3D printing patient-specific organ models

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3D printing patient-specific organ models

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Abstract

3D printing is increasingly used in many different industries and is quickly becoming more and more available. The medical industry have always been at the forefront of technological adaption and 3D printing can be used in many parts of the medical industry. 3D printing patient specific organ models can help the clinicians with diagnosing, treating and increase the success rate of operations.

The study aims to find the 3D printer technology as well as the material that is most suited for 3D printing patient specific organ models. The thesis is written in collaboration with The University of Oslo and The Intervention Centre at Oslo University Hospital Rikshospitalet, referred to as OUS in the rest of the thesis. It is part of the project "Establishment of new service at OUS: 3D printing patient specific organ models" financed by Health South-East. The project and this thesis will mainly focus on 3D printing a patient specific heart model because of the intricate anatomy of the heart. The idea is that if you are able to print a heart with good results, you would also be able to produce other types of less intricate organs.

Four test models of the same heart has been printed and evaluated by surgeons and cardiologists at OUS. The results give valuable insight into what type of material and printer technology they like the most. Further research could be done with models printed from the most suited printers to quantify and see how useful the models can be in real life cases.
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Part I

Introduction and general background
Chapter 1

Introduction

1.1 Intro

The medical industry has always been in the forefront of technological development. Clinicians today use a wide variety of different technology when diagnosing, treating and assessing the care of their patients. From CT or MRI scans for anatomical data, too robotic arms used in surgeries. 3D printing have popularly been described as the next industrial revolution and 3D printing could revolutionize many of the fields within modern medicine. In recent years the concept of 3D printing has attracted more and more attention from the industry as well as from the consumer market. The earliest 3D printing technology surfaced already in the late 1980’s. Charles (Chuck) Hull was the first to successfully create a 3D printer, or rapid prototyping machine which was the term at that time.[21]

The background for Hull's machine was to shorten the time it took to create a prototype, ergo the term rapid prototyping. Hull created the first machine based on stereolithography (SLA) and later co-found 3D Systems Corporation, the first 3D printing company. Today the 3D printing industry has a market value at 5 billion U.S. dollars, and as you can see in figure 1.1 on the following page it is forecasted to reach over 20 billion U.S. dollars by 2020.[10]
1.2 Medical technology

In today’s world, technology plays an important role in every industry as well as in our personal lives. Technology is a crucial help in health care and helps improving and saving life’s all over the world, every single day. 3D printing for the medical industry is growing and there are a lot of different areas in health care which can utilize 3D printing. Some examples are low-cost prosthetic parts, dental parts, tailor made sensors, equipment and medical models. The big advantage using 3D printing for these applications is that everything can be costume made for the individual patient. This guarantees that the part will fit exactly to the patient or show the exact model of a patients organ.

This study will focus on how 3D printing can be used to create an exact model of a patients organ, focusing mainly on printing a full model of a human heart. With these types of models the surgeon will be able to get a closer look at the actual organ they are performing a surgery on. This may aid in making better decisions before and during the actual operation. It can also make it easier to detect other problems that CT or MR images are not able to show. It will especially be useful in the planning for TAVI-patients, where an artificial heart valve is inserted through
the chest wall or through the artery vessels from the groin. And also for newborns where they are born with an abnormal heart anatomy.

### 1.3 Goals of the thesis

The goal of the thesis is to evaluate existing 3D printing technologies, basing it on how well it can be able to produce an organ model. As well as a brief intro to future technology of relevance. There are some important criteria that need to be taken into consideration when evaluating the different technologies. Listed under are some of the key criteria.

- **Quality**: How well does the technology replicate the actual organ? It is crucial to have good quality when preparing for real life, under the knife surgeries.

- **Material**: Which type of materials are suitable? Soft, hard or flexible are material properties to take under consideration. Also different colors and transparency may be vital for the clinical users.

- **Price**: The cost of producing the model needs to be as low as possible but without to much compromise regarding quality, printing time and the material.

- **Print time**: How long does it take to print the model?

The thesis will go thoroughly through the different 3D printing technologies and explain every detail about the process and available material. Thereafter it will be an evaluation of the different technologies based on the ability to create a good model, and meeting the criteria mentioned above. Future printing technology like bioprinting will also be evaluated, as well as making suggestions to enhancements on the present technology to match the criteria of a printed organ model.

### 1.4 Structure of the thesis

1. Literature study on medical 3D printing and heart anatomy
2. Study the process from data acquisition to printed model
3. Study the 3D printing process

4. Categorize all printer technologies and evaluate with emphasis on heart model printing

5. Print test models with suitable printers

6. Conduct an evaluation with clinicians to find the best model

1.5 Project during the thesis

The thesis is connected under an Innovation project financed through Health South-East where Ole Jakob Elle is project leader. The name of the project is "Establishment of new service at OUS: 3D printing patient specific organ models". The goal of this specific project is to find out whether or not 3D printed model’s can be useful. Some of the key questions and tasks are:

- How much will it cost?
- Will the time and cost justify the need?
- What type of material and print technology can be used?
- How much will the model help the surgeons before the operation?
- Segmentation of the CT and MR scans. Is it possible to use free software?
- Develop protocols for good CT or MR scans of the organ
- Is it possible for other fields to make use of the same printer. Will it be possible to print out spare parts or vascular simulation models?

The project can mainly be divided into three parts. The first part will be CT and MR scans. The second will be the image processing and segmentation. The third part will be how to print the model, what type of technology can be used and what types of materials are suitable. The end product will be the printed model which ties the three parts together. The quality of the print is dependent on the results from the three different parts. For this reason it is crucial to make good protocols at each part to make sure that it can be repeated in future cases. The printed model will be evaluated by surgeons and other professionals that may use this type of models in their work. As mentioned earlier this thesis will cover part
three in this project. Figure 1.2 shows a general workflow for creating 3D printed organ models. The squares with dotted lines will be covered in this thesis. This thesis will cover some of the basics behind CT and MRI, segmentation and model generation to get an overview of the whole process, but the study will mainly focus on the 3D printing process and 3D printing technology.
Chapter 2

General background

The general background will cover the history of 3D printing and how it has evolved over the years. Some of the larger 3D printing companies today will be presented as well. It will also cover some of the medical background to provide a better understanding of why 3D printed patient specific models could be useful for the clinicians. We will also look at some of the research that has already been done with 3D printing patient specific models.

2.1 Brief history of 3D printing

At the end of the 1980’s, 3D Systems launched their first commercialized 3D printer called the SLA-1. During the next years other large companies started develop their own types of printers based on SLA. Around that time Scott Crump invented fused deposition modeling (FDM), another 3D printing technology. FDM became the foundation for the company called Stratasys, which he co founded with his wife. In 1991, three new 3D printing technologies were commercialized, including FDM from Stratasys, solid ground curing (SGC) from Cubital, and laminated object manufacturing (LOM) from Helisys.[41]

FDM extrudes melted plastic to produce parts layer by layer. SGC use a UV-sensitive liquid polymer, solidifying full layers in one pass by flooding UV light through masks created with electrostatic toner on a glass plate. LOM binds and cut sheet material using a digitally guided laser. In 1992 the first SLS systems be-
2.1. BRIEF HISTORY OF 3D PRINTING

came available. Selective laser sintering (SLS) is powder based and uses a laser to fuse the powder material layer by layer. The remaining powder acts like support during the print, and is very easy to remove afterwards.\[41\]

Hulls 3D Systems and Crumps Stratasys went on to become two of the most influential companies in the field of 3D printing and rapid prototyping. For roughly twenty years, 3D printing technology quietly evolved and developed, and was utilized mostly by designers and engineers in the business space. This changed in 2005 when some of the key patents associated with the FDM technology expired and caused the start of the RepRap project. The RepRap project will be discussed in more detail in the next chapter.\[21\]

Today the three most well known 3D printers terms are FDM, SLA, and SLS. And as mentioned in the intro chapter, the market value of the 3D printing industry is around 5 billion U.S. dollars. The largest companies today are Stratasys, 3D Systems and Materialise. Where Stratasys and 3D systems are worth almost ten times more than Materialise. Still, 3D printers are mainly used by the industry and not by the consumer market. The main reason is the cost of printer and material. Another obstacle for the regular consumer is the steep learning curve in relation to using 3D modeling software on the computer.

2.1.1 The RepRap project

When some of the key patents on the FDM technology expired, Adrian Bowyer thought that it might be possible to build a FDM printer that could produce parts to more 3D printers. Bowyer was a lecturer in mechanical engineering at the University of Bath in the United Kingdom. He decided that he wanted to make his own 3D printer, but also share his parts online and encourage others to make improvements to his parts, as long as they would share the new improved part. He called this open source concept the RepRap project and this was the first step towards bringing 3D printers to the consumer market.\[21\]

2.1.2 MakerBot

In 2009 Bre Pettis, along with Adam Mayer and Zach Smith founded the company MakerBot. MakerBot builds on the RepRap project where Smith was a founding
member. They wanted to make a consumer friendly and affordable FDM printer and place it in every home. In April 2009 they started shipping their first kits to costumers, and the costumers had to assemble the printer themselves. MakerBot was one of the first companies to provide affordable desktop printers and was praised in the open source community for having an open source approach. They also launched a website called Thingiverse where everyone could share their 3D creations. MakerBot grew in a rapid pace and in 2012 they launched their first fully assembled printer, the Replicator. Unfortunately they decided to not be open source any more, this pushed Smith out of the company. The Replicator was a big success and in 2013, a $403 million stock deal made MakerBot a part of Stratasys.  

2.1.3 Formlabs

Formlabs is another desktop printer oriented company. In 2012, Formlabs raised a staggering $2.95 millions in funding during a Kickstarter campaign. The difference between MakerBot and Formlabs is that Formlabs uses the SLA technology in their printers. Like MakerBot, they want to offer cheap printers to the consumer market. These two companies have played an important role in the evolution of 3D printing. To make it more accessible and used, the technology has to be as cheap as possible, but still deliver good end results.

