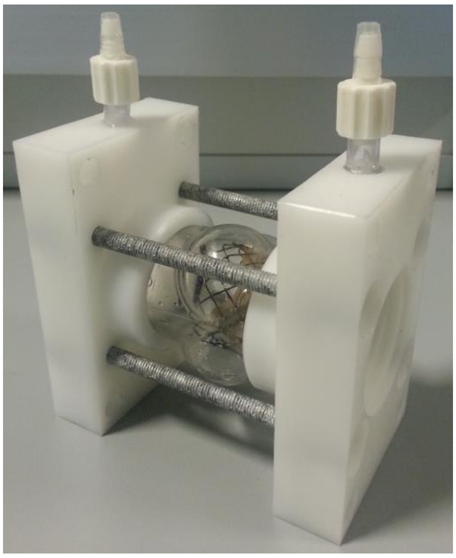

Figure 20 - Assembly of the aortic root (A.O.P.)

Before achieving the final model, some other ones were gone through. The shape of the fittings is one of the main changes between the first models and the final one, changing from circular to square. In the previous designs the connection between the fittings and the chambers was by using an O-ring in the chambers' walls recess. This idea was changed later on into silicone rings usage, due to leakage problems. Furthermore, in the previous models the inserts for the Millar catheters were in the sides of the fittings but afterwards, they were moved to the top area because it was easier and more convenient for the user.

Fittings for flow measurements

Due to the big size of the required flow meter, a re-version of the fittings was desired to be able to place it. Essentially it is the same idea but with the threaded rods positioned in another section.

To complete the assembly in order to make it useful to insert the flow meter a silicone tube was needed, therefore was designed a connector that will be positioned between the acrylic aortic root and the silicone tube. As the silicone tube has the same outer diameter as the aortic root, the connection between it and the fittings is also by an O-ring to minimize the leakage.

The aortic root's inner diameter is 27 [mm] and the silicone tube one is 25 [mm], so the pressure drop due to cross section can be neglected. The outer diameter of the silicone tube is 31 [mm], the same as the aortic root.

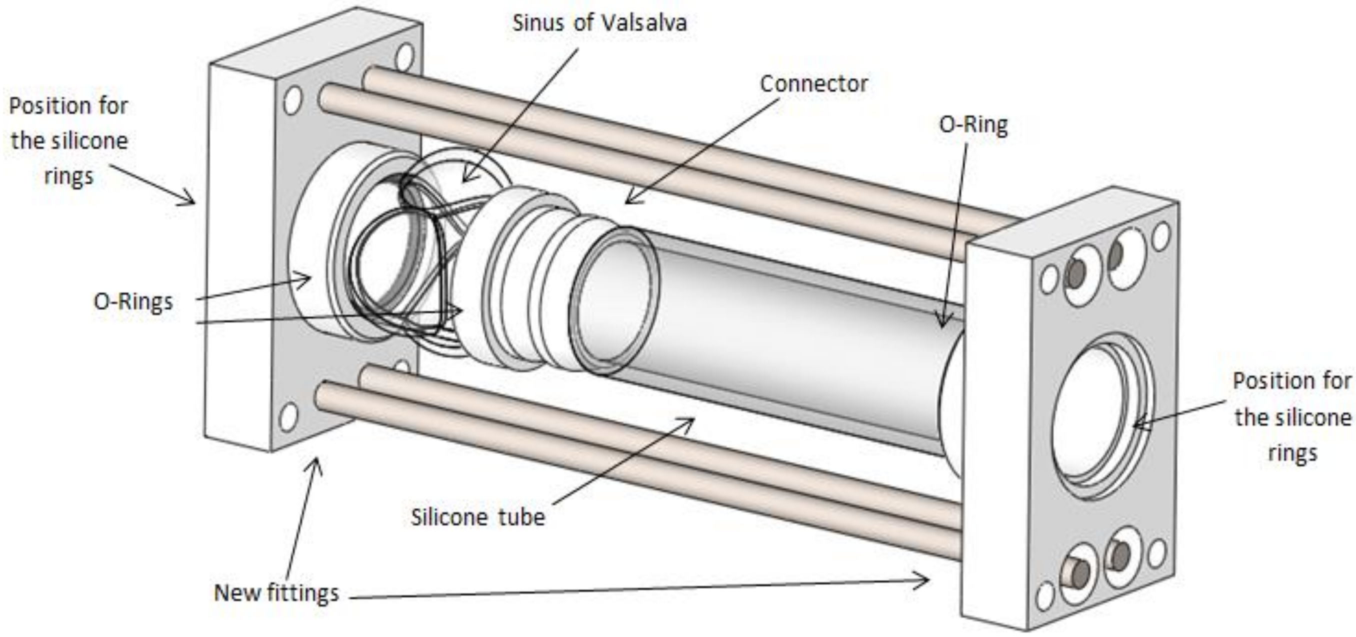

Figure 21 - Re-version of the assembly of the aortic root (SolidWorks) (A.O.P.)

4.2.3. Flow meter

A new position to achieve more accurate measurement of the flow was desired. The position for it was preferred to as closer as possible to the aortic valve section and with a cross section as similar as possible to the aortic root section. For that reason was decided to place it in the aortic root section by adding a silicone tube, instead of in the tube that connects the atrium and the compliance chamber as it was done in the previous model. In order to be able to place the flow meter in the aortic root, was designed the second fitting explained in the preceding section.

The company that provided the flow sensors is "Transonic". There are two models available: clamp-on and inline. The clamp-on model is the one chosen for two reasons. The clamp-on model has been used in the laboratory in previous analysis and the results achieved were accurate, it was decided to take advantage of this experience. On the other hand, the inline flow sensor requires one more connection since it is positioned within the tube, the less number of connection the better. With the clamp-on model there is no need to cut the tube.

[47] [48] The model selected is 20PXL clamp-on flow sensor, recommended by the company in order to fulfil the requirements. The sensor dimensions are: 58 [mm] along the tube, 46 [mm] depth and 93 [mm] length. These dimensions were taken into account in the aortic root re-design and when choosing the silicone tube length. The flow sensor has a resolution of 50 [ml/min] which means the smallest detectable flow change. The bigger the flow sensor is the lower the sensibility is to low flows and the higher the offset to zero, however this model was required for the model. The tubing necessary for each flow sensor has also to fulfil some requirements specified by the supplier. For this clamp-on model a silicone tube, PVC or polyurethane one is compatible, no rigid PVC or acrylic ones. For that reason a silicone tube was decided to be used. The tubing dimensions required are 1 [in] inner diameter and 1 ¼ [in] outer diameter. The sensor is calibrated according to fluid density and temperature of usage by the supplier to achieve the more accurate results possible, since these properties alter the signal.

Figure 22 - Clamp-on flow sensor model [49]

[47] http://www.transonic.com/
[48] Specifications in appendix section number 17
[49] http://www.transonic.com/

4.3. Ventricle chamber and Atrium chamber [50]

4.3.1. Ventricle chamber

The new compliance chamber has been designed with a completely new cylindrical shape to drive the flow in a more accurate way. The design consists in a cylindrical polycarbonate tube with two flanges attached, also made in polycarbonate. One side is connected to the pump, where there has been installed a silicone ring between the flange and the pump in order to reduce vibrations that the pump can trigger and to make a better fitting reducing the stress in the ventricle chamber's flange. The other flange is connected to the ventricle chamber by a POM ring. The usage of this ring is to fit the bag in the ventricle chamber, also an O-ring was incorporated to improve the adjustment. A second POM ring was desired to be designed for further experiments in the aortic valve; therefore a recess in the ring was made.

The main difference with the old model is the incorporation of a silicone bag, which is expected to create complain in the ventricle chamber. With this bag two cavities are created, consequently it is possible to separate the fluid forced by the pump, to the water in the rest of the model reducing the noise in the pressure curves.

There is also an opening in the upper part of the ventricle, which is used to fulfil the chamber with water when the bag is incorporated in the model and to take out the surplus air inside the chamber, like bubbles, when the bag is not.

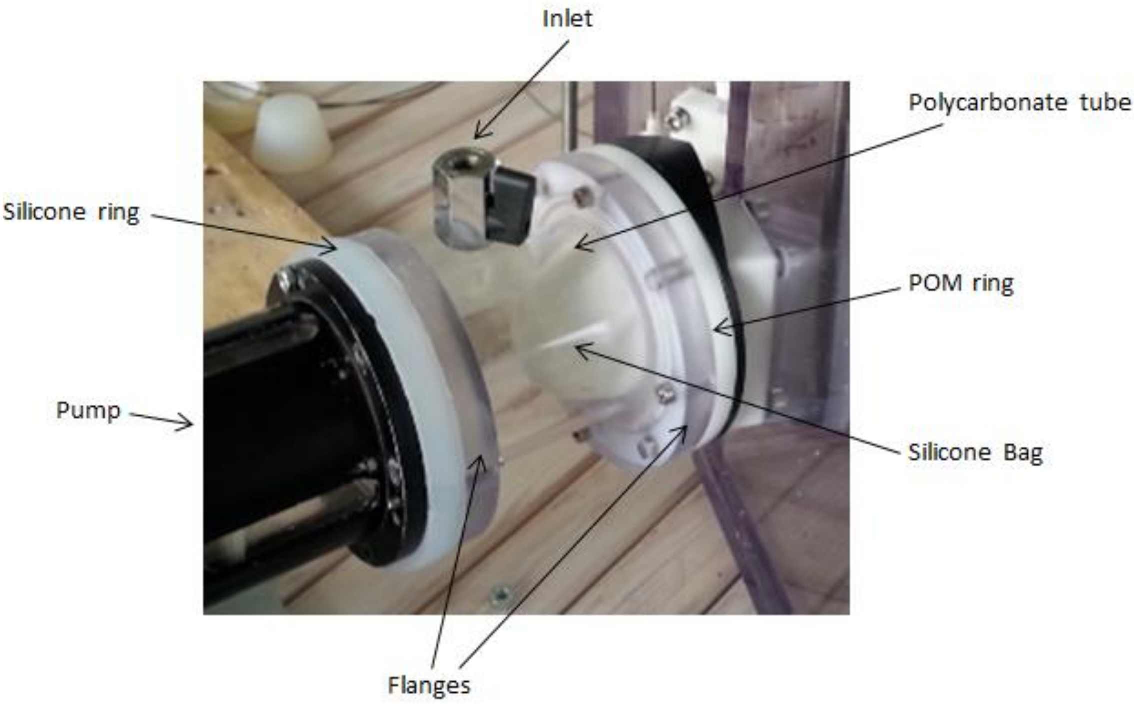

Figure 23 - Ventricle chamber (A.O.P.)

[50] This section was done by M7BACH14 – more detailed explanations in "Otimering af In Vitro model til fremtidige hjerteklap studier", 2014 – section 6

4.3.2. Ventricle module

It is a part used to connect the three chambers. It is attached to the ventricle chamber and due to its shape it is possible to connect the other two chambers to it. It has been designed with the minimum angle possible, to reduce as much as possible the assembly of the entire model.

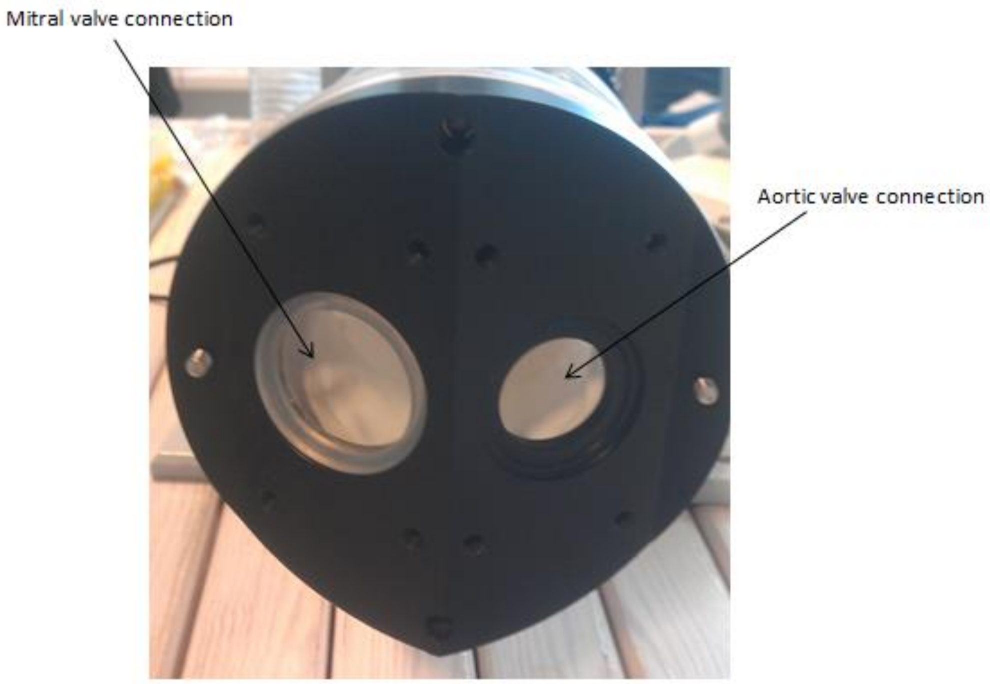

Figure 24 - Ventricle module (A.O.P.)

4.3.3. Atrium chamber

The old atrium was positioned on top of the ventricle chamber, and even with the improvements done in the previous model, the water level was unstable, especially at high cardiac outputs. Due to its small surface area there are large changes in hydrostatic pressure, which affect the pressure measurements. It was also seen a high flow rate through the system, so the higher this rate is, there more turbulent the flow behaves affecting the pressure measurements[51]. For these reason a bigger atrium chamber was desired, also the change in position influenced in the increase of size.

The atrium is an opened chamber and it has been designed much larger than the previous one. The new position is towards the compliance chamber and in front of the ventricle chamber. As the atrium is positioned in the same level as the compliance chamber, an increase in height was desired in order to achieve the requirement of 15 [mmHg] needed in the atrium chamber. The surface area has also been slightly increased to reduce the turbulence seen in the previous models, contributing in the decrease of flow rate going through the model.