2.1.4 Stratasys

Stratasys is one of the largest 3D printer manufacturer in the world. They have been at the forefront of 3D printing innovation for more than 25 years. They initially invented the FDM material extrusion printer and in recent years they have developed a wide variety of thermoplastic materials and printers. They have also developed other technologies like the material jetting process called PolyJet. Stratasys operates primarily in the healthcare, aerospace, automotive and education markets.
2.1.5 3D systems

3D system was founded by Chuck Hull and was the first 3D printing company in the world. Today, 3D systems is one of the leading manufacturers and have a wide range of different 3D printers in their portfolio. From SLA printers, to SLS and material jetting printers. Like Stratasys, 3D systems operates primarily in the healthcare, aerospace, automotive and education markets.[30]

2.2 Medical background

2.2.1 Medical use

In today's world we can say that the practice of medicine is inherently dependent upon health technology. The clinicians use a wide variety of technology when diagnosing, treating and assessing the care of their patients. As mentioned earlier, 3D printing offers a wide variety of applications to the medical industry. For medical devices, 3D printing has the advantage of being able to create anatomically matched devices and surgical instrumentation based on the patients medical imaging. As the 3D printing technology has become more refined and reliable the past years, it opens up for the possibility of using printed 3D models of different organs in many different ways. 3D printed models can be used in presurgical planning, education, testing and communication between patient and clinician.

2.2.2 Anatomy of the heart

Before printing an object, it is important to know as much as possible about the intricate details about the part. Knowing the ins and outs of the object is crucial to ensure a successful print. For this thesis, it is therefore important to understand the anatomy of the heart. A normal heart weighs between 200 to 400 grams and is a little larger than the size of your fist. The heart is a muscular organ which pumps blood to all the tissues in your body through a network of blood vessels. It consists of four chambers separated into two sides. The upper chambers are called the right and left atrium, the lower chambers are called the right and left ventricle. There is also a muscular wall separating the right and left side called
2.2. MEDICAL BACKGROUND

<table>
<thead>
<tr>
<th>Type of surgery</th>
<th>Number of cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Valve</td>
<td>1970</td>
</tr>
<tr>
<td>Coronary artery bypass</td>
<td>1455</td>
</tr>
<tr>
<td>Congenital</td>
<td>308</td>
</tr>
<tr>
<td>Aorta</td>
<td>239</td>
</tr>
<tr>
<td>Transplantation</td>
<td>71</td>
</tr>
</tbody>
</table>

Table 2.1: Numbers from Norwegian cardiac surgery register [14]

The hearts job is to take oxygen-poor blood from the body and make oxygen-rich blood that it can pump back into the body. The right side of the heart takes care of the pulmonary circulation which gives circulated blood new oxygen. Oxygen-poor blood from the body gets sent to the right atrium through the superior vena cava. Then it gets pumped into the right ventricle and the tricuspid valve prevents any back flow. The right ventricle then pumps the blood through the pulmonary artery which leads to the lungs. At the lungs the blood picks up oxygen and gets sent through the pulmonary veins to the left atrium. The left side of the heart takes care of the systemic circulation, the part that carries the oxygen-rich blood to the body. From the left atrium the blood flows to the left ventricle before it gets pumped back to the body through the aorta. There are valves both in the aorta and pulmonary artery that prevents back flow.[7]

2.2.3 Common heart diseases and disorders

Using statistics for cardiac surgery cases, enables us to see how many cases 3D printed models could be applicable. As well as discover whether or not it could be useful for the majority of cardiac cases. In 2015 there was a total of 4043 cardiac surgeries in Norway.[14] From table 2.1 you can see that there is a large number of Valve and coronary artery bypass surgeries(CABG). CABG is a surgical procedure to restore the normal blood flow from an obstructed artery. Normal procedure is to remove a vein from the leg and attach that to the top of the blocked
Figure 2.1: Anatomy of the heart[19]
artery and attach the other end to the same artery after the obstruction. It is also common to insert stents, which is a metal reinforcement to open up a blockage and strengthen the artery walls.

Valve surgery is the procedure where you repair or replace diseased heart valves. As mentioned earlier, the heart contains four valves, the Aortic valve, Mitral valve, Tricuspid valve and the Pulmonic valve. The aortic valve is the most common valve to be replaced and the mitral valve is the most common to be repaired. The pulmonary and tricuspid valve are very seldom repaired or replaced.[20] There are two types of replacement valves, mechanical and biological made of human or animal tissue. When it comes to the mechanical valves there are many different sizes and shapes to choose from. Deciding size and shape based on CT and MRI can be difficult and usually you have to try different valves during surgery. Using a 3D printed model to try different shapes and sizes before surgery can be really useful and result in shorter operations.

From table 3.1 you can also see that there is a fair amount of congenital diseases. Congenital heart defects is a problem with the structure of the heart, usually present at birth. At the children department at OUS, the most common heart defect is ventricular septal defect (VSD). VSD is a hole in the septum, the muscular wall between the right and the left heart chamber. A model of the patients heart could be very useful in the presurgical planning before these cases.

### 2.2.4 3D model applications

**Presurgical planning**

Surgeries today do not operate the same way as before. Many of today’s operations are done with minimal invasive procedures. Minimal invasive procedures involves small incisions before the use of an endoscope. The benefits of this type of surgery is the minimal size and count of incisions. Resulting in shorter wound healing time, less associated pain and reduced risk of infection. The downside is that the clinicians get a minimal view of the actual organ or part they are performing the surgery on. It also makes it harder to assess other problems that may not have been detected on CT/MRI image unlike when doing an open surgery. This limits the surgeons ability to make on the spot decisions during an operation.
Which in turn, makes it more important to properly plan the whole operation down to the smallest details.

A 3D model can be really useful in presurgical planning. It enables the surgeons to see and get a feel of the organ they are performing a surgery on. The model might reveal other problems or things to take under consideration, that may not have been clear with just the CT/MRI images. A good example is heart surgery on congenital heart defects. In this type of cases a 3D model can be very helpful for the clinicians to determine what can be done to solve the various problems this disease might cause. Using a 3D model can also make it easier to calculate the angels of the insertion of the endoscope. The importance of presurgical planning can not be underestimated, some of the benefits of correct planing is improved outcomes, less failed surgery’s and reduced surgery time.

**Physical simulation**

3D models can open for a lot of new applications. As mentioned earlier, valve surgeries can really benefit from patient specific models. The models can be used to physically test different valves to ensure that the shape and size is correct. This
will again reduce the time spent during surgery and reduce the risk of complications.

A group at Zhujiang Hospital have published an article about the value of 3D printing models of left atrial appendage. The objective of the study was to assess the clinical feasibility of generating 3D printed models of left atrial appendage (LAA) using real time 3D transesophageal echocardiogram (TEE) data for preoperative reference of LAA occlusion. Patients with LAA occlusion has a higher chance of getting strokes and a minimal invasive surgery were they deploy a watchman implant can be done to effectively prevent strokes. One challenge is the complex anatomical structure of the LAA. From the 2D images generated by the TEE it can be challenging to determine the size of the watchman implant. It will also be challenging to see at what angles you should insert the implant and how deep it should be inserted.[27]

In the study the STL file was generated from TEE data. The study consisted of 8 different patients with the same diagnosis. A Stratasys Objet 30 Pro 3D printer, and a rubber-like material was used for printing the LAA. The optimal size of the Watchman device can be selected through simulating the surgical procedure using the 3D printed model, which can be compared with those placed in the real operation. They also predicted the size using the 2D TEE images. In 7 out of 8 cases, using the 3D printed model gave the same result as using the 2D TEE images. The predicted sizes was also the ones that where used in the real operation. In one of the cases there was a discrepancy between the 2D TEE images and the 3D model. At the real operation they ended up with the size recommended by the simulation on the 3D model. The study concluded that the 3D model is superior to 2D imaging in that the 3D model can predict operating difficulty and complications (e.g. an unstable occluder and peri-device leak). Therefore, creating 3D models with the use of 3D TEE data for LAA occlusion is more desirable and shows great promise.[27]

There has also been published other articles where 3D models have been used for physical simulation. Frank Ing, a cardiologist at the children's hospital Los Angeles, recently made a modified stent to repair an 18 month old baby's pulmonary artery. He used a 3D printed model to test the modified stent before surgery. A stent is a mesh tube inserted to treat narrow or weak arteries. In this case, the size of the narrowing was to small for regular stents and the doctors needed to
create a customized stent. To ensure that the stent worked, they inserted it to a
3D model of the obstructed region. This enabled the doctor to make a smaller
stent that fit exactly to the model. Ing said that: "I have to say, the 3-D model was
very helpful because it gave me confidence that the size of the stent was going to
work"[39] Again, this shows how valuable a 3D printed model can be in complic-ated cases. Figure 2.2 on page 13 shows the 3D model of the obstructed area and
the customized stent inserted to the model.

Education and training

The complex anatomy of the human body can be hard to understand. In medical
education, they are dependent on different training tools to help students with the
understanding and visualization of different anatomical structures. Traditional
training tools are plastinated and commercial mass-produced models, cadaveric
dissections, practical in vivo surgical participation. Unfortunately there are many
limitations to each of these tools that may not apply for a 3D printed model.
Figure 2.3 on the following page shows some of the possibilities with 3D printed
models.