It has an inlet positioned in the back plate of the atrium chamber, which connects it with the compliance chamber by a silicone tube 12 [mm] of inner diameter. It also has an outlet where the mitral valve is placed, connecting it with the ventricle chamber.

[51] Flow rate through the system calculated in appendix section 14

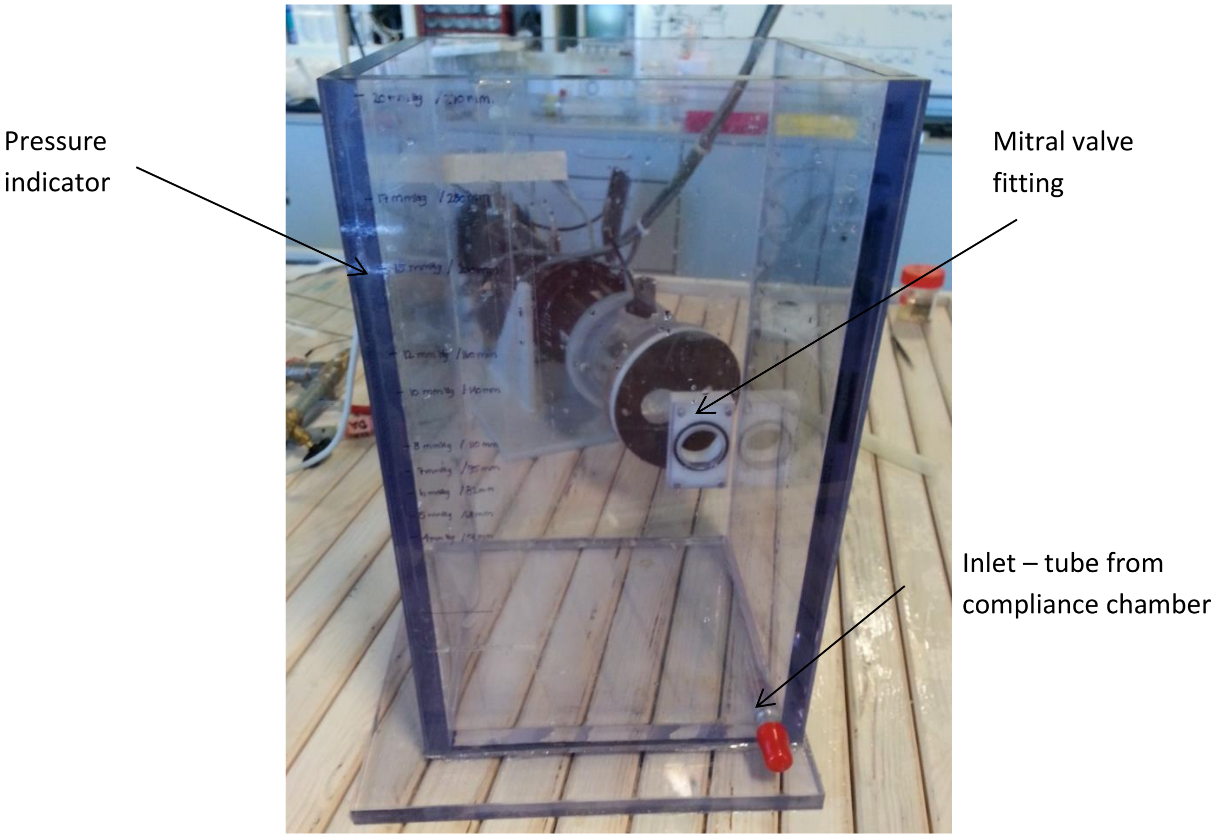

Figure 25 - Atrium chamber (A.O.P.)

4.4. Analysis of the new entire model

4.4.1. Pressure drops[52]

Pressure drops in the model have been calculated in order to minimize them as much as possible optimizing the model. Three kind of pressure drops have been taken into account in this model: pressure drops due to length in the aortic root, due to change in cross section in all the connections between chamber and due to bends in the ventricle chamber and in the tube that connects the compliance chamber and the atrium chamber.

[53] The pressure drop due to length in the aortic root is caused by turbulence and fiction in the walls. Note that has been used aortic root with blocked sinuses for this calculation, the sinus of Valsalva in the aortic root will generate less pressure drop[54] as it was probed in previous analysis since the sinus of Valsalva let the valve do a greater open. The model has been designed to be used with different aortic roots' lengths. Mainly, there have been analysed two possible lengths: the short one – designed for pressure measurements – and the long one – designed for flow measurements –. In the table below are summarized the pressure drops in both aortic roots and for two types of cardiac output. The average resting cardiac output is 5 [L/min] and 11 [L/min] is the maximum that the pump can perform.

Pressure drop *[mbar]*		***Cardiac Output***	
		5 [L/min]	*11 [L/min]*
Aortic Root	*Short*	0.01	0.05
	Long	0.03	0.13

Table 3 - Pressure drops due to length in the aortic root (A.O.P.)

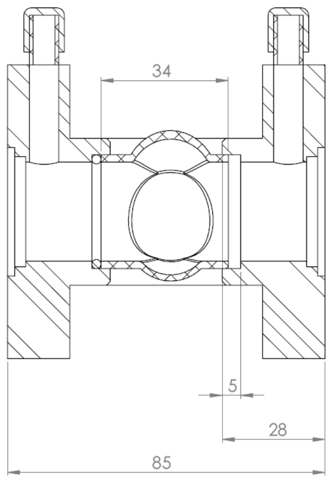

Figure 26 - Short aortic root relevant dimensions (A.O.P.)

[52] Detailed calculations are attached in the appendix – section 13
[53] Note that these calculations have been done by the web-page http://pressure-drop.com/
[54] This state was analysed in "The effect of Sinus of Valsalva on TAVI valves" report

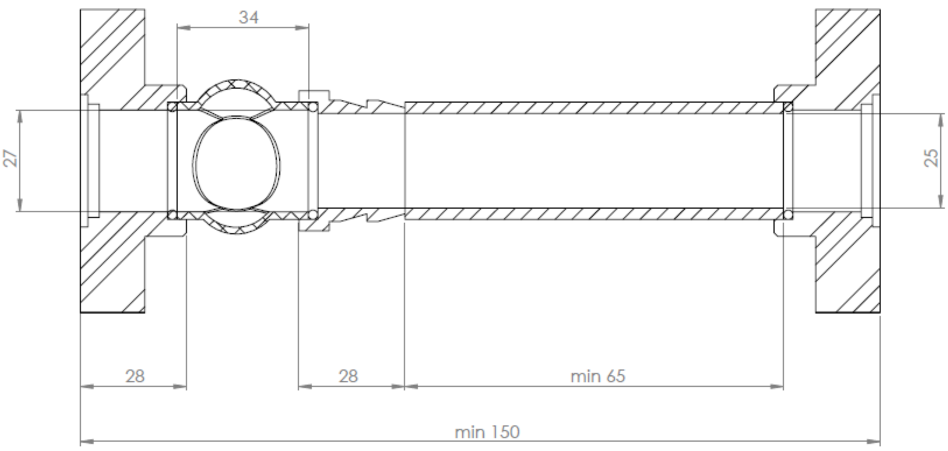

Figure 27 - Long aortic root relevant dimensions (A.O.P.)

It can be inferred that there is an increasing pressure drop with length but this change is not significant. However, as a recommendation to optimize the model is the usage of the shorter aortic root for pressure calculations. The long aortic root is recommended to be used when flow measurements are desired and therefore flow meter is needed to be inserted in the system.

Pressure drops occurs also due to cross section changes that are appreciated in all the model's connections. This calculation has been done for two different values of cardiac output, 5 [L/min] and 11 [L/min] by using Bernoulli equation[55]. It has been neglected the fiction factor because it is not relevant and also the height factor because there are no changes in height (in each connection analysed). The pressure drops in each connection of the model are seen in the tables below.

$$\Delta P = \frac{1}{2}\rho({c_2}^2 - {c_1}^2)$$

Equation 5 - Bernoulli equation (velocity)

CO = 5 [L/min]	**Connections**						
	Aorta	***Compliance***	***Tube***	***Atrium***	***Mitral***	***Ventricle***	***Aorta***
ΔP [Pa]	-10.47		-271.09		-14.07		
ΔP [Pa]	0	271.08		*14.25*		10.31	

Table 4 - Pressure drop due to changes in cross section for CO = 5 [L/min] (A.O.P.)

CO = 11 [L/min]	**Connections**						
	Aorta	***Compliance***	***Tube***	***Atrium***	***Mitral***	***Ventricle***	***Aorta***
ΔP [Pa]	-51.03		-1309.84		-68.56		
ΔP [Pa]	0	1309.76		69.43		50.23	

Table 5 - Pressure drop due to changes in cross section for CO = 11 [L/min] (A.O.P.)

55 Termodynamik. Teoretisk grundlag – Praktisk anvendelse. 3. Udgave. Nyt Teknisk Forlag

The bigger pressure drops are seen in the tube that connects the compliance chamber and the compliance chamber, also the pressure drop is considerable in the connections between the chambers and the valves (aorta and mitral). In order to reduce those pressure drops, the connections can be improved by doing a progressive change in section.

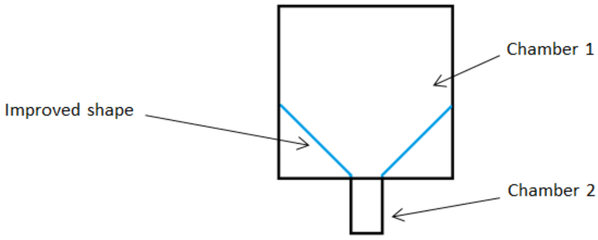

Figure 28 - New shape to approach (A.O.P.)

The third calculation of pressure drop is due to bending. It has been done using Bend loose equation[56] and compared with the values obtained in the web page. Firstly is calculated the bent of the tube that connects the compliance chamber and the atrium chamber. The results for theoretical and the web-page calculations are seen in table 6.

$$\Delta P = \frac{1}{2} f_s \rho u^2 \frac{\pi R_b}{D} \frac{\theta}{180} + \frac{1}{2} k_b \rho u^2$$

Equation 6 - Bend loose equation

Pressure drop	Theoretical calculations	Web-page calculations
5 [L/min]	5.5 [mbar]	4.97 [mbar]
11 [L/min]	29.23 [mbar]	19.43[mbar]

Table 6 - Pressure drop due to bend in the tube compliance to atrium chamber (A.O.P.)

It was secondly calculated the pressure loose due to bending in the ventricle chamber, by using the following hypothesis that simplifying the chamber like it is seen in the pictures below.

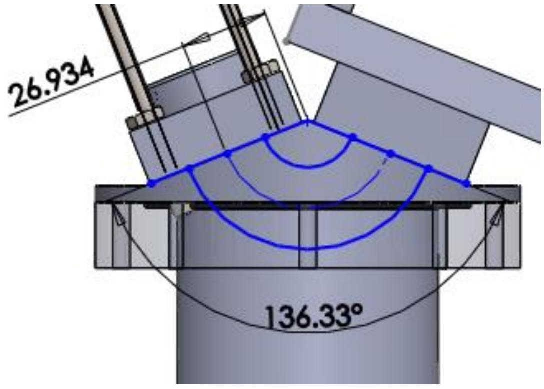

Figure 29 - Ventricle chamber hypothesis of bending between mitral and aortic valve (A.O.P.)

[56] http://thermopedia.com/content/577/?tid=104&sn=1422

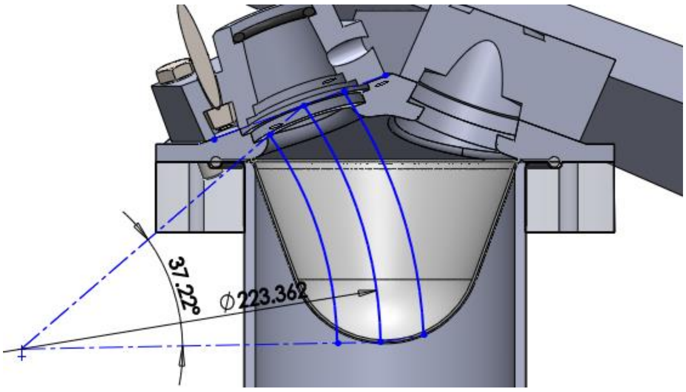

Figure 30 - Ventricle chamber bending between pump and aortic valve (A.O.P.)

The results for theoretical and the web-page calculations are seen in table below.

	Pressure drop			
	Bent Mitral to Aorta		Bent Pump to Aorta	
	Web-page calculations	Hand-calculations	Web-page calculations	Hand-calculations
5 [L/min]	0.12 [mbar]	0.084 [mbar]	0.03 [mbar]	0.017 [mbar]
11 [L/min]	0.45 [mbar]	0.36 [mbar]	0.13 [mbar]	0.072 [mbar]

Table 7 - Pressure drop due to bents in the ventricle chamber (A.O.P.)

Pressure loose due to bending has less relevant values compared to the change in cross section ones, but they are more relevant than the ones due to length in the aortic root.

4.4.2. Fluid passing through the entire model[57]

It has been calculated the amount of fluid passing thought the entire model each minute, achieving a less value in comparison with the previous model.[58] The old model has a value of $1.6[\frac{1}{min}]$ and the new one has a value of $0.95[\frac{1}{min}]$, which is almost half of the previous value meaning less amount of water is circulating each minute, i.e. the water is passing though the model more slowly, so can be inferred more laminar flow.

[57] Detailed calculations in appendix – section 14
[58] Based on the data provided by "The effect of sinus of Valsalva on TAVI valves" report

5- CONNECTIONS TESTS

[59] In this section problems in the connections that the current model has will be explained. Moreover, it will be explained some suggested solutions to solve them and the test done in order to prove if they are valid or not. It will also be explained the test procedure, the results and conclusions obtained in the experiments.

Some cracks are seen around the screw sections in the existing model. Hence, a torque analysis was thought so as to calculate the maximum torque the connection can support before breakage. Therefore, some torsion tests have been done not only in the old-connection but also in the different connections suggested, in order to discover which the best and toughest connection is.

The connection in the previous model was by the usage of nylon screws to connect the acrylic plates – 10 to 15 [mm] thick. Note that all the experiments have been done with metal screws instead, in order to be able to compare the different connections between the different tests.

5.1. Expected results – Theoretically

As it was seen in the previous model, the connections in the chambers were broken after running the model several times. Thus, there was an imminent necessity to settle this cracking problem, in order to improve the connection, increasing the life expectancy of the model and reducing leakage that may appear subsequently of an unsuitable connection.

After talking with suppliers, the suggested ideas were the usage of Helicoils® and QuickSerts®. Apparently the usage of QuickSerts® was a better option, up to the supplier and the information found in different sources. Both connections, and also de previous one, will be fully explained in each section.

[59] Note this section was done towards M7BACH14 group

5.2. Test procedure

In this section it is going to be explained not only the process to do the test, but also some items related, such as errors while proceeding.

The procedure should be the same with each connection, in order to achieve an accurate comparison of the results gained afterwards.

It is also important to take into account that the measurer should be the same in during the tests. Since, some problems can appear related with the measurements. Note that these tests were done towards the other group, so some inaccurate values may appear in the results. But it might be disregarded as the results are fairly truthful and reasonable, according to the expected results and the values obtained.

Note also that the test was done very quickly, instead of waiting some seconds after each torque application, which would have been the correct way to proceed. Therefore, some mistakes may appear in the results according to that.

First of all the specimens needed to start up with the analysis were designed by using SolidWorks program and manufactured in the workshop[60].

Once the specimens were made, the next step was to connect them in the diverse ways so as to start up with the analysis process. The different types of connections will be explained in each section, all of them connecting two acrylic specimens with a 90 degree angle.

Not all the specimens were built threaded. For those ones which were without a hole, was needed to make one. So, a milling machine was used to do it suitably. To do the threaded part, two machines were used. For the Helicoils® connection, was used a manual thread milling machine, however when making the QuickSerts® connection some cracks problems were appreciated in the upper part, hence the milling machine was needed in order to avoid them.

The procedure, for all of them, was to apply an initial torque of 2 [Nm] and increase gently the torque value until the first crack was seen in the material. Once it was achieved, the fact was to continue applying force until the whole connection breaks.

Three kinds of connections were evaluated and, for each connection, there were six specimens to analyse. It is attached a table with the results obtained, in which it is possible to read the torque values for the first breakage and the value when the connection definitely breaks. Note that the breakage starts when the first crack is seen and ends when the threat is completely broken. Before the first crack, was easy to appreciate the stress.

[60] Drawings can be found in M7BACH14 “Otimering af In Vitro model til fremtidige hjerteklap studier”, 2014.

5.3. Diverse connections – Results of the tests and explanation

5.3.1. Connection 1 - Test 1

The first connection tested consisted in the most common one, with a bolt and a washer. In the following paragraphs are going to be explained the characteristics, advantages and disadvantages of connection.

This is the type of connection that the current model has. It is not the most accurate one, since many cracks are been seen. The reason of testing this connection was to have a reference to be able to compare it with the new options. Thereby, it was expected to have better results with the new options than with this connection.

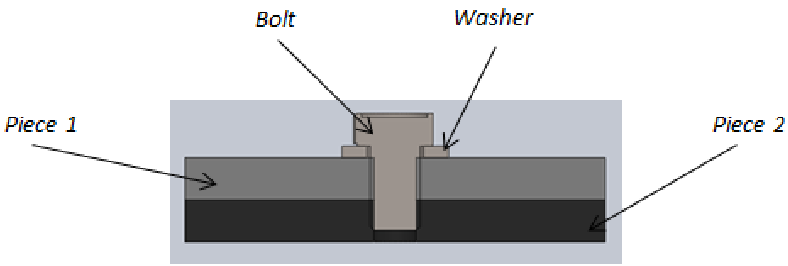

Figure 31 - Connection 1 – Bolt and washer (A.O.P.)

Characteristics

This kind of connection is the most typical one for machine design and construction. The connection consists in a bolt and a washer. Securing the connection by the use of threaded screws.

In the joint, the bolt and others clamped components, if there were, are designed to transfer the load through them. In the joint design it is important to be aware that the clamp load has a value below the external tension forces, which are forcing the joint to be separated.

The screws used in the test were made of steel in order to be possible the comparison with the other kind of joints; otherwise the ones in the model are in nylon. This nylon material is going to generate other problems, which will be explained in further sections.

Test notes

The specimens used to test this sort of connection were the ones done completely in the workshop, with the hole already done and threatened for M5.

The bolt dimensions used were: M5x25 – A washer was added in the bolt connection.

Note that during this test, the problems associated with the measurer weren't already been taking into account, so that, some mistakes can be appreciated in the results since the measurements were done by me and my other group partner.

Test results

	Specimen 1 [Nm]	*Specimen 2 [Nm]*	*Specimen 3 [Nm]*	*Specimen 4 [Nm]*	*Specimen 5 [Nm]*	*Specimen 6 [Nm]*
Breakage started	5-6	3.9	4.2	4.3	3.2	3.3
Breakage ended	8	8.4	7.4	7.1	7.5	8.4

Table 8 Test results for the 1st kind of connectionDiscussion of the results (A.O.P.)

The analysis of this connection had the aim to have some referent values. Results of the rest kind of connection can therefore be compared with these ones, in order to determine if the new connection improves or not the current one.

During the test, was noticed that once the piece flaws, with a small breakage, it grows alone and slowly, in the axis direction. It was possible to apply about 2 – 3 [Nm] more before the entire connection broke.

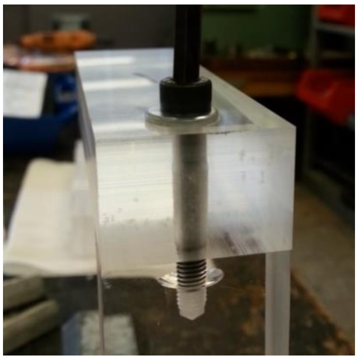

Figure 32 Connection 1 (bolt) (A.O.P.)

Figure 33 Bolt before and after the breakage (A.O.P.)

5.3.2. Connection 2 - Test 2[61]

The second connection tested was using Helicoils®, bolt and washer will be required as well. In the following paragraphs are going to be explained the characteristics, advantages and disadvantages. The way to install them and the typical applications of this sort of connection will be explained too.

The Helicoils® supplier is the company "Böllhoff" and the model used in this experiment are the M5 ones. To calculate the room needed to position the helicoils, proper tables were used to achieve the values.

Figure 34 - Helicoil plus [62]

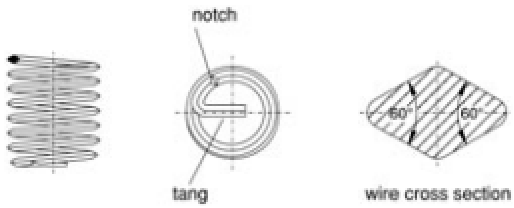

Figure 35 - Parts of the helicoil and its shape [63]

Characteristics

Helicoils are a kind of threat inserts which create high-strength fastenings in metal low-strength materials. They are made of stainless steel and they are formed into elastic spirals from wire with rhombic profile.

- *Heavy-duty connection*: thread inserts ensure heavy-duty connection capability in low-shearing strength metal materials. They ensure high-strength threads transferring forces from flank to flank into the holding thread.
- *Structural shape*: due to its ideal fitting structural shape, it is easy for them to be inserted and screwed up like if it was conventional screw.
- *Wear and tear resistance*: thread inserts have a high surface quality, which ensures the wear resistance and a heavily loaded threat with low and constant friction torque. The torsion stress is reduced.

[61] http://www.boellhoff.de/en/de/fasteners/special_fasteners/thread_technology/helicoil.php
[62] http://www.boellhoff.de/en/de/fasteners/special_fasteners/thread_technology/helicoil.php
[63] http://www.boellhoff.de/en/de/fasteners/special_fasteners/thread_technology/helicoil.php

- *Load carrying capacity:* the flexible characteristics of this connection provide a uniform load and tension distribution, and therefore optimum flank contact. Therefore an ideal force transfer is achieved between the bolt and the nut thread, improving the quality of the connection.
- *Corrosion resistance and atmospheric stability:* material properties of the Helicoils® protect screws from corrosion.

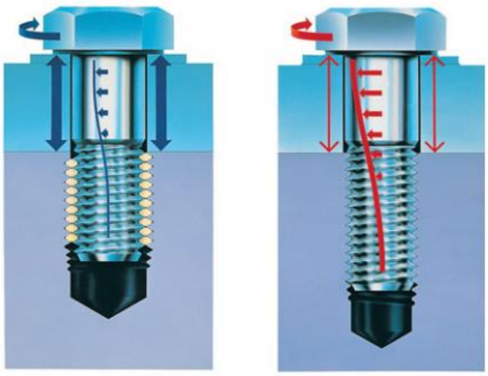

Figure 36 - Force distribution. Usage of Helicoils® and non-usage of Helicoils® [64]

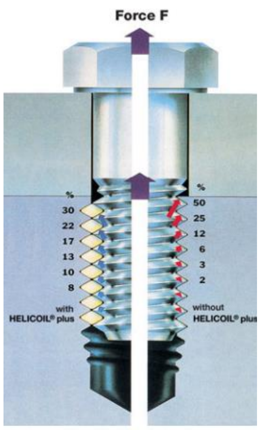

Figure 37 - % of Load and stress distribution [65]

Applications

There are some situations when it is well recommended the usage of Helicoils® in order to improve the connection. For instance, when low-strength materials are used, it is unavoidable to use them for thread reinforcement. Another situation might be for permanent and stable repair of damaged and worn out threads since the inserts have low price.

[64] http://www.boellhoff.de/en/de/fasteners/special_fasteners/thread_technology/helicoil.php
[65] http://www.boellhoff.de/en/de/fasteners/special_fasteners/thread_technology/helicoil.php

Installation

The installation of the Helicoils® is very simple, it is possible to position and screw them like a normal screw. Note that a threaded hole is needed before placing it. To install Helicoils®, there is only required to use an installation mandrel with similar dimensions to screw it. Once installed it is possible to break off the tang from the notch.

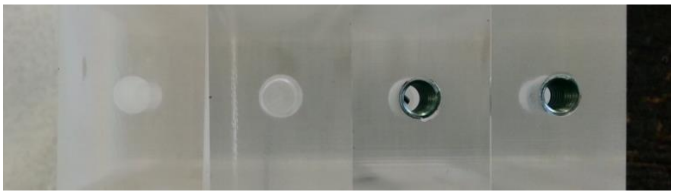

Figure 38 - Steps for mounting the Helicoils® (A.O.P.)

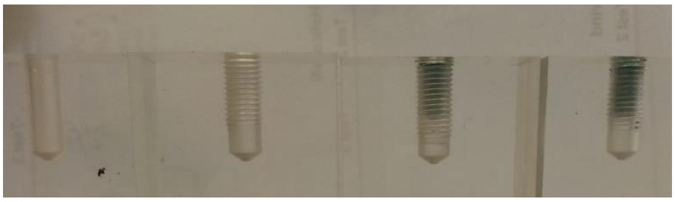

Figure 39 - Steps for mounting the Helicoils® (A.O.P.)

Test notes

The hole dimensions done in the specimen were: ϕ = 5.2 [mm] and 15 [mm] long – The clearance hole was done with the milling machine – and the threaded hole with a manual thread milling machine. The length of 15 [mm] is too much compared to the data provided by the supplier, but it was to ensure the dimensions.

The bolt dimensions used were: M5x25. Note that a washer was also added in the bolt connection.

Test results

The following table shows the values obtained in the experiment.

	Specimen 1 [Nm]	*Specimen 2 [Nm]*	*Specimen 3 [Nm]*	*Specimen 4 [Nm]*	*Specimen 5 [Nm]*	*Specimen 6 [Nm]*
Breakage started	2.3	4.1	2	2.5	2	3
Breakage ended	8.4	9.6	9.6	9.8	4	10.9

Table 9 - Test results for the 2nd kind of connection (A.O.P.)

Discussion of the results

The values compared to the first sort of connection, with only the bolt and without Helicoils®, are rather similar. Hence, there is not a significant improvement in this connection. What is more, it is likely to see cracks even before than the ones in first test, when applying a torque around 2-3 [Nm]. However, the life expectancy of this sort of connection is slightly bigger compared to the bolt connection, it is possible to apply around 1-2 [Nm] more torque before the connection is completely destroyed.

During the test, was easy to notice that once the piece cracks, with a small breakage, it grows alone and slowly, in the axis direction.

Once the torque application was stopped and the connection was dismounted, it was seen that the Helicoils® were gently above the normal position. This phenomenon was because of the torque applied, which is forcing the connection to get opened.

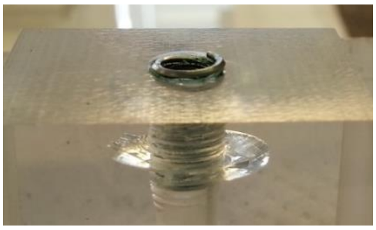

Figure 40 - Final position for the Helicoils® (A.O.P.)

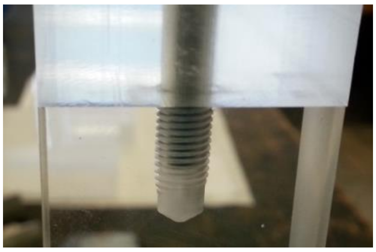

Figure 41 - Assembly for the 2nd connection (A.O.P.)

5.3.3. Connection 3 - Test 3

The third connection tested consisted in a bolt with a QuickSerts® and a washer. In the following paragraphs are going to be explained the characteristics, advantages and disadvantages, and also de way to install them, for this sort of connection.

[66] QuickSerts® supplier is the company "Böllhoff" as well, and the inserts used in these experiments are M5. To calculate the room needed to position the QuickSerts®, proper tables were used to achieve the values.