Anatomical models is the most relevant for this thesis and when it comes to
plastinated models there are some crucial limitations. Plastination is a process
to preserve a body or body parts. First of all they are expensive and there is usu-
ally a distortion in the structure and tissue. The rigidity of the model will also lack
realism. When it comes to variation of different types of models it is a challenge
for plastinated models, they are dependent on people willing to donate their body
to science. Commercial mass-produced models are also quite expensive. They are
usually rudimentary and not suited for advanced procedures or special cases. The
models are often based on a hypothetical anatomy and is often limited to only a
few anatomical variations.[17]

3D printing anatomical models as well as 3D printing models for simulation could
be a valuable tool for medical education. The most obvious benefit is the ability
to replicate almost any type of anatomical structure. You could also able to print
a range of different clinical scenarios, both for simulated surgery and models for
visualization and demonstration. Studies on the training outcome with 3D prin-
ted models concluded that there was an improved learning efficiency. They also
2.2. MEDICAL BACKGROUND

Figure 2.3: Ear nose throat surgery model made with a multi-material jetting 3D printer.[17]

experienced an increased interest and enthusiasm among the students as well as a better learning outcome.[17] Almost all studies on this theme report 3D printing to be a cost effective solution. There have been reports that suggest about 90\% to 95\% cost reduction when using 3D printed models instead of plastinated models.[1] You are also able to create several models at a much lower cost than commercial models and the ability to create several models makes it possible for students and teacher to be more hands on with the model.

Another advantage is the fact that 3D printed models are all based on an STL file. This enables you to modify the model on a computer as you please. For instance, it is possible to enlarge or compress the model. Enlarging the model can increase the visibility of small anatomical structures that may be hard to distinguish on a normal scaled model. The STL file can also aid in education and communication between different institutions. If for example OUS gets a patient with a unique heart pathology. A model may not be useful only for OUS but also for other institutions. The ability to instantly share the file with others, may result in better communication and knowledge sharing between different institutions and fields.[17] 3D printed patient-specific models can be used in training courses...
targeting surgeons and clinicians. A model can aid in visualizing and training surgeons and clinicians for special or new cases.

Communication

Communication is vital, and a 3D printed model can in many situations be helpful. Both within a surgical team and between the clinicians and the patient. Within a surgical team, the ability to use a model to get a clear view of dimensions and position of the area of interest can be crucial to avoid miscommunication. When using CT/MRI images there is a risk for misconception because we humans tend to have different ways to interpret 3D objects on a 2D screen. Easier and better communication within a surgical team will result in a more accurate diagnosis. It can also help decrease the number of failed surgeries and problems during surgery.

Communication is vitally important to doctors and patients/parents. How to effectively communicate between an expert and non-expert can be challenging. From the doctor’s point of view it can be challenging to explain a complicated diagnosis or treatment plan to a person with little to no experience. For the patient it can be very overwhelming to comprehend the fact that something is wrong and then try to understand why. By using a 3D printed patient specific model the doctor may be able to communicate easier with the patient and the patient may be able to easier understand the diagnosis and the way forward.

As mentioned earlier, one of the most common heart defects for children at OUS is VSD. In this case, when communicating with the parents, a model of their child’s heart can be a really useful tool, both for the parents and the doctor. The parents will be able to clearly see what’s wrong, and the doctor can easily show how the problem will be fixed in surgery. An article published by Giovanni Biglino[5] showed that parents and clinicians both found 3D printed models to be very useful and helpful when discussing congenital heart defects. They concluded that Patient-specific models can enhance engagement with parents and improve communication between clinicians and parents, potentially impacting on parent and patient psychological adjustment following treatment.[5]
3DHEART

Quantifying the positive impact 3D printed models have in the pre planning process and when diagnosing can be a challenge. Even though the majority of clinicians says that 3D printed models are useful there have not been many studies that can quantify the positive impact they give. Pediatric cardiac doctors at Children’s Hospital of Philadelphia and Children’s National Medical Center have put together a proposal to study the effects of utilizing 3D printed models of patients’ hearts during pre-operative planning. The study is called 3DHEART and will consist of 400 pediatric patients in total. Stratasys Direct Manufacturing, one of the world’s largest 3D printing and advanced manufacturing service providers, is 3D printing heart models for 200 patients on Stratasys Connex multi-material, full color 3D Printers. These models are based on the patients’ MRI or CT scans and enable the surgeon to evaluate and “practice” on an accurate replica of the patient’s heart prior to actual surgery. The results of these 200 patients are being compared to the results of 200 patients who are being treated without the aid of 3D printed heart models. This study will help quantify the positive impact 3D printed models have and the result can make 3D printed heart models a standard in all future heart cases.[22]
Part II

Technological background
Chapter 3

Creating the computer model

This chapter will cover the main aspects around creating the computer model of a patient's heart, from image acquisition to image segmentation. It is done to get an overview of these processes and to identify possible problems that might impact the accuracy of the end result.

3.1 Workflow

The steps from first time consultation to finished 3D printed model can be divided into five steps.

1. Generating CT or MRI images.
2. Segmentation of the CT or MRI images.
3. Create a 3D computer model from the segmentation.
4. 3D print the model.
5. Post process the printed model.

To get a better understanding of the whole process from diagnosis to print, this chapter will go through the workflow with emphasis on the medical part. This will also show some of the areas that directly impact the end result of the 3D printed model. More details around the 3D printing workflow will be discussed in later chapters.
3.2 Image acquisition, CT and MRI

Image acquisition is the start of creating a 3D printed model. The end result is dependent on good images of the actual organ and poor image quality could result in discrepancies between the 3D printed model and the actual organ. It is therefore important to get a small introduction to how organ images are acquired today.

3.2.1 Computed tomography (CT)

CT uses special x-ray equipment to create multiple pictures of the inside of the body. The pictures are used to help detect a wide variety of diseases and conditions. During a CT scan, multiple pictures are taken from various angles to produce a large series of cross-sectional images. The images are analyzed by a computer and overlaying structures are removed. This enables the user to isolate the area of interest and see what’s inside without cutting and opening the body. Using digital geometry processing the user can create a 3D model of the images. CT is widely available, a generally quick procedure and painless for the patient. CT is the only method that provides detailed images of bones, soft tissue and blood vessels. Some of the disadvantages is the exposure to radiation and for some, an allergic reaction to contrast material.[11]

3.2.2 Cardiovascular CT

Cardiovascular CT is usually used to asses the extent of occlusion in the coronary arteries. Before the scan the patient is injected with an intravenous dye. The intravenous dye is a radiocontrast agent which enhances the visibility of the blood on the CT images. Using a high speed CT scanner, the radiologist can assess the blood flow to and from the heart. Blood flow and enhanced visibility of the blood is crucial to be able to distinguish the different parts of the heart to make a good 3D model.[11]
3.2.3 Magnetic resonance imaging (MRI)

MRI uses strong magnetic fields, radio waves, and field gradients to generate images of the inside of the body. MRI is based upon the principle of nuclear magnetic resonance. This is a physical phenomenon where a nuclei in a magnetic field absorb and re-emit electromagnetic radiation. In clinical applications, hydrogen atoms are usually used to emit this electromagnetic radiation which are detected by a scanner. Hydrogen atoms exist naturally in the body, particularly in water and fat. An MR examination is made up of a series of pulse sequences. Different tissues (such as fat and water) have different relaxation times and can be identified separately. By using a “fat suppression” pulse sequence, for example, the signal from fat will be removed, leaving only the signal from any abnormalities laying within it.\[4\]

3.2.4 Cardiac magnetic resonance imaging

Cardiac MRI uses the same principles as usual MRI, but there are some optimizations for use on the cardiovascular system. The fundamental challenges of cardiac MRI imaging is that movement of the heart throughout the cardiac cycle and the movement of the lungs during the respiratory cycle produce motion disturbances in the image. To reduce this problem specialist use ECG gating during the scan. ECG gating enables the user to take images at the same time of the cardiac cycle. This means that there is only collected data at a specific point in the cardiac cycle, typically at the point where the heart is not moving. Cardiac MRI have the advantage that it can combine a variety of different techniques into protocols. During the same scan you can use different protocols to get a comprehensive assessment of the heart and the cardiovascular system. Like CT scans, some of the protocols requires the use of a contrast agent to make the blood more visible.\[9\]

3.3 Image segmentation

To create a 3D model from CT or MRI images you need to do different segmentation techniques on the images. Image segmentation is a process where you divide a digital image into different segments. The goal of segmentation is to simplify
and/or change the representation of an image into something that is more meaningful and easier to analyze. In cardiac image segmentations, you want to be able to distinguish the different parts of the heart to make an accurate model. The accuracy of 3D printed model is dependent on good segmentation, which in turn is dependent on good images from CT or MRI. There are many different types of segmentation methods, but the main categories are listed below.

3.3.1 Thresholding

Thresholding is probably the most used technique to segment an image. Thresholding uses a grey value remapping operation to segment the image into two segments, identified by the pixel values 0 and 1 respectively. Images with bright objects on a dark surface are very suited for thresholding. Figure 3.1 on the next page shows how the blood in the heart is highlighted with thresholding. In this example, thresholding is used to try to distinguish the different parts of the heart. If you raise the threshold level, a larger part of the blood will be highlighted. Lower the value and less will be highlighted. Finding the right balance can be hard, and the complex anatomy of the heart is prone to overlapping errors, where for example the right ventricle and the right atrium is shown as one part. Thresholding is a very primal approach and is usually combined with other segmentation techniques.[32, 25]

3.3.2 Edge based segmentation

Edge based segmentation is a well-developed field on its own within image processing. It is based on the fact that there usually is a sharp adjustment in intensity at the region boundaries and that boundaries and edges are closely related. Finding the edges is important to define the different parts of the heart.

3.3.3 Region based segmentation

Region based segmentation works on many of the same principles edge base segmentation. But instead of finding the edges of the object and then filling in the object. You start from the inside by choosing one or multiple seed points in the
3.3. IMAGE SEGMENTATION

Figure 3.1: Cardiac segmentation in mimics software

MR images for a selected region. Afterwards, the initial region begins to grow by searching similar pixels nearby or inside the specified region. If a pixel meets the designed criterion, it will be allocated to that region. When none of the surrounding pixels qualify, the region stops growing as it may have reached the boundary of the tissue.[32, 25]

3.3.4 Clustering

Clustering is used to group image pixels with the same properties together. In theory, this will split the pixels representing different types of tissue and blood into different categories. This can make it easier to distinguish the different parts.[32, 25]

3.3.5 Matching

When we know what an object we want to identify in an image looks like, we can use this knowledge to locate the object in an image. In a cardiac example, if you manually can label the major parts of the heart, like the ventricles, aorta and the septum. Different computer programs can use built in automatic segmentation tools to segment the pictures based on this information.
3.4 Cardiac segmentation

Cardiac image segmentation plays a crucial role and allows for a wide range of applications, including quantification of volume, computer-aided diagnosis, localization of pathology, and image-guided interventions. However, manual delineation is tedious, time consuming, and is exposed to human errors. This task is also prone to intra- and interobserver variability, which means that different clinicians may produce different results from the same material. One clinician can also produce different results when evaluating the material more than once. Building 3D models of the heart requires delineating all of the cardiac structures in a patient’s MRI, including the entire blood pool, epicardial surface and the great vessels. Clinically available tools often require 4-8 hours of user interaction to manually segment 100-200 slices covering the entire heart and the great vessels.[31]

To shorten this time, many specialists and large companies focus on developing efficient segmentation methods and programs for cardiac segmentation. Computer programs like Materialise Mimics and Osirixs are some of the most used medical image processing applications. There are also a lot of open source programs like InVesalius, Blender, Segment and ITK-Snap. The program most relevant for this thesis is the commercial program Materialise Mimics. Materialise is a 3D printing company with emphasis on the medical industry. They offer 3D printing with many different technologies and also develop software like Mimics. Mimics has a lot of built in segmentation tools specialized for cardiac segmentation. A research in collaboration with Materialise[6] shows that using the interactive segmentation tools are faster than other segmentation methods. They concluded that without the CT heart tool an experienced user used around 144 minutes to obtain an accurate left heart segmentation. While unexperienced users using the CT heart tool in Mimics used an average of around 54 minutes to complete the same process.[6]

The need for standardized protocols, segmentation tools and segmentation methods are vital when establishing 3D printing in the hospital. As mentioned earlier, the project at OUS is divided into different parts. The part with segmentation and image processing is handled by Robin Bugge, a physicist hired for this project. He has used multiple programs and segmentation methods, as well as working on
his own algorithm for whole heart segmentation. He is working on a publication about this part of the project and it will be published in the near future.

## 3.5 Model generation

After segmentation, the model needs some post processing before it is ready for printing. The segmented model is usually the blood volume of the heart and you need to create the heart walls around the blood volume. There are a lot of 3D modeling programs available which uses different geometry types to build the models. How 3D modeling programs work will be reviewed in the next chapter. 3Matic is a post processing program you get with the mimics package from Materialise. The models printed in this project have been processed with 3Matic and the program was used to extrude the fake heart wall, normal to the blood volume. There are also functions for combining different parts of the segmentation, possibility to edit the shape of the model and export the model to STL file or 3D-pdf. Figure 3.2 on the facing page shows a model created with 3Matic.
Figure 3.2: Post processed heart ready for printing
Chapter 4

The 3D printing process

There are several different steps in the 3D printing process and this chapter will cover the whole process. It will introduce the different types of computer modeling, cover the file formats used by 3D printers. As well as go through the different decisions you can make with the 3D printers software and how these decisions impact the end result.

4.1 3D printing workflow

It can be hard to visualize how a 3D printer works. Many also base their understanding on what is shown in the mainstream media. In the media, it is almost always a desktop consumer printer showing how it can print a small plastic figure or model. This results in a wrong perception of the technological abilities for a 3D printer. The most common misconception is that you only can print plastic models. To get an overview of the multiple steps in the 3D printing process, this chapter will go through each of the main steps when 3D printing. The diagram below shows the steps in the 3D printing process.
4.2 3D modeling

The first step in 3D printing is to create a 3D computer model of the object you want to print. This can be done in multiple ways and can actually be made from scratch using a computer-aided design (CAD) software. There is also an increasing number of people that is creating and posting 3D models online, which you in many cases can download for free. Scanning an object to create a model is also an option. As mentioned in section 3.2, scanning the body is how you can create 3D models of organs and anatomical structures. Regardless of how the model is created, there is usually a need for CAD software to either modify the object or to repair it if for example a scan does not get every part right.

Computational 3D modeling is basically the process of developing a mathematical representation of any three dimensional surface. Models can be created with different mathematical principles and geometry types, or a combination of several principles and types. CAD software is diverse and is often specialized for different fields of application. We may define two main types of 3D modeling, which can be considered as two different "worlds" within computer aided design.
Parametric modeling is usually a set of parametric steps to create the model. Parametric models are parts made with a combination of simple mathematical shapes. Most common is squares, rectangles, cylinders, ellipsoids, pyramids and conics. This gives the part a "machine like" appearance which is more relevant when constructing engineered parts. Software specialized for these types of models can be used to create spare parts and development of medical equipment and tools.

3D mesh models are made from more advanced mathematical functions. This creates arbitrarily models that have a more organic like impression. Patient specific organ models is considered freeform shapes and is therefore dependent on software specialized in these mathematical functions.

Figure 4.1 on the next page shows two basic examples of the difference between mesh and parametric models. As you can see in figure 4.1b, the parametric model contains measurements. This means that there are predefined parameters which decides the shape of the object. Parts like this are first drawn as a 2D image and then extruded. The finished object is usually put together with extruded parts which results in sharp edges and "seams" between the parts. As mentioned, this is more relevant when developing spare parts and tools. Spare parts have predefined parameters, usually found by measurement and in the design process it is crucial to follow the parameters to the letter. Figure 4.1a shows an example of a 3D mesh figure created in Blender. You can clearly see that there is a more organic look and is vastly better at smooth curves and shapes that are not bound by exact measurements and relations. Mesh models are usually design with a polygon mesh and subdivision of the surface. Software specialized in polygon meshes and subdivision is recommended to use when extracting the heart wall based on the blood volume, this ensures a smooth finish and organic look.

4.3 The STL file

Since the launch of the 3D printing industry, all commercial 3D CAD systems have developed software that is able to export the CAD model to STL file format. The STL file is the standard within the 3D printing industry and is supported by most
4.3. THE STL FILE

(a) Mesh figure made in Blender
(b) Parametric model made in Solidworks

Figure 4.1: Example of a mesh model and parametric model

of today’s printers. It was developed in 1987 for 3D systems to allow data movement from CAD software to their stereolithography machines. Even though STL is widely used, the definition of the acronym STL is still under debate. It’s widely believed to be an abbreviation of the word Stereolithography, though sometimes it is also referred to as “Standard Triangle Language” or “Standard Tessellation Language”.[18, 34]

The STL file works by approximating the geometry in the CAD file. It uses a triangular mesh to recreate the surface geometry of the object. It also strives to accurately approximate the data with as few elements as possible. Figure 4.2 on the following page shows how a triangular mesh can represent a sphere with different quality. To 3D print a smooth sphere, you need a high resolution and therefore have to use more triangles to represent the object. Higher resolution equals larger files, more detailed objects and longer print time. A STL file can be exported in either ASCII or binary format. ASCII is a character encoding standard to represent text as numbers in a computer. For example the ASCII code for uppercase M is 77. Raw ASCII STL files are easier to read for a human because of the characters. However, this drastically increase the file size and therefore the binary format of the STL file is more used.[18, 34]

A STL file simply consists of the coordinates for every single triangle facet in the
4.4 Future of the STL format

Since the development of the STL file, printer manufacturers have developed new and innovative 3D printers. Modern 3D printers can print at a considerable higher quality than their predecessors. Some also have the possibility to print with different materials, color, textures or support material. The STL file lacks information on materials, model orientation and position, textures, colors, sub-structures, and multi-material geometries. To describe object characteristics such as materials or colors, the STL format have to be modified, most often on the OEM or support software side. Today, one can work with a standard STL file or a number of custom and/or proprietary STL format. This means that there is no standard file format but various modifications that only works with the manufacturers machine. This is inefficient and unsustainable in a world with great technological advances and innovations.

Leading the 3D printing file format revolution is the 3MF Consortium, a group of...
4.4. FUTURE OF THE STL FORMAT

Figure 4.3: ASCII STL file example code

```plaintext
solid
    facet normal  0.121  0.380  -0.917
    outer loop
        vertex 1.5000  1.8882  0.0511
        vertex 1.5000  2.2500  0.2010
        vertex 1.9302  1.9783  0.1450
    endloop
    endfacet
    facet normal  0.175  0.175  -0.969
    outer loop
        vertex 1.9302  1.9783  0.1450
        vertex 1.8882  1.5000  0.0511
        vertex 1.9302  1.8882  0.0511
    endloop
    endfacet
...
endsolid
```
leading technology companies which lists Microsoft, Autodesk, HP, Stratasys, 3D systems and Siemens to mention a few. They are developing a new 3D printing file format called 3MF. Their main goal is to make a standard format that allows design applications to send full-fidelity 3D models to a mix of other applications, platforms, services and printers. As mentioned, the development is a joint effort among companies within the industry and the access to and implementation of the 3MF specification will always be free of royalties, patents and licensing. 3MF is a XML-based data format which is both human and computer readable. It is designed to contain all of the necessary model, material and property information in a single archive. The format is also designed to be interoperable, ensuring the ability to meet the demands of both present and future 3D printers.[26]

4.5 3D printer software

Before printing, the STL file needs to be prepared with a 3D printing software. This is where you decide the orientation of part, generate support material, part placement, slicing and generate the final build file. Making the right decisions with these settings is crucial to ensure a good print result. Most 3D printer software analyze the STL file and automatically chooses settings. This is adequate in most situations but it is important to know how the main settings can impact the final result. Every 3D printer is different and the settings needs to be adjusted based on the previous print turned out. Even though every printer is different, there are some main pointers to consider to ensure a successful print.