Figure 42 - QuickSerts® [67]

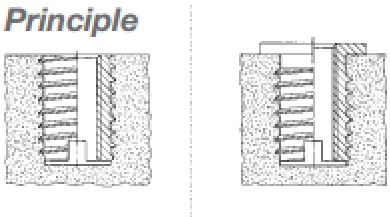

Figure 43 - Principle for the QuickSerts® [68]

Characteristics

QuickSerts® are a kind of thread inserts in the group called AMTEC, from the company Böllhoff. They are suitable for installation in plastics, so they are a good option for the in-vitro model new design. In this group, there are many kinds of inserts like: QuickSerts®, HitSerts®, ExpansioSert® or SpredSert®, among others. They all have some advantages to be used in plastics; however, according to the supplier, QuickSerts® were selected because of its properties.

The QuickSerts® consist of a cylindrical basic body with internal and external thread. The external thread is special, which means that it has a small flank angle and expands asymmetrically towards the thread root. Additionally, the bottom part of the insert is with a cutting slot.

- *Injection*: the injection cycles are reduced, therefore lower manufacturing costs. There is no risk of damage to the injection mould from falling out metal parts.
- *Insertion*: it is accomplished a very good tight-fit.
- *Breakage*: the shrinkage control around the metal part is easier, hence it is possible to reduce the stress cracks or, at least, they are more difficult to be achieved.

[66] http://www.boellhoff.de/en/de/fasteners/special_fasteners/thread_technology/amtec.php
[67] http://www.boellhoff.de/en/de/fasteners/special_fasteners/thread_technology/amtec.php
[68] http://www.boellhoff.de/en/de/fasteners/special_fasteners/thread_technology/amtec.php

- *Load distribution*: it has an ideal distribution of the load.
- *Stress*: it has a stress-free anchorage with high pull-out and torque values.
- *Self-tapping screws*: there is an advantage associate with the property of being a self-tapping screw, it is that the joint can be detached as often as required, without damaging the thread.

Installation

There are many methods to install the AMTEC inserts like: thermal installation, ultrasonic welding, expansion anchoring, self-tapping insertion or pressing-in. In this case, the way to insert the QuickSerts® is the self-tapping insertion.

To be able to install the QuickSerts® was before needed to do a hole. According to the supplier, the recommended dimension for it was 7.2 [mm]. However due to some problems while mounting them a bigger size, 7.4 [mm] diameter, was therefore needed. Subsequently, a thread was desirable. After that, it was just a matter of screwing manually the inserts.

Test notes

The hole's dimensions done in the specimen were: ϕ = 7.4 [mm] and 15 [mm] long – Some troubles happened during the installation of the QuickSerts®. The length of 15 [mm] is too much compared to the data provided by the supplier, but it was done to ensure the dimensions.

The bolt dimensions used were: M5x25 – A washer was added in the bolt connection.

Test results

The following table shows the values obtained in the experiment.

	Specimen 1 [Nm]	*Specimen 2 [Nm]*	*Specimen 3 [Nm]*	*Specimen 4 [Nm]*	*Specimen 5 [Nm]*	*Specimen 6 [Nm]*
Breakage started	10	11.2	17.5	>16	>19.5	>17.5
Breakage ended	14.7	-	-	-	-	-

Table 10 - Test results for the 3rd kind of connection (A.O.P.)

Discussion of the results

In the first specimen, when the torque value is 14 [Nm] it is seen that the friction in the part above is bigger than the below one, so it was appreciated movement between both parts. Finally with a torque of 14.7 [Nm] the tool was broken, that's why in the following test after the first crack the torque application was stopped in order not to break it.

The obtained values compared to the first and second kind of connection, are fairly distant. The breakage value for the connection with QuickSerts® is bigger and, what is more, for some specimens was impossible to break them, before the tool did. That was the case for specimens 4, 5 and 6; in which was impossible to obtain the value of the breakage due to friction problems that were seen before it.

In addition, the breakage shape is bigger than the previous tests and its expansion is faster as well. In these tests, it is not seen a small crack and then its slow expansion, it is a fast and big one.

Finally, note that when the connection was dismounted was possible to see three different and curious phenomena. Once the torque application was stopped, the QuickSerts® was gently above the normal position. This was because the torque applied was forcing the connection to open, the same idea as was seen in the second sort of connection, with the Helicoils®. It was also appreciated that the washer and the bolt, once the connection was disassembled, were together stuck, being impossible to separate them. There reason for this phenomenon is the high force applied. Finally it was seen a small recess in the washer area due to the high torque applied.

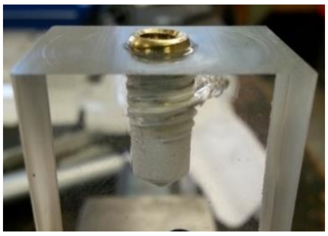

Figure 44 - Final position for the QuickSerts® (A.O.P.)

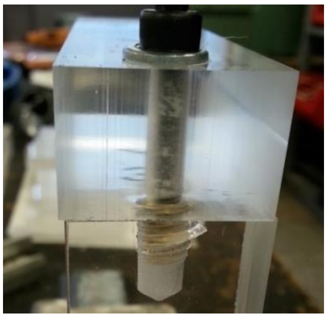

Figure 45 - Crack and friction problems (A.O.P.)

5.4. Other relevant tests

According to the results different tests were required. The expected breakage was a vertical fracture, as it was seen in the previous model. However during the connection tests the breakage seen was horizontal.

Figure 46 - Horizontal breakage, top view and lateral view (A.O.P.)

Figure 47 - Vertical breakage, top view and lateral view (A.O.P.)

After getting informed[69], the conclusion was that the problem according to that vertical breakage was related with the nylon screws used in the model. Theoretically, these nylon screws expand when they are in contact with water, since they absorb the water due to its high dilation coefficient (around 9%). Furthermore, pressure conditions that surrounded the connection while the model is running would intensify this growing property (dilation).

For that reason, some tests were required so as to be able to represent this phenomenon. Nylon screws were inserted in the acrylic specimens (the same as used in the model) and they were placed into water in order to see if they dilate enough to break the sample. These tests did not produce any significant conclusion, since no results were seen on them.

With the idea of represent the same situation as happened in the in vitro model, was decided to have some days the specimens with the nylon screws inside the water and some others outside. In the in vitro model, there is a recurring situation of contact and non-contact with water. During the days the nylon screws were inside the water, they would absorb water and get expanded. After that, they would be outside the water, to dry and hence, shrink. These tests did not produce any significant results.

[69] Lars Erik Bräuner (Associate professor – Department of Engineering – Materials Engineering)

[70] Finally, as the material was changed into polycarbonate instead of acrylic, check-up tests were done in order to verify the conclusions found with the acrylic. The results were expected better due to better properties that the polycarbonate has[71]. Those tests proved better behaviour in the new material, even though inserts have been used in the model to improve the connection and avoid undesirable cracks.

5.5. Discussion of the results

By comparing the results, the optimal solution for a screw connection is the usage of QuickSerts®. Although one of the requirements is to avoid the screw connection as much as possible, they will be used in some specific cases if required.

An alternative to avoid the failure in the connections is changing the material, for instance it can be used POM instead of acrylic, due to better properties.

On the other hand, neither the torque application tests nor the water tests did provide the information desirable to explain what was happening in the model according to the flaws seen around the screws. So more information was required to explain that problem, but no more tests were done. Therefore, the solution provided will be a theoretical one.

The solution for the breaking problem in the previous model (15 mm acrylic plates with nylon screws) will be the usage of nylon screws but with some millimetre of thread removed from the upper part of the bolt. Briefly, it can be said that this breaking problem would be owing to stress characteristic in a bolt connection, adding the influence of having pressure inside the chamber. Dilatation properties in nylon screws may also have an impact.

[70] More details about the results can be found in M7BACH14 "Otimering af In Vitro model til fremtidige hjerteklap studier", 2014.
[71] More information about material properties in section 7

6- MOULD FOR THE SILICONE RING

[72] To connect the different chambers minimizing the leakage, it has been decided to do connect them with silicone rings. For the ring design a mould was built in aluminium.

In this section is going to be explained the silicone used, the mould design and the results seen once tested in the model.

6.1. Theoretical part

[73] [74] [75] Some chemical reactions happened between the mould and the silicone, and that is why some troubles were seen along the design mould period. The silicones provided by the supplier are RTV-ZA12 A+B mixed half –half in weight proportion so as to improve its properties, such as hardness. Furthermore it was also provided another kind of silicone required for the bag design of the mould due to problems such as bubbles or sticky and soft final material. However, these sticky properties are positive for the connection between the aortic root and the chambers since it improves the fitting helping to avoid leakage.

As the silicone reacts with the mould due to the OH groups, the mould was tried in several materials, in order to try which one was the better option. Finally the mould was decided to be made in aluminium, and covered it with some solutions in order to avoid the chemical reaction. These coating are a mixture of Styrofoam and Acetone and a mixture made of Styrofoam and Toluene. The Styrene has no OH groups; hence it won't react with the silicone so it does create a coat between the materials.

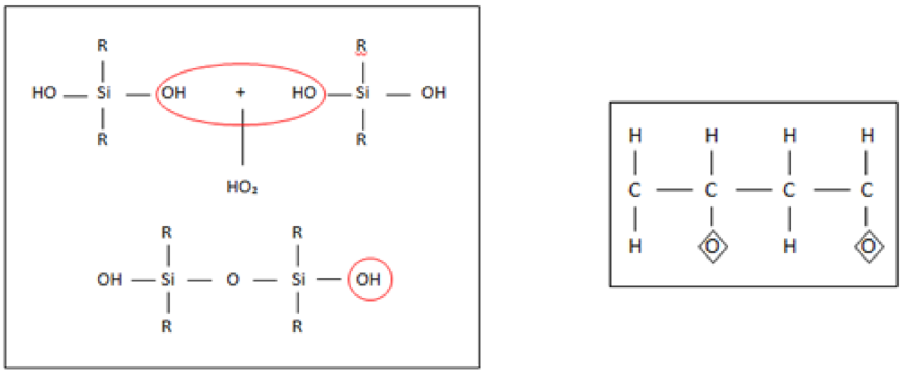

Figure 48 - Chemical reaction of the Silicone (left) and Styrene (right) (A.O.P.)

[72] The experience to do it was based in M7BACH14, since there were some occasions working together in order to achieve the silicone bag mould
[73] The theoretical knowledge gained about this material is explained in the appendix section 15
[74] Finn Monrad Rasmussen (Associate professor – Engineering College of Aarhus – Materials)
[75] Stevens, Malcolm P. Polymer chemistry: an introduction. 3rd ed. New York: Oxford University Press, 1999. Print.

6.2. Mould design – SolidWorks

The mould has been done in aluminium, as it was the material easy to be provided at the workshop. This material allows the weight to be minimized, compared with other materials, which means a significant advantage. However some disadvantages according to chemical reactions have seen between the silicone and the aluminium.

The mould has two parts, the female and the male part. To connect both parts two screws were used so as to ensure an accurate closing; hence it is possible ensure the hole in the correct position. The female part has the shape of the final desired ring, with some grooves at its top surface in order to let the silicone go out of the mould when the mould is being refilled. The male part is used to close the mould and has a cylinder in the middle which size is the internal diameter needed for the ring[76].

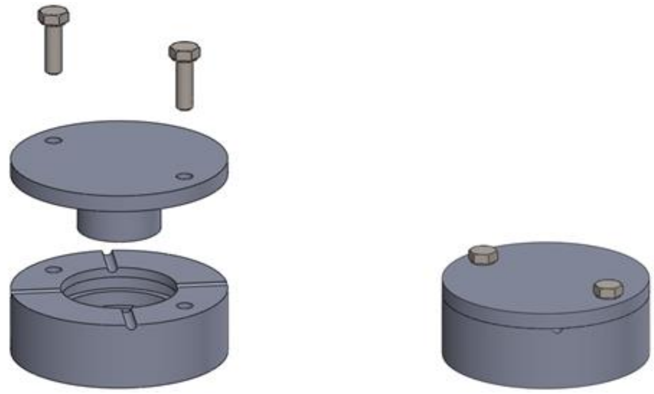

Figure 49 - Silicone Ring mould – SolidWorks (A.O.P.)

Figure 50 - Silicone Ring mould (A.O.P.)

Figure 51 - Silicone ring (A.O.P.)

[76] Drawings attached in appendix section 6

6.3. Silicone ring obtained

Once the silicone ring was tested in the model, its contribution to avoid the water leakage was positive. The ring eliminates completely the leakage between the chambers. To position it there is need to screw the fittings to the chambers with the ring between them, note it is no required to tighten them excessively.

In order to improve the connection one of the flanges of the ring was removed by cutting it, since the ring is too thick and once was in between the chambers it closes reducing the inner diameter, which it is not desirable.

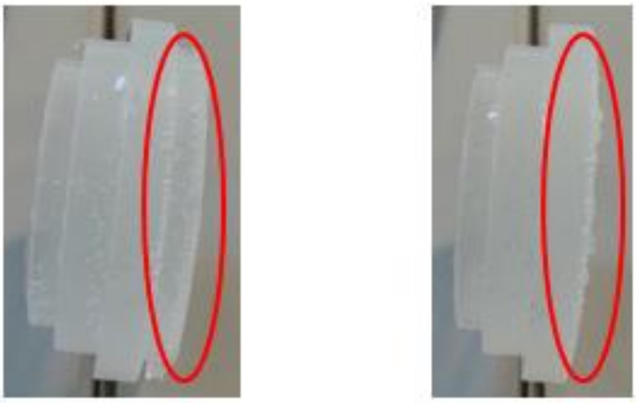

Figure 52 - Silicone ring change (A.O.P.)

7- Materials

In this section is going to be explained the different kind of materials used to do the model. In the previous model, acrylic was the material for its construction. However, it has been changed into polycarbonate for almost all the parts and POM for some of them.

7.1. General description

PMMA (previous material)

[77] [78] Polymethyl methacrylate, PMMA, also known as acrylic is a transparent thermoplastic. It is often used as glass alternative due to its remarkable properties of transparency, aesthetic and scratch resistance. Furthermore, it has reasonable properties such as good behaviour with the weather, optical good-looking, easy processing, relatively high stiffness and dimensional stability and low cost. However, it is not recommended for some applications due to its brittle behaviour under impact forces since it has poor impact resistance. It also recommended avoiding situations with high stress concentrations or when alcohol or petrol contact is required. Some situations when PMMA is used are: glass substitute for windows, glazing in aircrafts or showcases for exhibitions in museums. Sometimes this material is reinforced with other materials to improve its properties.