4.5.1 Object orientation

Orientation of the object during printing can influence the quality, print time and use of support material. Therefore, the balance between quality and print time needs to be carefully considered when deciding the orientation of the object. The height of the object have a significant impact on the build time for most of todays technology. Higher object means more layers, and creating new layers is far more time consuming then creating thicker layers. In most systems, there is usually a small setup between each layer. This may include plate/nozzle repositioning, calibration and material leveling. Even if these setups are completed quickly, they
add up a lot of time if you have many layers to print. Printing a tower for example will take a lot longer time if you print it straight up then if you print it on the side.

Changing the layer height is also possible. Smaller layer height will increase the quality of the final product, but increased layer height would also result in an increase in total layers. 3D printers today create the object layer by layer, all objects will therefore exhibit some degree of "stair stepping" shown in figure 4.4. Unless all the features of the object is parallel with the horizontal or vertical line. Printing a square box will not feature stair stepping, but if the box features holes or rounded edges, both the holes and the rounded edges will show signs of stair stepping.[18]

Decreasing the layer heights will minimize the stair stepping effect on the part, but in return increase the print time. Orientation can affect quality of some features, a trough hole for example should be aligned with it's centerline along the z axis. If the centerline is aligned with the x axis, the hole will be approximated with the stepped layers and may take on an oval shape as well as a stepped finish.[18]

When it comes to printing a heart model, the quality of the print is essential to accurately represent the actual heart. That’s why the models should be printed on highest quality regardless of the time consumption. As mentioned, orientation will also prescribe the amount and location of support structures and will be discussed in the next section.
4.5.2 Support material

All types of 3D printers need a form of support material to prevent the object from shifting during the build. Support structures also prevent sagging and slumping of overhanging features. On the other hand, support structures will have an impact on the surface finish and the time needed for post processing as well as the print time. Systems based on selective binding or laser sintering utilize the unused, excess material to totally surround and support the object. Other systems build the object within a liquid or in open space and needs to print support structures in all overhangs.[18]

Support serves two functions, attach the part to the build platform and support overhanging geometry. Fixing the object to the build plate is done by adding support structure to the base of the object. The support is firmly attached to the build plate and create a pedestal on which the object is created. This ensures that the object won’t shift during printing and makes it possible to remove the object from the build plate without damaging the object surface, only the support material. In stereolithography, without this base support, the object would shift within the build area as the liquid resin is disturbed by plate movement.[18]

The other function of support structures is to retain a feature that has no layers below it. For example, if you want to print a T straight up, when the printer comes to the first layer of the horizontal part of the T, there will be no previous layer to support the first layer of the overhanging features. In this case, support structures would be printed all the way from the build platform to the first layer of the overhanging part of the T. As mentioned earlier, the object orientation will impact the amount and placement of support structures. In the T example, right object orientation can eliminate the need for support structures. Either by printing it up side down or printing it laying down. Laying it down would be the best solution to reduce the number of layers, which in turn reduces the print time.[18]

Support material and structure design is predicated by the system manufacturer. Within each technology, there can be various configurations to accommodate different build scenarios. The most common and used structure design is the checkerboard pattern. Thin walls are printed in both the x and y direction, creating a grid or checkerboard structure. This makes up a porous structure which is easy to remove with some force. Other support structures can be solid materials or small...
columns of material. Solid materials can be wax or a water dissolvable material. This type of support can be easily removed by either heating up the object to melt the wax or submerge the model in water or another solution which dissolve the support material.[18]

As mentioned, some systems use a self-supporting strategy. They use excess and unused build material to support the object. An example is selective laser sintering, each new layer starts with a fresh new layer of powder. After sintering a layer, the unsintered material remains and supports the new structures. When the print is finished, the support can be removed by either brushing or blowing the powder off. Support structures is automatically generated in most 3D printer softwares, but in some advanced cases, manual interference could be needed. Support structures will usually increase the print time, material consumption and post processing time.

Another consideration with support material is the impact on surface finish, feature retention and post processing time. After the print is done, the support needs to be removed manually in most cases. This can be tedious and time consuming work if there is a large number of support structures, especially if the support is surrounding small features. When removed, support structure often leave a mark or remnant. This can affect the accuracy of the model, so in cases requiring high accuracy, it is crucial to spend time removing as much support as possible. In most systems, some force is needed to remove support structures. When printing objects in a soft material, it is important to consider how much force you can apply when removing support structures. When printing a heart for example, there is a lot of small features and thin walls within the heart that is crucial to keep intact. To retain these features accurately and minimize the possibility of tearing the soft walls of the heart, you need to be careful when removing the support structures during post processing.

Different technologies use a variety of ways to remove support and this can affect the choice of printer type. If the goal is to develop soft models with intricate small features, support removal may exclude some types of printers. Choosing support material and printer will depend on the intended application of the printed object and operational preferences. This will be discussed in depth in later chapters. Another consideration is accessibility, if a technician cannot get access to the support structure, it will remain within the part. Within a heart, there is usually small
and narrow passages that lead to hollow pockets. If the passage leading to one of these pockets is too narrow, it may be impossible to remove the support structure within the pocket.

### 4.5.3 Part placement

Most 3D printers have the capability to produce multiple objects in the same print. As long as the objects are within the build area, it is possible to print multiple objects at the same time. During one machine run, you can print either multiple examples of the same object or different types of objects. Part placement is specified in the vendor-supplied software and usually needs human interaction to maximize the placement relative to the build area. Printing multiple objects at the same time will reduce print time and operational efficiency. You save time with the setup, the printer only needs to run one time and as mentioned earlier, it is more time consuming to create a new layer then to add more on the same layer. All this adds up to significant time reduction when printing multiple parts in the same print.

A good example of the balance between orientation, support and placement is printing the plastic part of a ballpoint pen. First of all, the part can be printed straight up to get the best quality and eliminate the need for support structure. Secondly, the part can be printed laying down, this requires less layers and time, but in turn needs support structure inside the plastic part. Printing one pen straight up could take around 5 hours, printing 2 pens at the same time would only take about 5.5 hours. If you have the build area to print 100 pens at the same time, it will only take 1 hour to produce each pen.[18]

In stereolithography and laser sintering, part placement can affect dimensional accuracy and feature definition. Stereolithography uses a fixed laser to cure the resin and scanning mirrors is used to redirect the laser in the X-Y plane. In the center of the object, the laser point will be perfectly round, but when the laser reaches the edges of build area, the beam takes on an elliptical shape. Even though the difference is very small, it may result in added material which reduces the accuracy at the edges of the build platform. This problem also occurs in laser sintering, but there is also a problem with uneven temperature in the powder bed. It is usually warmer in the middle of the powder bed then on the edges of the bed.
4.5. 3D PRINTER SOFTWARE

Parts or features on the outer area of the powder bed can easily experience curling or warping at the part surface.[18]

To take full advantage of the space in the build envelope, the mix of parts should have relatively the same height in the z direction. If you have one part that is 10 cm high and the rest is around 2 cm, the 10 cm high part will carry the overhead for the top 8 cm. Trying to print parts of the same height will give the best operational efficiency and lowest operating expense. When printing a heart, you can maximize the operational efficiency by dividing the heart into two. By doing this, you can print the two parts side by side and reduce the height and layers. After printing it is possible to glue the two parts together to form the full heart. This adds another step to the post processing process which increases the time. On the other hand, if you print it in two parts it will be easier to remove the support structures from the two parts. So in total, printing the heart in two pieces should reduce both print time and post processing time. This possibility will be discussed more in detail in a later chapter.

4.5.4 Slicing

After completing the build layout with object orientation, part placement, layer thickness, support generation and various other parameter choices, the software slices the part into thin horizontal cross sections that represent one layer. These layers becomes the "tool paths" that drive the laser, light, print head or extrusion tip in the 3D printer. Layer thickness depends on the type of printer and most printers offer the user the ability to choose layer thickness within a manufacturer defined range. Thinner layers result in higher accuracy and longer print time, while thicker layers reduce accuracy, quality and print time. To maximize quality and reduce print time, it is often possible to specify multiple layer heights within the same object. This means that areas of the object with fine details can be printed with thinner layers than the rest of the object that may lack these details.[18]
4.5.5 G-code

The final step in the file processing is to create the build file for the 3D printer system. Based on the parameters and settings, the 3D printer software generates a file containing G-code. G-code is the most widely used numerical control programming language and is used mainly in computer-aided manufacturing to control automated machine tools. In simple terms, G-code describes to the printer system how to build the object. Typical G-code functions include commanding an extruder to heat up to a particular temperature, instructing the printer to pause until an extruder reaches a certain temperature, moving the extruder to some \((x, y, z)\) position, and conducting similar activities. The code describes how the entire object will be printed and the instructions drives the laser, print head or extrusion tip to the right place. Conceptually, the print object can be seen as multiple points and the g-code simply tells the system how to connect the points to create the full object. G-code for machine tools evolved gradually, with different variants for each tool manufacturer. A standard of sorts called RS274D stabilized in the mid-1980s. Because the computer numerically controlled (CNC) market was pretty stable when the first low-cost 3D printers came along, a lot of the early users borrowed firmware and concepts to program those machines, and so a G-code dialect for 3D printers developed.[21]

G-commands

G-code operates on a very simple syntax and is typically written such that all the commands are interpreted one at a time sequentially. There is a long list of codes and commands that can be used to create an object in g-code. An example of a G-code file is shown under. The printer always starts at the top of the file and moves down through the commands. As mentioned there is a long list of different commands, so we will go through some of the commands for 3D printing.