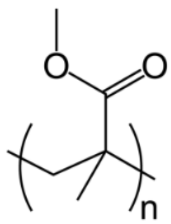

Figure 53 - Chemical equation for the PMMA [79]

[77] http://plastics.ides.com/generics/3/acrylic
[78] http://vink.dk/
[79] http://en.wikipedia.org/wiki/Poly(methyl_methacrylate)

PC (current material)

[80] Polycarbonate is a transparent thermoplastic polymer. It is often used owing to they are easy to work with and its attractive properties like high impact strength, high hardness, good stiffness, great heat resistant or high electrical insulation. Although PC is a durable material, it has other disadvantages such as low scratch resistance. It is also recommended to avoid its procedure in an oxidizing area or with water above 60º continuously. Some states when PC is used are: displays when high impact resistance is essential or when high pressure is present. Polycarbonate is produced by injection, moulding or extrusion. In addition, sometimes it is also reinforced with other materials, normally with glass.

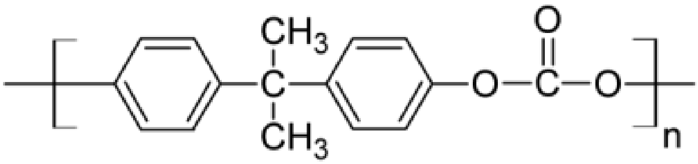

Figure 54 - Chemical equation for the PC [81]

POM (current material)

[82] Polyoxymethylene, also known as acetal, polyacetal and polyformaldehyde is a thermoplastic used due to its good mechanical properties , normally is used in good-looking precision parts which require high stiffness, hardness or toughness, low friction and fine wear characteristics, high dimensional stability and high resistance to many chemicals. However, it is recommended to avoid hot water contact and acids and oxidizing chemicals contact. Some applications when POM is used are, for instance: gears, plain bearings, guide rails or wheels.

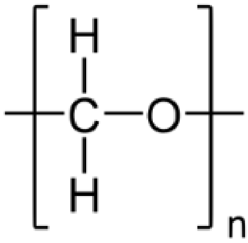

Figure 55 - Chemical equation for the POM [83]

[80] http://deigaard-plastic.dk/
[81] http://en.wikipedia.org/wiki/Polycarbonate
[82] http://vink.dk/
[83] http://en.wikipedia.org/wiki/Polyoxymethylene

7.2. Analysis of characteristics[84] [85]

In this section are going to be analysed the properties relevant for plastics used in this model, in order to be able to compare them and explain the reason of the change. Principally is going to be compared PMMA and PC, although some properties for the POM are going to be explained as well.

Starting with this analysis is firstly important to remark the properties that the in-vitro model has to fulfil. The material of the model must be transparent since one of the principal uses of the model is to analyse aortic valve's behaviour. It is needed therefore to see it through the model. In addition, one of the aims of the project is to achieve a more durable model, avoiding the cracks seen before. In addition the material cannot react with salty water in standard conditions.

The properties which are going to be analysed are: mechanical properties, optical properties, chemical properties, physical properties and price.

Mechanical properties

[86]The mechanical properties relevant for this section are tensile strength, ductility, Young modulus, fatigue limit, hardness and compressive strength. Finally it will be shown the strain-stress diagram for both materials.

[87]An important curve for materials comparison is the stress-strain curve. Below it is shown a general stress – strain curve with all the important points. Figure 57 shows the specific strain – stress curves for the PMMA and PC.

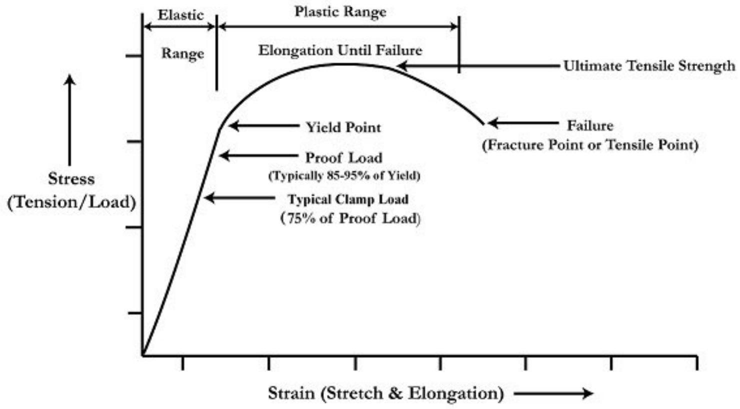

Figure 56 - Stress – strain diagram [88]

[84] http://ocw.usal.es/eduCommons/ensenanzas-tecnicas/materiales-ii/contenidos/PLASTICOS.pdf
[85] "El ABC de los plásticos" – María Laura Cornish Alvarez
[86] http://tecnologiadelosplasticos.blogspot.dk/2011/06/propiedades-mecanicas.html
[87] http://ocw.mit.edu/courses/materials-science-and-engineering/3-11-mechanics-of-materials-fall-1999/modules/ss.pdf
[88] http://www.smartbolts.com/wp-content/uploads/2012/10/fastenal.tensile_stress-strain.jpg

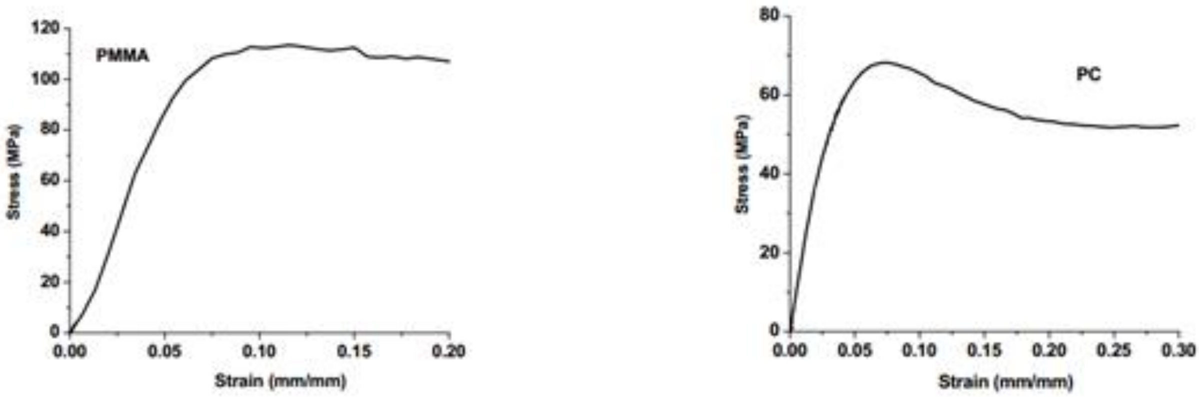

Figure 57 - PMMA (left) and PC (right) Tensile stress-strain diagram [89]

Young modulus or tensile modulus measures the stiffness of an elastic isotropic material. It is the slope of the linear portion of the stress-strain graph, the more slope it has the more Young modulus value is. Young modulus is the ratio of linear stress and linear strain and its units are [MPa], its calculation can be achieved by tensile tests. The higher the modulus is, the more rigid the material is, which means it can deform less elastically.

At the early low strain portion of the curve, the materials obey Hooke's law, which expresses that the stress is proportional to the deformation; it is only adequate until the yield point. It is therefore achieved the Young Modulus definition.

$$E = \frac{\sigma}{\varepsilon} = \frac{F/S}{\Delta L/L}$$

Equation 7 - Definition of Young Modulus, Hooke law

The Young modulus for the PMMA is 3.3 [GPa] and for the PC is 2.3 [GPa]. Therefore, PMMA is more rigid than PC i.e. for the same stress applied the PC can deform more elastically before starting plastic behaviour which is not desired. So this property drives PC as a better option than the PMMA.

Another important property for this analysis is the resilience and the toughness, which can be also appreciated by the stress – strain curve. Resilience is the capacity of the material to absorb energy when it is being deformed elastically and toughness is the capacity of the material to absorb energy when it is being deformed plastically without breaking. Looking at the curves in figure 58 is seen that the PC has less toughness value than the PMMA.

[89] Army Research Laboratory (Extracting Stress-Strain and Compressive Yield Stress Information From Spherical Indentation

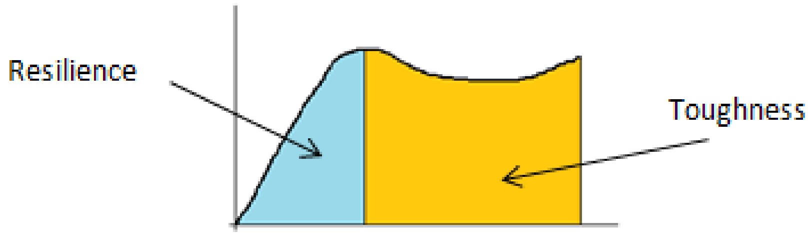

Figure 58 - Resilience and toughness seen in the stress-strain curve (A.O.P.)

Depend on the shape of the curve the material is brittle or ductile. Ductility is the ability to deform plastically under a tensile load and its units are [%]. This value is desired to be a high value, in order to let the material deform as much as possible without cracking. The PMMA has a value of 6 [%] and the PC value is 120 [%]. Even though the PMMA is not a brittle material, this difference is greatly bigger compared with PC. This property was relevant for the material to be changed. The dissimilarity between a brittle and ductile material can be easily seen in the graph below.

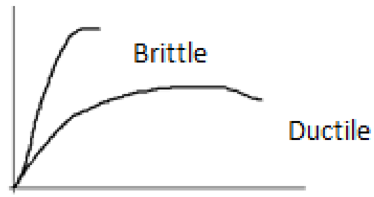

Figure 59 - Brittle V.S. ductile material (A.O.P.)

Tensile strength or ultimate strength is the maximum tensile stress a material can tolerate before cracking, its units are [MPa = N/mm²]. This value is needed to be the highest possible in order to allow the material withstand the maximum possible before failure. For the PMMA, tensile strength value is 76 [MPa] and for the PC is 70 [MPa]. Although for the PMMA this value is slightly higher, the PC was chosen due to other properties.

Compressive strength is the maximum stress a material can tolerate before compressive failure; its units are [MPa]. As the walls in the model were slightly compressed due to the nylon screw connections, it might be a property to be checked. However, as the new model has been designed with different way to close the chambers avoiding the bolts inside the plastic walls, it is not a decisive property in the material choice.

Optical properties

The only optical property which is relevant for the in-vitro model is the luminosity since ARAMIS calculations will be performed with the model. There is a great importance of having a good lighting environment for those analyses. Hence, the comparison of luminosity values is required. For the PMMA this value reaches 92% and for the PC is 89%; the difference is not too big and it may not affect, both materials are transparent. POM is a translucent material; it only allows a small amount of light, therefore is only possible to see shadows through it. This is the main reason to reject this material for the construction of the walls.

Chemical properties

Chemical resistance is the ability to resist damage caused by solvent actions. They may cause changes in the material like: discoloration, alteration of shininess, softening, swelling or detachment of coatings. The in-vitro model is run with salty water and both materials, PMMA and PC, are not affected by water. It is important to notice that the water only possible to be used under 60º, however the model works with fluid at around the standard state (20º and 1 bar).

Since water does not affect the studied materials, corrosion will not be therefore a problem in them. Corrosion for plastics is completely different as is in metals, which creates a loss of material. Corrosion for plastics may cause partial dissolution, deformations, some change in colours, scratch origination and whitening.

Moisture absorption is also a concern since leakage exits in the model, driving the water to get inside the connections, so that the material absorbs moisture. If the value of absorption increases, the traction resistance decreases, which means that the material will experience an earlier breakage. This value for the PMMA is 1.75 [%] and for the PC is 0.35 [%]. This property infers PC as a better option to be chosen.

Physical properties

The main significant physical property for this analysis is the density, ρ. Density is defined as mass per unit volume, and its formula is shown following.

$$\rho = \frac{m}{V} \; [\frac{kg}{m^3}]$$

Equation 8 - Density equation

For the model it is not a requirement but it is desired to have considerably low weight. The density for the PMMA is 1.19 [g/cm³] and for the PC is 1.2 [g/cm³]. Therefore, this property is not decisive, due to they are pretty close values. On the other hand, the density for POM is 1.41 [g/cm³].

As the wall's thickness was desired to be increased, it was also needed to take into account the maximum available material thickness by the suppliers.

Thermal properties

The temperature while working is in the range of standard stages (20º and 1 bar) there is no need to calculate any thermal property. No problems according to them are expected.

Price[90] [91]

There is a significant difference of price for the PC and PMMA materials, being 1696 [dkk/m²] for the PMMA and 2277 [dkk/m²] for the PC. The price for the POM is 98 [dkk/kg].

Conclusion

To sum up, polycarbonate is more ductile and less rigid than acrylic with quite distant values far from it, furthermore PC absorbs less percentage of moisture. Those properties led to the decision of changing the PMMA into PC. Basically the PC may be a better option for the walls in order to delay or definitely avoid the breakage in the screws due to the stress caused by the bolt connections.

As the PC is transparent enough was possible to be used in the model. However POM, even though some of the properties might are better than the PMMA ones, was rejected since the beginning due to its lack of luminosity which is one of the requirements that the material must fulfil.

Notice that also the material choice is conditioned by the supplier. Some parts, such us the fittings, were impossible to be made in the desired material due to infeasibility in finding the material in large thicknesses. Therefore, all the parts in which no transparency was needed (and because of its dimensions could not be done in PC) have been done in POM, which is a worse option compared to PC but better compared to PMMA.

Below is a summary of the properties that have been analysed. More detailed properties' list is attached in the appendix section number 16.

Properties	*Units*	*Material*		
		PMMA	PC	POM
Young modulus	[GPa]	3.3	2.3	2.8
Ductility	[%]	6	120	50
Tensile Strength	[MPa]	76	60-70	66
Luminosity	[%]	92	89	"Shadow"
Moisture absorption	[%]	1.75	0.35	0.8
Density	[g/cm³]	1.19	1.2	1.41
Price	[dkk/m²] PMMA & PC; [dkk/kg] POM	1696	2277	98
Maximum thickness	[mm]	30	15	-

Table 11 - Summary of the properties for the three materials studied (A.O.P.)