Commands starting with G usually tell the controller what type of movement is wanted. G commands is used to position the extrusion tip, build plate, laser or print head, as well as tell what kind of movement is wanted. G01 for example, describes linear interpolation and the controller calculates the intermediate points to pass through that will yield a straight line. G0 on the other hand, has a more rapid movement and is not bound to follow a straight line. G0 i therefore most
used if you want to move along one axis. There is also a G command for circular interpolation, NURBS machining, full circle and different positioning commands.[16]

G28 ; Home all axes
G0 X12 ; move to 12mm on the X axis
G0 F1500 ; Set the feedrate to 1500mm/minute
G1 X90.6 Y13.8 E22.4 ; Move while extruding 22.4mm material

**M-commands**

M-commands is described as a miscellaneous function, but in most cases an M-command calls for a machine function. These commands typically controls machine functions like start and stop the whole system. It also controls other system functions like reading the SD card, setting feed rate, controlling cooling fan and set/get extruder temperature.[16] Under is a code example with some of the M commands.

M21 ; Initialise SD Card
M0 ; Stops everything
M17 ; Enable all stepper motors
M18 ; Stop all stepper motors
M106 ; Fan on
M107 ; Fan off

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**4.6 3D Printing**

Conceptually, 3D printing work similarly to building a brick wall. The 3D printer is of course a lot more flexible in what you can build, but the principals are very similar. 3D printing is based on the same concepts as conventional ink-jet and laser printers, which creates most of the documents and pictures in today's society. These create text or images by controlling the placement of ink or toner on a piece of paper. A 3D printer works the same way, but instead of creating only one layer, you place multiple layers of a build material on top of each other, much like building a brick wall.
Exactly how the 3D printer creates the layers of material depends on what technology the printer is using. Today there is a large number of different 3D printers within each technology. Broadly speaking, 3D printing technologies work in one of four basic ways. To make it easy to categorize and understand the different variations within each technology, there will be a broad definition of each in the following chapter. The next chapter will also go through the theory behind the different types of technologies.
Chapter 5

3D Printer technology

In this chapter we will go through the different types of 3D printer technology. It will mainly focus on the theory behind each printer as well as briefly discuss whether or not the technology is capable of printing a heart model. There will also be a section with future technology that might be suited for printing heart models.

5.1 Types of printer technology

5.1.1 Extrusion-based modeling

Extrusion-based 3D printers work by extruding a melted or liquid material from a print head nozzle at specified positions. The most common is 3D printers that melts a filament of thermoplastic that sets very fast after it leaves the nozzle, but there is also 3D printers that use other types of filament. In the food/restaurant industry some have started to use 3D printers to make culinary creations. Melted chocolate or batters are some of the “filaments” that can be used with a specialized 3D printer. There are also extrusion-based printers that extrude concrete, metal and glass, but thermoplastic is the most used filament within this technology category. You can get thermoplastic 3D printers for personal use or professional use, ranging from small desktop printers to large industry printers.[3]
5.1.2 Selective solidification

This technology uses photopolymerization to create the object layers. Photopolymerization is a process where molecules stick together in a chemical reaction to form polymer chains or three-dimensional networks. 3D printers utilizing this process use a liquid resin, also called a polymer, which cures when exposed to a light source. Some printers build the object within a tank filled with liquid, using a build platform to lift the model out of the liquid or into the liquid. Other printers, like Stratasys Objet series, work more like conventional printers. A print head sprays a single layer of resin onto a build platform, ultra violet light cures the layer before the print head sprays the next layer.[3]

5.1.3 Selective binding

Selective binding technologies make the 3D printed object out of a powder. The powder can be a variety of different materials and the object is created by either a heat source fusing the granulates together, or an adhesive that makes the granulates stick together. An example is a selective laser sintering (SLS) 3D printer. The SLS printer uses a laser to fuse the powder together. It fuses the first layer to the build platform before a thin layer of powder is added on top of the old one. One of the advantages is that the powder will act as its own support. Therefore, the model does not need extra support material and the excess powder is easy to remove and can be used again. There is also some printers that use different types of powder adhesion instead of fusing the granulates together. The adhesives used may be wax, nylon or different types of metal.[3, 21]

5.1.4 Lamination

This category of 3D printers use lamination to build the object. Layers are made by thin adhesive covered sheets of paper or plastic. The sheets are cut by a blade or a laser in the desired form. The build platform moves down before a new layer is cut over the previous one. This technology is relatively cheap because of the raw material which I usually paper. Figure 5.1 on the next page shows the visible layers of the lamination process. Objects created with paper will have a wood-like character, this makes it possible to work on the model after completion.
and make modifications or a better finish by hand. The downside is the lack of different material options and the dimensional accuracies is not as good as other technologies. This makes it nearly impossible to make intricate and detailed models with this technology. For example the inside structures of a heart will be impossible to make with this type of technology, and will therefore not be considered a viable option for the rest of this thesis.

5.2 Standardization

All of todays 3D printers fall under one of the four categories mentioned in the previous section. Unfortunately, in a world with patents and trademarked technology labels, it may not be that easy to understand which category it falls under. Individual manufacturers use their own terms and acronyms to refer to what are effectively the same 3D printing process. This situation is much like it was in the early days of personal computing. An example is with regular printers, some manufacturers marketed their proprietary "bubble-jet" printers as a distinct
alternative to the "inkjet" printers, even though they where based on an almost identical technology. In personal computing, standard terms emerged after some time and the manufacturers adopted these terms. This has yet to happen in the 3D printing industry, and manufacturers are still using different names for the same processes.[3]

To deal with this disorganization around the different terms and names, the International Organization for Standardization (ISO) and American Society for Testing and Materials (ASTM), have worked for the past years to develop various standards within the 3D printing industry. The latest of these standards where introduced in December 2015 and is called the ISO/ASTM 52900[3]. In that publication, they defined seven additive manufacturing process categories which expand on the four more generic categories introduced in the previous section. The seven standard 3D printing technologies are listed below.[3]

1. **Material extrusion**: a nozzle extrudes a semi-liquid material to build up successive object layers.

2. **Vat Photopolymerization**: a laser or other light source solidifies successive object layers on the surface or base of a vat of liquid photopolymer.

3. **Material jetting**: a print head selectively deposits droplets of a liquid build material that is cured or fused solid using a UV light or heat, or which solidifies on contact.

4. **Binder jetting**: a print head selectively sprays a binder onto successive layers of powder.

5. **Powder bed fusion**: a laser or other heat source selectively fuses successive layers of powder.

6. **Direct energy depositing**: a laser or other heat source fuses a powdered build material as it is being deposited.

7. **Sheet lamination**: sheets of paper, plastic or metal are stuck together.

Hopefully more and more manufacturers will follow the standardization and market their 3D printer under the ISO/ASTM 52900 categories. The standardization will be adopted later in this chapter with a technology review based on each of the seven categories. It will go through the theory and process behind each techno-
logy, except sheet lamination because this has already been identified as not suited for organ model printing. A comprehensive review will result in a wider understanding of each category and the theory will help uncover limitations within the categories. When reviewing each category with emphasis on printing patient specific heart models, some of the theoretical or mechanical limitations may exclude some of the 3D printers.

5.3 Material extrusion

Material extrusion is the most common 3D printer technology when it comes to units sold and used. This is the process where a semi-liquid filament is added layer by layer by a computer controlled nozzle. Material extrusion is a relatively simple concept and the actual printers can be built with cheap hardware. It is a commonly used technology within desktop and hobby printers because of its inexpensive hardware and material. There is a wide variety of different materials that can be extruded, including concrete, ceramics and metal. However, the most widely used material is thermoplastic.

Material extrusion of thermoplastic was invented by Stratasys, they labeled the technology fused deposit modeling (FDM). FDM has become the most common acronym to use when referring to material extrusion even though Stratasys have trademarked the name. As mentioned in the previous section, these types of trademarks forces other manufacturers to come up with other names for their printers that ultimately is based on the same principles. 3D systems for example, labels their thermoplastic extrusion printers "plastic jet printers" (PJP). Other names for the same process is "Melted and extruded material" (MEM), "Fused filament modeling" (FFM) or "Fused filament fabrication" (FFF).[3]

Figure 5.2 on the following page illustrates a material extrusion 3D printer. A spool with filament feeds the nozzle through a tube. The nozzle is usually heated to somewhere between 180°C and 250°C depending on the type of filament material. The first layer will be extruded onto the build platform where it rapidly cools down and solidifies. The printhead moves in the 2D plane parallel to the build plate and traces out the first layer of the object based on the sliced STL file. To easier understand the movement of a material extrusion printer, we can say that
Figure 5.2: Material extrusion 3D printing[29]
5.3. MATERIAL EXTRUSION

the height of the object is along the Z-axis, while the width and depth of the object is along the X-axis and Y-axis. In some systems, the printhead moves in both the x and y direction while the build platform only moves in the Z-directions. In these systems, after the first layer is extruded, the printhead moves to the start position of the new layer while the build platform lowers itself slightly to make room for the new layer. Alternatively, some printers only move the printhead along the X-axis while the build platform moves in both the Y and Z direction.[3, 29]

Once the first layer is deposited the build platform is lowered slightly and the printhead starts to extrude the new layer on top of the first layer. This process is repeated for each layer until all of the object layers are printed. Depending on the complexity and size of the object, this process can take many hours to complete. The figure 5.2 on the preceding page only shows one print head or nozzle. Using one print head is common on older models, but newer printers actually have multiple printheads. The extra printhead can either be used to output a second type of material or color, as well as it can be used to output a material specialized for support structures.

Support structures can either be constructed with the build material itself or with a specialized support material. When using the build material, the support structure is usually constructed in a checkerboard pattern with very thin walls. This makes it possible to remove the material with your hands or with a sharp object like a knife or a flat iron screwdriver. Removing this type of support structures within deep cavities and intricate geometry may be impossible without breaking parts of the actual object. To deal with this issue, manufacturers have developed systems with multiple printheads and specialized support material. Ultimaker is one of the most popular printers within the desktop printer market. They recently came out with the Ultimaker 3 which have two print heads and a specialized support material called PVA. Ultimaker PVA is a water soluble material for multi-extrusion 3D printing. With a good thermal stability, Ultimaker PVA is ideal for printing complex models that require supports for large overhangs, deep internal cavities, and intricate geometries.[38]

As mentioned earlier, material extrusion based printers are widely available due to it’s relatively low price. Entry level printers can be bought for around 200$, these are self assembly kits which requires expertise from the costumer to assemble and run. Fully assembled, "plug and play" printers are available for around
5000$. Printers in this price range is usually desktop sized printers, targeted for the consumer market. Low-end professional printers cost between 5000$ and 20 000$, while mid-range printers could vary between 20 000$ and 200 000$. Top-range printers targeting professional factory use and development can exceed 500 000$. There are many differences between the high end printers and the consumer desktop printer, but the main differences is the build volume, accuracy and material selection available.