[90] http://vink.dk/
[91] http://deigaard-plastic.dk/

7.3. Glue

[92] Apart from the screws used to connect the top and bottom walls, and the recess made on them, there was desired to attach the different walls each other in the whole model by using a glue connection in order to do the union more stable and reliable. The material used is epoxy for all the chambers but the compliance chamber which is glued with Ruderer 108[93] due to better properties required since it is supporting higher pressure and the direct force from the pump. The glue was chosen by looking along the list of materials with can be briefly seen below[94].

Materialer	ABS	CA + CAB	PA	PC	PMMA
ABS	O 8, 9, 13 / K 7, 11, 18	K 7, 4, 18	K 7, 18	K 7, 18, 4	K 4, 7
CA + CAB		O 1, 5, 6 / K 6, 1, 7	K 16, 7	K 7	K 1, 4, 7, 10
PA			O 10, 11, 12 / K 8, 7, 16, 18, 11-13, 8-13, 8-18	K 18, 8-18	K 16, 7, 10, 18
PC				O 5, 7 / K 4, 7, 18, 17	K 4, 18
PMMA					O 5, 7, 8, 14, 15 / K 4, 1, 6, 7, 16, 17, 1-2

Figure 60 - Different possibilities of gluing [95]

4. Acrylat
5. Polystyren
6. Cellulosenitrat
7. Polyurethan
15. Carbamid
16. Resorcin
17. Umættet polyester
18. Epoxy

Figure 61 - Explanation of the numbers of gluing possibilities [96]

[92] Hansen, Steen. Klæbning af plast. [Nyt oplag] ed. Taastrup: Dansk Teknologisk Institut, Plastteknologi, 1993. Print.
[93] Recommended by Nordisk Plast, http://www.nordiskplast.dk/
[94] More detailed glue list is attached in the appendix – section 18.
[95] MTKMA1 Slides – Finn Monrad Rasmussen (Associate professor – Engineering College of Aarhus – Materials)
[96] MTKMA1 Slides – Finn Monrad Rasmussen (Associate professor – Engineering College of Aarhus – Materials)

8- Evaluation of the new model

8.1. Test procedure

The in-vitro model has been redesigned in order to improve the previous one and avoid the problems seen before. These changes have been done by taking the advantage from previous experiences. To verify if the changes in the model, tests were required to be performed to demonstrate if the changes made in the model provide better and more lifelike results than the previous model. As the number of changes is high enough, the evaluation of each one should be separately. Furthermore, the results are going to be compared with the previous results, done with the old model. By using that way also is possible to know which of them is more significant.

Steps to be followed

[97] To test accurately the following steps must be followed.

1- Calibration of the Millar catheters
2- Check the level of water in the atrium chamber (It must be 15 [mmHg] to be able to compare them with the previous model's results)
3- Starting the waveform generator (Waveform D must be used in order to compare the results with the previous model's ones)
4- Ensure the frequency in the generator is the closer possible to 70 [BTM] as it is recommended by the U.S. Food and Drug Administration draft guidance for testing valves. (In the pump available in the laboratory the closest value is 72 [BTM]).
5- Turn on the piston movement
6- Adjust the stroke volume. It can either be regulated up by turning the rotary knob to the right, or down by turning the knob to the left. When turning the stroke volume up, the pressure and flow increases and by turning the stroke volume down the pressure and flow decreases.
7- Adjust the peripheral resistance. It will either be increased by closing the clamp or decreased by opening it. When closing the clamp and increasing the resistance, the flow will decrease and the pressure increase, by opening the clamp and decreasing the resistance, the flow will increase and the pressure decrease.
8- Add compressed air into the compliance chamber
9- Adjust 6, 7 and 8 steps to ensure a physiological pressure curves
10- Push the trigger (Recording for 21 [s])

[97] The results are compared with the results achieved on the "The effect of Sinus of Valsalva on TAVI valves" report

TAVI valve no. 3, five cardiac outputs and one aortic root with intact sinus of Valsalva were used for testing the model. The cardiac outputs that have been analysed are:

- CO = 1-2 [L/min]
- CO = 2-3 [L/min]
- CO = 3-4 [L/min]
- CO = 4-5 [L/min]
- CO > 8 [L/min]

8.2. Signal processing

[98] In order to capture and analyse the cardiac output curves Labview program has been used. They must be investigated carefully and taking into account some aspects.

The aim of the project is to reduce the amount of recorded noise. Start systole and start diastole are the areas of interest.

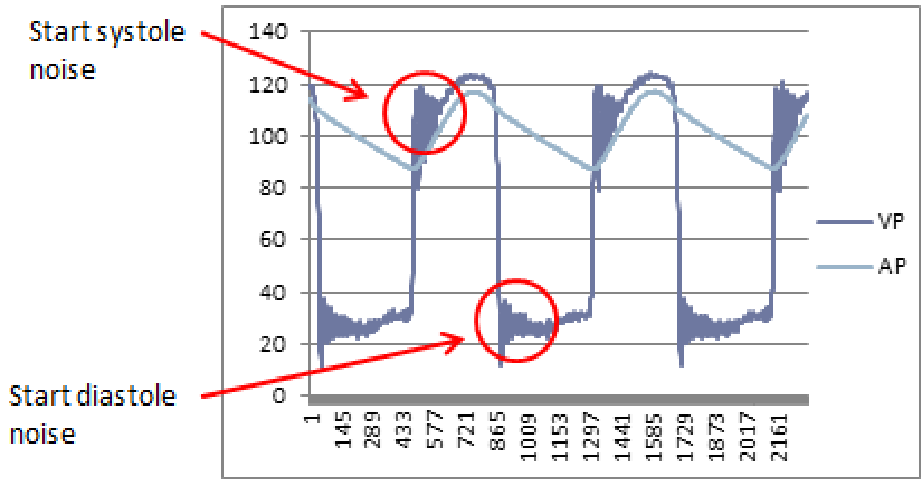

Figure 62 - Noise in the cardiac output that should be reduced (A.O.P.)

During the recording of the model, there are two kind of noise: the one due to environmental conditions, external to the model and the noise due to constant systematic variables in the model which is the one to be improved. Therefore, to be able to analyse the noise due to design, the curve has to be treated to eliminate the random noise due to environmental circumstances. This can be achieved by taking advantage of the fact that a cardiac cycle is periodic and each measured data can be compared and therefore set a mean cardiac cycle that will contain only the constant systemic noise. To ensure validity of the mean curve, 15 cardiac cycles are compared. The calculation of the mean cycle will be performed in the signal processing program Labview.

[98] More information about signal processing and methods carried out in appendix – section 20

8.3. Comparison of results - Analysis methods

[99] Once the curve has been treated, two methods are carried out in Labview to achieve the area and the frequency of the appropriate cardiac cycle. Labview can be programmed to detect peaks and valleys, trend lines are created to evaluate the amplitude.

In order to measure area, the solution is to isolate the fluctuations and calculate the area bounded by peaks and valleys that define the noise by integration. When deciding the number of peaks to be included it should be as many peaks, as possible as long as the period remains constant, the rest of the curve can be considered to be random and should not be included. The number of peaks included has to be evaluated manually for each curve, to make sure the calculations are comparable.

On the other hand, the frequency is calculated by measuring the distance between the peaks and valleys. In order to calculate an accurate frequency, since the program does not discriminate between peaks in the constant systemic noise and random noise, not marking the distance between the points that can be considered to be a period, this therefore also needs to be evaluated manually.

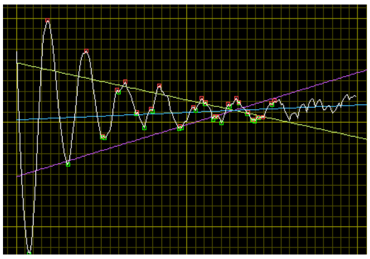

Figure 63 - Labview image of the noise in start diastole

As the cardiac cycle is a time domain signal, by Fourier transform can be transformed into spectral domain. The spectral analysis of the cardiac cycle will also be compared with the old model. The cardiac cycle consists of every single frequency of sinus from 0-500 [Hz], with various amplitudes, however many of the frequencies are due to noise, so this graph can be clarified by checking the mean cardiac cycle curve. In the old model some peaks were seen around determined frequencies suggesting that there is something in the system vibrating. The new model therefore will be analysed to find out if they have been eliminated or not.

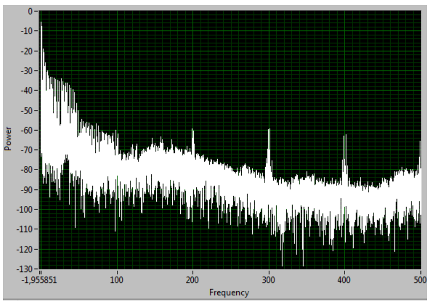

Figure 64 - Spectral analysis of the cardiac cycle without the noise being reduced

[99] More information about signal processing and methods carried out in appendix – section 20

8.4. Different tests done in the new model[100]

8.4.1. Square compliance chamber and ventricle chamber without the bag

This test will show what improvements the change of the position of the chambers have done to the pressure curves and psychological conditions in the model. It was found that lifelike pressure readings were obtained for this initial test. The graph shows that there is a presence of noise in the ventricular chamber in systole and diastole. No noise was detected in the compliance chamber where the aortic pressure is recorded. The low aortic pressure can be due to faulty calibration.

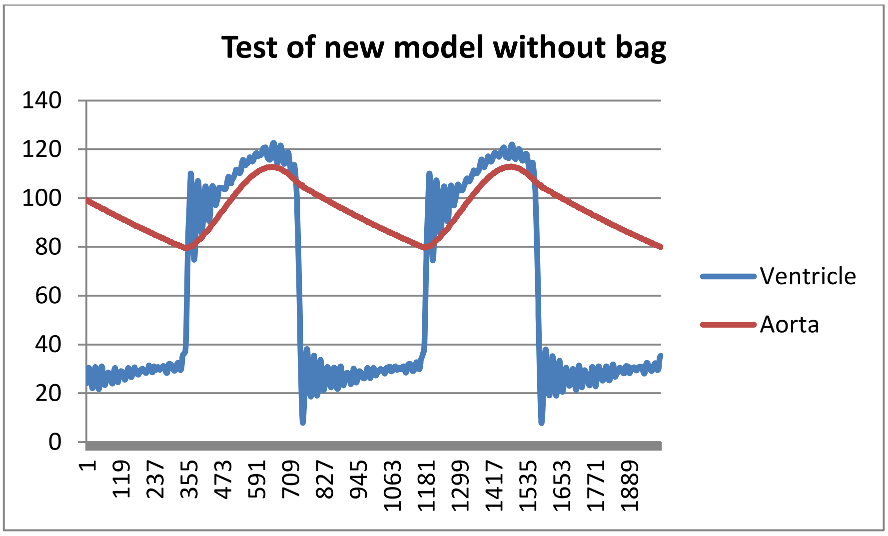

Figure 65 - New model without bag, CO 4-5 [L/min], waveform D

8.4.2. Square compliance chamber and ventricle chamber with the bag

With the silicone bag it is possible to add even more compliance to the model. For this test it is expected to see a reduction of noise in the ventricular chamber, because the presence of the elastic silicone bag should add some extra compliance.

From the graph it is seen that lifelike pressure curves was obtained, but systole and diastole noise was not eliminated for this test see figure 65. In fact the pressure during diastole seems to fall below zero. This might be due to faulty calibration of the pressure sensors. In order to determine the effect of the bag, data will have to be investigated further.

The graph also shows that the aortic pressure is higher than the desired 120 [mmHg] in systole, the reason for this is that sensor was not aligned with the ventricle pressure sensor, but was positioned a few centimeters below. In order to eliminate this problem, the sensors should be calibrated for their respective positions or the aortic pressure sensor should be moved to same position as ventricular sensor.

[100] Detailed data set are attached in the appendix section 19

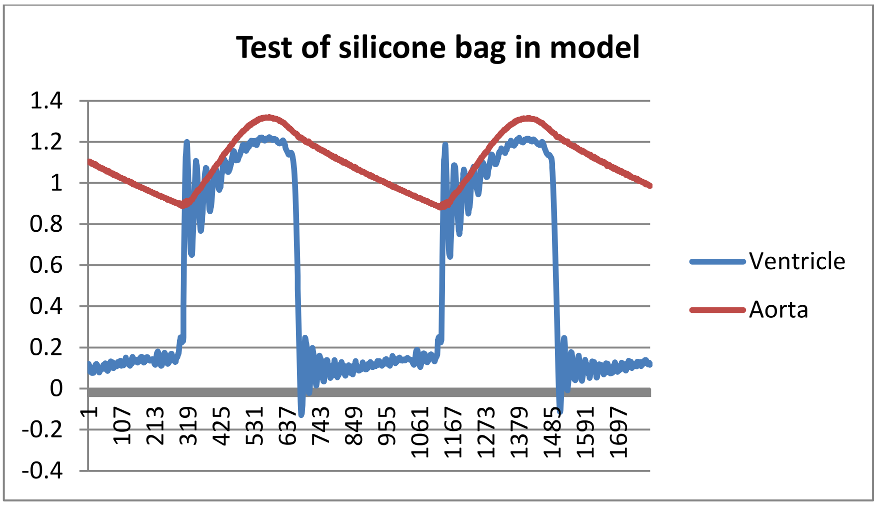

Figure 66 - New model with silicone bag, CO 4-5, waveform D

8.4.3. Trapezoidal compliance chamber and ventricle chamber without the bag

The trapezoidal chamber was built in order to make the assembly of the model easier. The shape of the chamber may influence the pressure readings and will therefore be tested. It was found that lifelike readings could be obtained, with presence of characteristic noise as seen from previous tests. It does not seem that the shape of the chamber has had a negative or positive effect on the pressure readings. The aortic pressure curve is perfectly aligned with the ventricular curve, simulating physiological behavior. This is due to the pressure sensor in the chamber, which is aligned with the ventricular sensor.

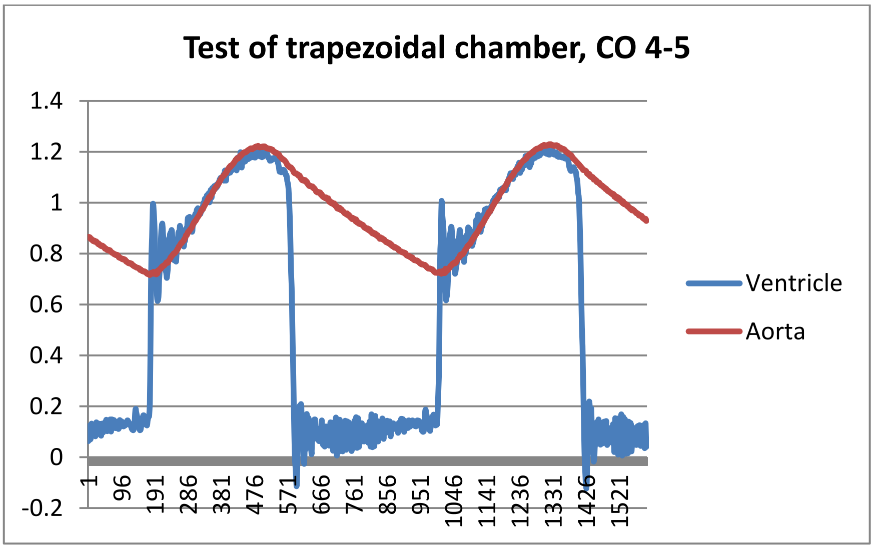

Figure 67 - Trapezoidal chamber without bag, CO 4-5, waveform D

8.4.4. Trapezoidal compliance chamber and ventricle chamber with the bag

Effects of the geometry of the chamber will also be investigated with the presence of a silicone bag in the ventricular chamber. Again it is noted that the shape of the chamber has not had any apparent negative or positive effect on the pressure readings since it displays same characteristics as seen in previous test. Again it is noted that the aortic pressure behaves physiologically.

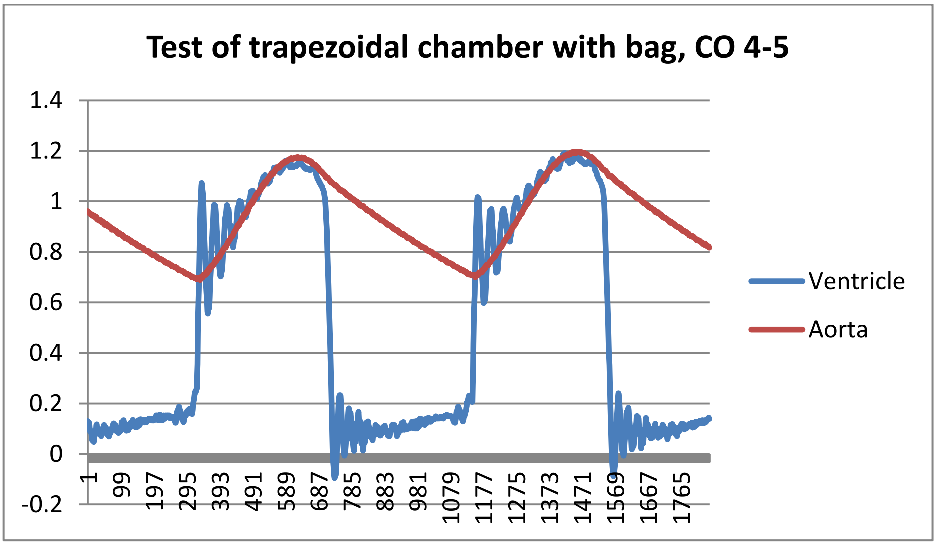

Figure 68 - Trapezoidal chamber with bag, CO 4-5, waveform D

8.4.5. Discussion of the waveforms

The results for different waveforms have been analyzed in order to determine if the waveforms have a significant influence on the results.

It can be seen that the results will vary depending waveform, which must mean that the different setups for the in vitro model do in fact influence the amount of noise.

It was found that waveform B has the lowest area for distal noise while waveform D has lowest area in systole. This pattern is seen for every test that was made. It is also seen that irregular tendencies for the cardiac output increase occurs randomly, but the general tendency is that the area of noise will increase when the cardiac output increases regardless of the Waveform.

The frequency seems to be fairly constant independent of waveform and increasing cardiac output.

8.4.6. Comparison between the new model without bag and the old model

The old and new model will be compared to establish if a reduction of noise in the new model has been achieved, and to determine if there is a difference between the square chamber and the trapezoidal chamber.

The area of noise was calculated and compared[101]. For the old model there only exist data for Waveform D, therefor the results for waveform D will be compared. By calculation of the area of noise it was found that the trapezoidal had a lower area of noise than the square chamber. The old model had the lowest area of distal noise. There seems to be no connection between the size of the area and the size of the frequency. The calculated frequency for the trapezoidal chamber in diastole is considered to invalid due to the unusual frequency obtained for CO 2-3 [L/min].

The graph shows that the duration of a cardiac cycle last longer with the square chamber and the trapezoidal chamber. The noise is very much defined by distinct periods in start systole with rapid decreasing amplitude going into systole.

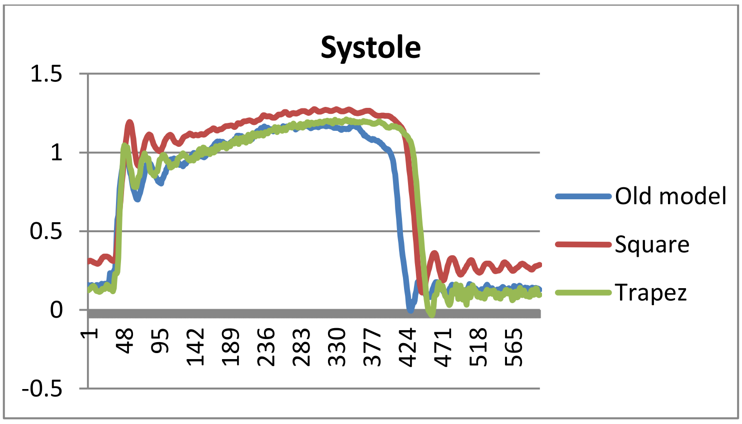

Figure 69 - Pressure curve for all the models plotted together, CO 2-3

The area of noise in diastole for the square and trapezoidal chamber was twice the value of what was found in the old model. In spite of this there is no visible or distinct difference between the characteristics of the curve as they seem to behave in similar a manner.

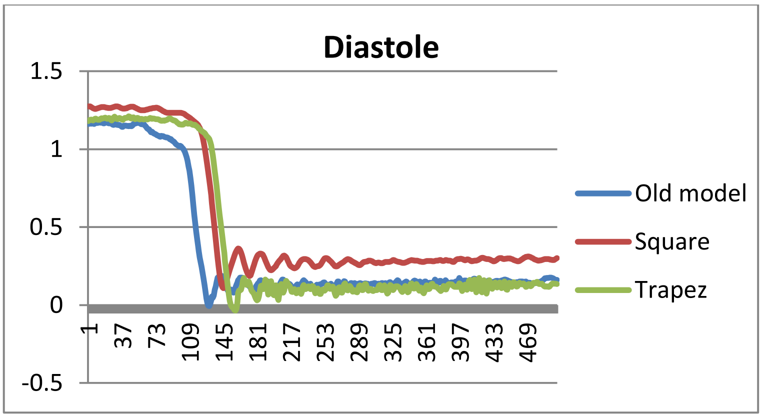

Figure 70 - Diastole pressure for all models plotted together, CO 2-3 [L/min]

[101] Table with all the results can be found in the appendix section 19

8.4.7. Comparison between the new model with bag and the old model

The old model and the new model will be compared again. This time the pressure has been recorded with a silicone bag in the ventricular chamber. The aim is to establish if the bag can change the character of the noise or reduce it, as the presence of it should add some compliance to the model.

Again nothing conclusive can be obtained from the calculation of the area of noise. However it is seen that the presence of the bag has reduced the frequency in the square chamber and in the trapezoidal chamber.

Comparing the results from this test with the test made without the bag it can be concluded that the presence of the silicone bag altered the characteristic of the pressure curve. Considering the graph in figure 71, it can be seen that fluctuations are more distinct when entering the systole phase. The duration of the cardiac cycle was reduced and the duration is now almost equal to the cycle duration obtained from the old model.

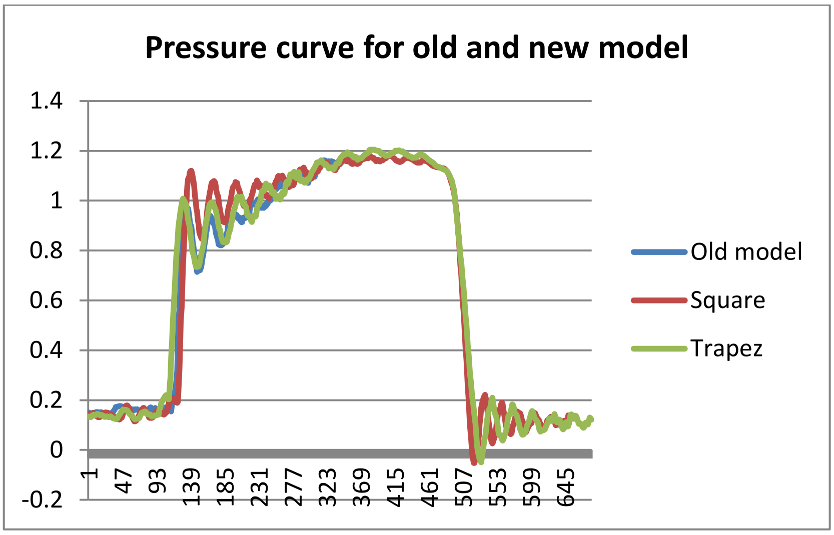

Figure 71 - Pressure curve for all the models plotted together, CO 2-3 [L/min]

8.4.8. Addition of compliance in the ventricle chamber

One of the aims of the project was analyzing if adding more compliance to the in vitro model would have a positive effect in reducing the noise. By adding compliance in the compliance chamber it has been seen that aspects of the pressure curves improves. Added compliance to the ventricle chamber was therefore also desired to be investigated.

As the ventricle chamber has been divided into two parts by using a silicone bag, it was possible to introduce some air in the pump chamber. Pressure curves for different amounts of air in the pump were thusly investigated.

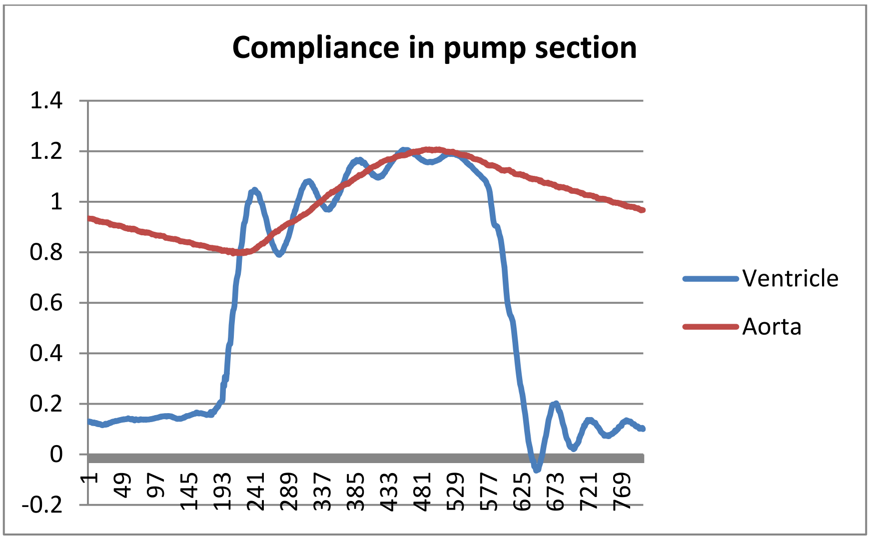

Figure 72 - 1/3 of the pump section filled with air

The area of noise is reduced as the amount of air is increased. It is also noted that the addition of compliance moves the noise from start systole so it extends into end systole. Too much added air cause some physiology loses[102].

[102] The bag with only air in the pump chamber - https://www.youtube.com/watch?v=P8Vtb03yyjI&index=12&list=PL5cR6etRgFA-PUzJrO5uIeBxxvEKZCpiM
The bag under a normal test - https://www.youtube.com/watch?v=CfojY7XV6TE&index=4&list=PL5cR6etRgFA-PUzJrO5uIeBxxvEKZCpiM

8.4.9. Additional test

To find out where the different noise in the pressure curves comes from, there is after the ordinary tests made a number of small tests to try to figure out what the reason is to the noise. The tests made are only usable for looking at the noise, and the properties of the silicone bags.

Properties of the silicone bag

To verify that the bag is operating as it is supposed to, it is needed to test its properties. This can be done in different ways.

First it is needed to see if the bag seals completely. This will be done, by putting in fruit dye in the pump chamber. If the green water gets to the model, the bag does not seal completely. The result for this test was that the bag completely seals the fluid in the pump from the ventricular chamber. There was no green water in the model after 1 hour of tests.

The silicone bag was also tested with nothing but air in the pump chamber, constantly subjecting the bag to stress due to pressure difference. As the bag was intact after the test it showed that the bag is very elastic and strong. The following two videos will document that fact.

Comparison between the new and old bag

To see what difference it makes to the model, what kind of material the silicone bag is produced in, there will be made a test with an old bag, and the new bag, produced in this project. While test was running the hole in the top of the old bag was blocked.

Figure 73 - Left; new silicone bag - Right; old silicone bag

The two bags are made from different materials. The new bag has been made in a more elastic material and is thinner than the old one; it can therefore be assumed that they have different properties that might affect the pressure curves. By comparing the two it is seen that the new designed bag performs better than the old, the design and properties of this bag is therefore considered to be satisfactory[103].