Build volume is the size of the build plate and height of the build area. The build volume determines the size of the object you want to print and an object can not exceed the build volume parameters. Desktop consumer printers typically start at 100x100x100 mm and up to around 200x200x200 mm. Professional industry targeted printers can have a build volume 5 times the size of a normal desktop printer. The Fortus 900mc by Stratasys for example have a build volume of 900x600x900 mm and is targeted for large scale prototyping and part production for factories. As well as making larger parts, printers of this size is capable of making multiple smaller parts in the same print, thus reducing the print time per part drastically.

5.3.1 Material extrusion considerations

Material extrusion printers are able to create a wide variety of objects in a very simple way. As with other technology, material extrusion printers have some limitations that needs consideration. First of all, when comparing it to other printing technology, there is a significant possibility for stair-stepping. Stair-stepping will impact the overall surface finish, accuracy and resolution of the part. The stepping degree is a result of the layer thickness, smaller layers result in less stair-stepping. Today, the best industrial printers are able to print thin layers between 0,12-0,15 mm, while conventional desktop printer usually operate on a layer thickness around 0,2-0,3 mm. Even though you are able to control the layer thickness, thinner layers may not result in better quality. The accuracy of the final part is limited to material nozzle thickness. If you have a 0,4 mm nozzle and sets the layer thickness to 0.1 mm, the nozzle will still extrude 0,4 mm of material. This means that the leftover material will be pushed to the side and impact the overall accuracy and quality of the part.
Another consideration is the possibility for warping, curling or shrinking during printing. This may occur if different parts of the object cools at different times. To prevent this, low-end printers usually have a heated build plate so that the lower layers holds the same temperature as the top layers. Industrial machines tackles this problem by completely enclosing the build area. This way the temperature can be the same in the whole build area, enclosed build areas also eliminates the impact from outside drafts and temperatures.[3]

Support structures also require some consideration. As mentioned earlier in both this section and the previous chapter, use of support structure can reduce the surface finish quality and increase the total print time, as well as the post processing time. Traditional material extrusion systems with one print head uses the build material to create support structures. It can be challenging to remove support from simple parts and impossible to remove all the support from intricate objects with cavities. A heart for example could not be printed with regular support structures. These types of intricate objects is dependent on a soluble support material that is easy to remove. Simpler models within the medical field like bones and jaws should on the other hand not be a problem to print using traditional one nozzle printers.

### 5.3.2 Build materials

A wide range of material can be used in a material extrusion printer. Acrylonitrile butadiene styrene, also known as ABS is the most common. ABS is a petroleum based thermoplastic with versatile mechanical properties. A variety of modifications can be done to alter the impact resistance, thoughness, and heat resistance. The mechanical properties can be changed by tweaking the ratio between the different compounds. ABS can come in a wide variety of colors and is a relative cheap material to use. This is why ABS is ideal for iteratively prototyping where you can prototype often and test thoroughly. When it comes to build materials, manufacturers usually offer their own variant of material labeled a special name. It can therefor be challenging to decide what type of build material that suits your need.

There is a wide range of build materials which does not consist of the same compounds as the ABS thermoplastic. For example, one of the downsides with ABS is
that it is UV sensitive, this means that the plastic degrades faster when exposed to sunlight and other UV lights. Using a different type of polyamid called ASA will solve this issue. Other build materials are nylon, polycarbonates (PC), co-polyester (CPE) and TPE/TPU. Each build material has its own unique properties like color, translucency, weight to strength ratio and flexibility, to mention a few. Ultimately, it comes down to how the printed part is going to be used. This will decide what type of build material suits the part criteria.[3, 13]

5.4 Vat photopolymerization

Vat polymerization uses a vat/tank of liquid photopolymer resin to construct the object layer by layer. A photopolymer is a polymer that changes its properties when exposed to light. In the 3D printing world, photopolymer based build material could be referred to as a light-activated resin or just a resin. When exposed to a light source, photopolymers goes through structural changes which often is hardening of the material. Curing is the term that refers to this toughening or hardening of a polymer material. Curing is a result of cross-linking between polymer chains where the chains link together on a chemical level to alter the physical properties of the material. 3D printers with this technology utilize this process to create layers out of liquid resin. The fact that the layers are created with a chemical reaction on a molecular level, leads to far greater surface quality compared to material extrusion printers. The most common Photopolymerization printers are stereolithography (SLA) and digital light processing projection (DLP). They are based on the same curing principles but can be differentiated by the light source used to cure the resin.

5.4.1 Stereolithography

As mentioned in the introduction chapter, SLA was the first commercially available 3D printing process. SLA uses a computer-controlled laser beam to selectively cure layers to build a 3D object within a tank of liquid photopolymer. Chuck Hull, the inventor of SLA, described the method as creating 3D objects by successively “printing” thin layers of a material curable by ultraviolet light, starting from the bottom layer to the top layer. As with material extrusion based printers, there
is also different types of variations between SLA based 3D printers. The main physical differentiations lies in the arrangement of the core components, such as the light source, resin tank and build platform. Some printers are built so that the object gradually gets submerged into the resin, while others gradually lift the build platform and object out of the resin.

Figure 5.3 shows how the right-side up SLA process works. The build platform would initially start at the surface of the resin. UV light from the laser will be directed to outline the shapes of the first layer and cure the resin at the specified points. At this point the first layer will stick to the build platform. After the first layer is complete, the build platform gradually descends a distance equal to the layer height into the liquid resin. New resin will either naturally flow over the cured layer or a resin filled blade will sweep over the surface and add fresh material. Like a material extrusion printer, this also creates the object layer by layer and repeats the same process until the object is finished. Finally, the build plate is raised to the surface where the object can be detached from the platform.[36, 3]

This approach is mainly used in larger industrial targeted SLA printers. Printers using this approach usually offer some of the largest build volumes in the market.
During printing, the object is exposed to minimal force from the process itself which in turn gives you high details, accuracy, and less failed prints. There are some considerations with this approach, first of all the build volume needs to be entirely filled with resin. This results in longer maintenance time due to the time-consuming task of handling, maintaining, filter, and swap materials. Because the sweeper runs right over the object, it is crucial that the machine is level, any inconsistencies may result in the sweeper hitting the model and cause the print to fail.[36, 3]

Figure 5.4 shows how the upside-down approach works. This process may also be referred to as “inverted” SLA because it’s turned up side down compared to the traditional right-side up approach. Instead of submerging the build plate and object in a large volume of resin, the build platform will pull the object out of the resin. This process requires the resin tray/tank to be transparent and have a non-stick coating such as silicon in at the bottom. The process starts by lowering the build plate down to the surface of the resin. As with the right-side up process, layer thickness determines how far the build platform is lowered. Because of the non-stick surface in the tank, the build platform is lowered so that the distance between the bottom of the tank and the build platform equals the determined layer height. The bottom of the tank acts as a substrate for the liquid resin to
cure against. UV light from a laser beam gets directed by series of mirrors placed underneath the tank and outlines the first layer based on the coordinates from the STL file. Resin will be cured to the build plate and against the bottom of the tank before a combination of vertical platform and horizontal tank movement separates the layer from the bottom of the tank. To add fresh material, the build platform is raised out of the resin to let new resin enter the tank. Some systems also use a wiper that passes across the tank to circulate the resin and remove semi-cured resin while the platform is up. The build platform is then lowered into the resin again and the process will be repeated until all the layers is printed and the object is finished.[36, 3]

Unlike the right-side up approach, this approach only needs a small amount of resin at a time to be able to print the object layers. This makes it easier to maintain, handle and change the resin from print to print. Lower material needs also enables manufacturers to make significantly smaller SLA printers, that’s why all desktop SLA printers use this approach. On the downside, the fact that the layers needs to be separated with force from the bottom of the tank may impact the result of the print. This separating force also requires the use of more support structures to keep the part attached to the build platform. Because support structures are made by the same material as the rest of the object, it limits the use of flexible materials. If the support structures are to flexible, it would result in an unstable connection between the object and the build platform.

Both the right-side up and inverted approach depend upon the use of support structures for most parts. As mentioned, the support structures are made out of the same material as the actual object. In right-side up SLA, support is used to keep the object in place and ensures that all details have something to attach to. In inverted SLA, support is used the same way as in right-side up SLA. The difference is how much support structure is needed to ensure a safe and secure attachment to the build platform. Unlike right-side up SLA, inverted SLA needs to consider the gravitational force on the object, as well as the force on the object during the detachment from the bottom tank. Figure 5.5 on the following page shows the support structure for both approaches. As you can see, the support structures are made out of a set of thin toothpick like structures. After printing the support can be removed either by hand or with sharp tools. The figure also illustrates the difference in how much support structure the different approaches
5.4. VAT PHOTOPOLYMERIZATION

After the object is finished printing it is usually washed with a solvent before it gets rinsed in fresh water. Some object also need some post processing in an UV oven. This is determined by the material used to build the object and the UV oven cures the material that did not cure properly during the print. Large industrial SLA printers based on the traditional approach are still quite expensive. Some of the best printers out there have a build area around 1500x750x550 mm and cost around one million dollars. Desktop printers on the other hand is available from around 4000$.