[103] New bag: https://www.youtube.com/watch?v=tG7rAqFG3qM&index=8&list=PL5cR6etRgFA-PUzJrO5uIeBxxvEKZCpiM
Old bag: https://www.youtube.com/watch?v=jpux7RyaUkE&list=PL5cR6etRgFA-PUzJrO5uIeBxxvEKZCpiM&index=5

Pressure sensor moved from the compliance chamber wall to the aortic root fitting

Theory suggested that pressure drop could be avoided if aortic pressure readings were recorded closer to the aortic valve instead of in the compliance chamber. By moving the pressure sensor into the aortic root section more lifelike conditions can be obtained.

Figure 74 - New position of the Millar catheters

Moving the pressure sensors has a detectable effect on the pressure readings. It is noticed that the noise usually appearing in the ventricle is now detected in the aortic pressure curve. This is especially apparent in start systole.

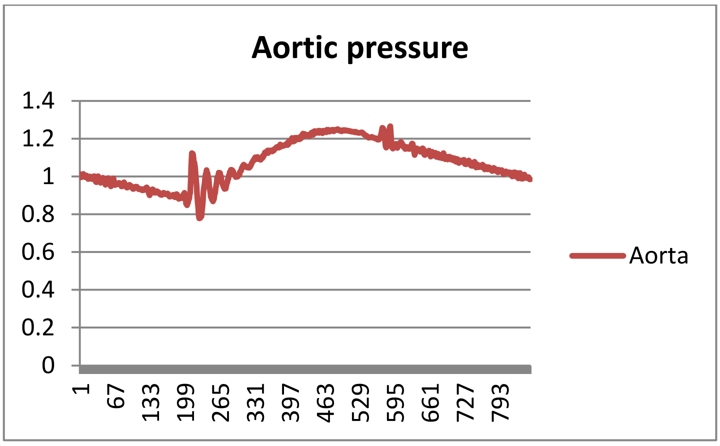

Figure 75 - Pressure sensor in aortic valve fitting, CO 4-5 [L/min]

As the result was unexpected, possible reasons for the presence of the noise will be explored. One reason could be that the pressure sensor experience more turbulence due to the opening and closing of the aortic valve or experience turbulence due to increased flow velocity in the aortic root. The pressure sensor has been moved closer in direct line of the pump action, this might induce some vibrations or pulses that affect the recorded pressure. This is a plausible theory as it is seen that the noise is similar to what the ventricular pressure sensor experiences. The main difference is the level of the effect, as it seems like the effect of the noise is weaker in the aortic pressure readings. For further tests the aortic pressure will be measured in the compliance chamber.

Model without valves

The aim of this study was to investigate if the pump could be the source of the noise recorded in the aortic root, and to examine what effect the aortic valve has on the pressure curves. This study is prompted by the unexpected results obtained when moving the pressure sensor to the aortic root. The test was performed without an aortic valve and with the pressure sensors located in the aortic root.

Recordings were made for the model running with only mitral valve and no aortic valve. In the figure 75 can be seen that the characteristic systolic noise was again observed.

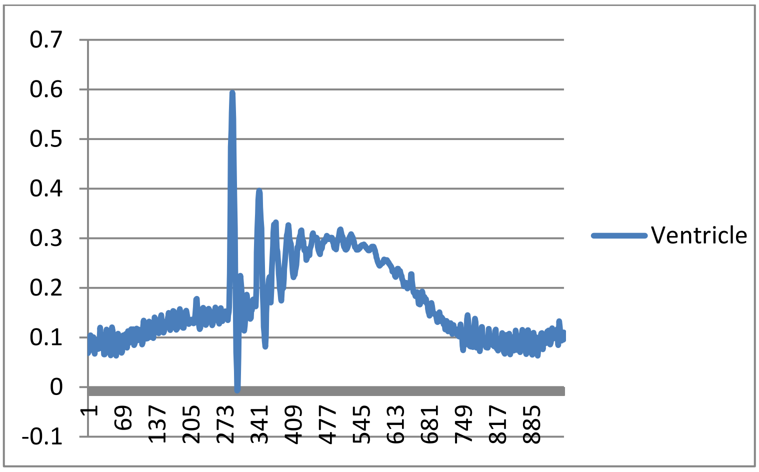

Figure 76 - Model running with mitral valve but without aortic valve

Further recordings were made where the mitral valve was blocked with a silicone plug and the graph in figure 76 was obtained. It is noted that when blocking the mitral valve, the systolic noise disappeared from the ventricle curve and the aortic curve.

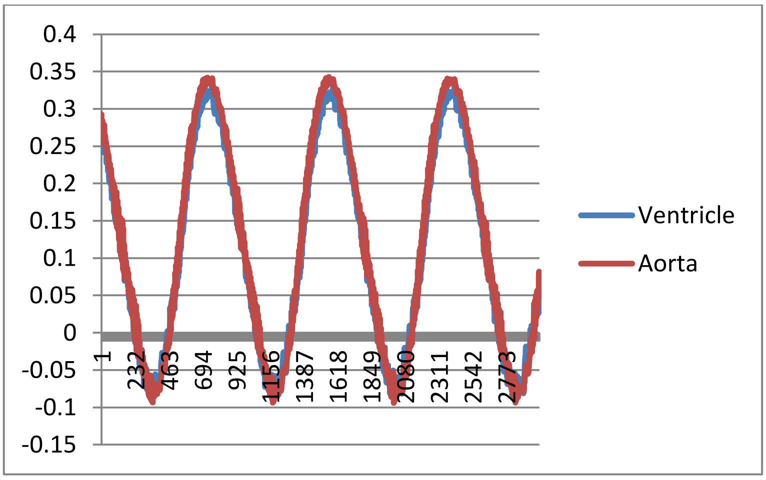

Figure 77 - Model running with mitral valve blocked and without aortic valve

As these results were unexpected more tests were performed in order to deduce what effect presence – or lack of valves – has on the pressure readings. The next step was to investigate the model without any valves in order to see if the pump alone would have notable effect. The result was the presence of some inscrutable noise.

In order to induce some pressure differences the mitral valve inlet was again blocked. The results can be seen in the figure below. Non physiological curves were obtained and the characteristic noise is absent. This may imply that the pump is not the cause of the systemic noise that detriments the physiology of the in vitro model.

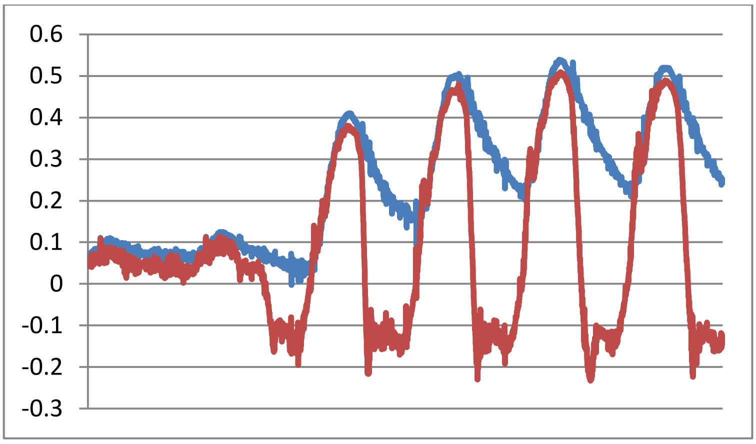

Figure 78 - Model without aortic valve and mitral inlet blocked

The initial theory of this study was that the pump was the main source of the noise; this can be rejected due to the results obtained for these tests. Another theory was that the opening and closing of the aortic valve was to blame, but since the noise occurs regardless of the presence of the aortic valve this theory was rejected. It was however discovered that the opening and closing of the mitral valve can reproduce the characteristic noise seen in previous studies, it can therefore be concluded that the presence of the mitral valve has a significant impact on the on the noise observed in the pressure readings.

8.5. Interpretation of the results

The curves have the characteristics of decaying oscillations which implies that the model may behave like a damped second order system. The characteristic of the curve depends on the damping ratio. If a system is critically damped it will have an exponential decaying curve that never reaches zero. If the system is less than critically damped the curve will oscillate with larger amplitudes that decrease over time.

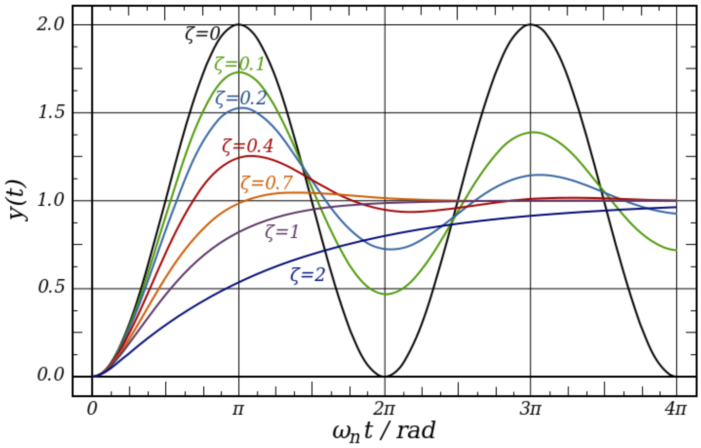

Figure 79 - Damping ratio

Since damping has not been taken into consideration when developing the chambers for the new model, it can be concluded that the method to calculate the area of the noise was incomplete. For further studies it is suggested the damping factor to be calculated. By knowing the damping ratio, the shape of the curve can be known and therefore provide more information for the noise calculation. Additional tests and calculations must be performed in order to discover the main source of this response and therefore try to abolish it.

The graphs indicate that the damping factor for the new model is below 0.2, the desired value would be around 0.7 as the curve then would have a smooth transition into the systolic phase.

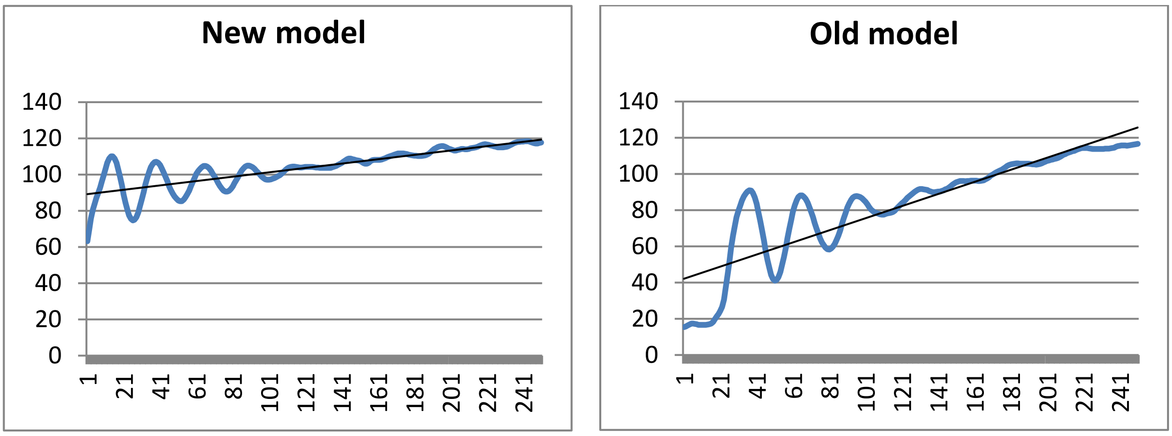

Figure 80 - Damping ratio comparison between old and new model in systole and CO 4-5 [L/min]

9- Perspectives

[104] As a model for medical devices analysis – heart valves replacement – has been designed there is need to follow some guidance and standards. The guidance provided has some recommendations for the preparations of the IDE (investigational device exemption) and (PMA) premarket approval. In it are explained the FDA's (U.S. Food and Drug Administration) recommendations for different items such as manufacturing, in vitro model testing, preclinical in vivo studies. However, for this study is only going to be taken into account the ones which refer to testing the model.

In order to test the model accurately according to the recommendations, the ISO 5840:2005 has to be followed. (ISO 5840: International Organization for Standardization for Cardiovascular Implants – Cardiac Valve prostheses). It is also recommended in the guidance to provide detailed explanations for all the tests including the conditions, the sample selection and the reports for:

- Material property testing
- Biological safety
- Hydrodynamic performance
- Structural performance
- Device durability
- Component fatigue assessments
- Device specific testing

For each test is also recommended to include the protocol (including the sample size, the environmental conditions, the test parameters and the test durations), the acceptance criteria and the results.

New pump is in designing process and will be possible to achieve combinations of waveforms desired in some cases to improve results in the curves. An exactly 70 [BTM] frequency will also be possible to reach.

[104] http://www.fda.gov/medicaldevices/deviceregulationandguidance/guidancedocuments/ucm193096.htm

10- Conclusion

The updates in the in-vitro model have provided a more durable model since the material has been changed into polycarbonate which ensure better properties. The model has been designed avoiding as much as possible screws connections. Those places where a bolt connection is required, the usage of QuickSerts® will delay the breakage. These inserts denote an improvement in the connections.

The new model has been designed moving the chambers into the same level presenting therefore a more lifelike shape.

A tough designing period has been performed during the whole semester. It has been therefore possible to reach a new in-vitro design with almost no leakage between the connections of each chamber. A noticeable improvement in the model is that it is possible to add more compliance, as a result of the increased shape of the compliance chamber and due to the incorporation of a silicone bag in the ventricle chamber. By adding compliance more lifelike pressure curves are obtained.

Based on the tests results with the new model it has been possible to achieve physiological curves. For some determined conditions more physiological conditions than previous has been achieved models since is possible to reach cardiac outputs higher than 5 [L/min].

It is not possible to determine if the trapezoidal compliance chamber has been an improvement or not for the in-vitro model since no conclusive data has been achieved. Fluctuations were seen in the trapezoidal compliance chamber when decreasing the height of water; therefore a higher deposit should be built in order to avoid these oscillations while reaching the amount of compliance desired inside the chamber.

The model can therefore be used for valve's analysis. ARAMIS studies are also possible since visual access to the test segment is plausible.

The noise was not possible to be accurately calculated since the method used can be named as incomplete. Some results were possible to achieve by its usage but in most of the occasions the results were inconclusive. It has not been possible therefore to reduce the noise area neither determine the cause of it. However, some possible sources of noise have been discussed as a result of the analysis of the tests run with the new model.

11- List of figures, tables and equations

List of figures

List of tables

List of equations