5.4.2 DLP projection

Another process which utilize photopolymerization is the use of digital light processing to cure the layers. Both SLA and DLP follow the same principles, but the different light sources can produce significantly varying outputs. DLP works similarly to SLA in the way that both use a light source to cure a liquid resin, they also use the same type of tank and build platform to generate the object layer by layer.
The big difference between the two is that instead of using an UV laser to cure sections of a layer at a time, DLP uses a digital projector to flash a single image of each layer across the entire platform at once. Flashing the whole layer at a time means that the layers will cure faster than with an UV laser.

Because the projector is a digital screen, the images projected to the bottom of the tank will be made out of square pixels. This means that each layer is created by small rectangular bricks that usually is called voxels. The surface finish and accuracy of objects created with DLP is defined by the projector resolution, how many pixels the projector uses to create the image correlates to how many voxels each layer is made out off. Most DLP pictures today can achieve a high level of accuracy and the layer thickness can be down to about 0.0025mm. One of the considerations with DLP is that the build volume is restricted by the projector resolution. When printing objects close to the build volume size, this means that you will get large voxels and a coarse finish compared to SLA. If you want to build small detailed parts, it is possible to shrink the image which result in more pixels/voxels on each layer. The downside is that this will also shrink the size of the build area, therefore DLP is not suited to print many small detailed parts at a time compared to SLA.

5.4.3 CLIP

CLIP stands for "continuous liquid interface production" and as the name implies, this process is able to print the whole object without raising and lowering the build platform between each layer. CLIP is developed by Carbon3D and their first printer, the M1, hit the market in April 2016. The process works similarly as inverted SLA and DLP projecting, but places a "dead zone" of uncured resin between the object and the bottom of the tank. A continuous sequence of UV images, generated by a digital light projector, is sent through the oxygen-permeable window below the liquid resin bath. Oxygen passes through the window and creates the one third of a human hair thin dead zone layer. In the dead zone, oxygen prohibits the light of curing the resin situated closest to the bottom of the tank. This allows fresh resin to flow into the dead zone and beneath the printed object in a continuous stream. Just above the dead zone, the UV light from the projector causes a partial curing of the part. This allows the build platform to continuously draw
the part out of the resin. After the print is done, the part will go through a second stage of thermal curing, either in an oven or in a thermal bath. The second curing stage is programmable and is used to achieve the desired mechanical properties of the part. [23, 3]

Because the build platform is able to continuously move out of the resin, the CLIP technology is able to create objects 20 to 100 times faster than other 3D printing processes. Reduced time usually equals lesser quality, but objects created with this process have a superior surface finish, better accuracy, higher material strength and due to the continuous motion and partly cured resin, there are no visible layers. Carbon 3D offers a wide variety of different materials, from consumer product elastomer’s to high-temperature automotive materials. Today, you are not able to buy the M1 or M2, they are only available for leasing. The newest M2 cost 50 000$ a year, while the M1 cost around 22 000$ a year. You can also rent a specialized washer for around 10 000$ a year.

5.4.4 Photopolymerization considerations

First of all, whether or not the object is created using SLA, DLP or CLIP, they require a considerable amount of post processing compared to other 3D printing processes. Models printed out of a resin are always sticky with leftover resin and needs to be washed in a bath of isopropyl alcohol. There is also usually need for a second curing process to solidify the object completely and alter the mechanical properties of the object. Removing support structures is also done during the post processing. Removing the toothpick like support structures are relatively easy to do when it supports outer structures. Removing support from inner structures can be quite hard and result in long and tedious manual work. Removing support from the inside of a printed heart model may be impossible due to the narrow and intricate features inside the heart. Inside the heart there is also real structure that looks similarly to the support structures and it may be impossible to distinguish the support and real structure. Because the support structures need to be created with the build material, you are not able to create water soluble support structures. This means that it would be impossible to print a full closed heart and you would have to print open sections of the heart and glue them together.
5.4.5 Build materials

The fact that the build material is made out of a liquid resin, empowers photopolymerization 3D printing to create a wide range of functional parts for different industries. Resins consist of monomers and oligomers which is the carbon chains that will make up the solid parts. It also consists of photoinitiator molecules that react when exposed to UV light and additives such as pigments or dyes to alter the visual appearance. The composition of these core components alter the mechanical properties of the resin. This enables manufacturers to create a wide range of different materials with properties like hard/flexible, color/transparent as well as properties like heat resistance. Standard resin from manufacturers cost from 160$ for 1 liter, there is also some third party sites that creates their own resin which is compatible with a wide range of SLA and DLP printers. At makerjuice for example, standard resin for Formlabs printers cost 65$ for 1 liter. In comparison, material extrusion materials cost around 40$ per kilo from the manufacturers. This means that it in some cases could be three times more expensive to print on SLA or DLP compared to a material extrusion printer.

5.5 Material jetting

Material jetting is based on the same principles as a standard inkjet printer and is based on the solidification of a liquid material, like SLA and DLP. Standard inkjet printers use a print head to spray liquid ink on to a sheet of paper to create text and images. Material jetting works similarly, but instead of printing one layer, it will print multiple layers on top of each other to create the full object. Most material jetting printers use a multi nozzle print head to spray liquid polymer, and support material on to a build platform. Attached to the same print head is a UV light which instantly cures the deposited material. The print head is usually moved in the x and y direction while the entire build platform is moved in the z direction. When the first layer is created, the build platform moves down one layer thickness before the print head starts to deposit the new layer. Unlike most 3D printing technologies that deposit, cure or sinter build material through point-wise deposition technologies, material jetting operations deposit build material in a rapid, line wise fashion. This enables you to create multiple objects during the
same print with no effect on the print time. A heart for example could be printed with significantly less time if you split the model and print the parts besides each other.[3, 40]

Material jetting printers are relatively expensive and is mostly used by professional users. Stratasys and 3D systems are the most common manufacturers within material jetting. Stratasys have trademarked their material jetting technology "PolyJet" (Short fort photopolymer jetting), while 3D systems have labeled the technology "MultiJet printing" or "MJP". At the low end these types of printers start at 50 000$. While at the other end, some of the printers from Stratasys and 3D systems cost from 200 000$ to 300 000$. The main difference between the printers are the same as with other print technologies, and that is the size of the build area. Larger build area will always be more expensive compared to desktop or smaller printers. Other features that differentiate material jetting printers is the ability to print multiple colors or materials during the same print. This is one of the biggest difference between material jetting technology and other print technology. With high end printers like Stratasys J750, you are able to print up to six different materials at the same time. Choosing between combinations of rigid, flexible, transparent or opaque materials and their composites to create a single multi color/material model.

Material jetting is one of the most accurate 3D printing technologies and produces high detailed parts with a very smooth surface finish. This is due to the fact that the layers are cured throughout the printing process which result in a near homogeneous part. Material jetting printers are also able to create thinner layers then for example DLP or SLA printers. This ensures an accurate representation of intricate and complex object features. Another major advantage of material jetting is the fact that you are able to print two different materials at the same time. This means that you are able to print the support material in a different material then the actual object. Support material is usually made out of a dissolvable material which makes it relatively easy to remove after printing. Compared to support structures made out of the original build material, solvable support will usually result in a surface that shows no indication of support at all. While support structures that requires force to remove from the object may damage the surface finish. Removing support is also the only post processing step that is needed before the part is finished, unlike SLA and DLP there is no need to cure the object a second
Material jetting printers can fully cure the object because there is no extra resin to drain out like in SLA and DLP [3, 40].

5.5.1 Material jetting considerations

First of all, the cost of buying and operating could be an issue with this technology. As mentioned, the printers themselves are quite expensive to acquire. The cost is also driven up by the fact that the build material is considerably more expensive compared to other technologies. Unlike FDM or SLA that print support as a low volume, material jetting prints support as a solid mass, filling the whole model, resulting in a large amount of waste. Solvable support material could also be challenging to remove if you for example print a whole heart. You would need to have some type of system that could circulate water or solvent through the heart. Support could also be removed with a pressure washer, but you would risk the possibility of tearing or destroying features in the object that should be there. In a heart, for example, there is a possibility of tearing the outer and inner walls if they are too thin. 3D systems printer use a wax-like support material which melts when put in a heated oven. Support would then be removed by tilting the heart and draining out the wax material. This could prove to be a more gentle and suited support material for heart model printing.

Material jetted objects are like SLA and DLP printed objects, not as strong as other technologies. This is due to the brittle nature of acrylic resin and this can be an issue when it comes to physical testing. Because the build resin is light sensitive, you will also experience some deterioration due to exposure to light, temperature and air. The lack of temperature resistance and strength in the parts as well as low durability means that the ability for them to be used in functional testing, or real-world applications, is limited. Creating spare parts for hospital equipment for example could be challenging due to the low part strength. Patient-specific organ models would, on the other hand, not be that dependent on the strength and durability of the object.
5.5.2 Build materials

One of the biggest advantages of printing with the material jetting process, is the multiple material print capabilities. Because the print head can output up to six different materials during the same print, you are able to create not only multi color materials, but also objects with both rigid and soft materials. Material jetting materials come in all colors, opaque and transparent, as well as flexible and rigid. There is also some materials that are made to handle temperature better and some ABS-like materials for better strength. Another advantage is that some printers are able to blend different materials together to form new material properties. For example a soft rubber like material, and a hard rigid material, can be blended to form a variety of different hardness levels of rubber. As mentioned earlier, resin for material jetting printers are almost 4 times more expensive then build material for other technologies. Material jetting printers also use more material due to the large amount of support material used. On the other hand, material jetting is by far the technology that offers the widest selection within materials and material combinations.

5.6 Binder jetting

Until now we have been through 3D printing technologies that solidify liquid and melts plastic to create the object. The last two categories within 3D printing are all based on sticking together powdered build materials and the first we are going through is binder jetting. A layer of powder is placed in the build platform. These build platforms are usually referred to as powder beds within these technologies. When the first layer is deposited a roller or blade sweep over the powder bed to ensure an even layer and build surface. When the powder is even, an inkjet printhead will selectively spray a binder solution on to the powder in the shape of the first object layer. The powder bed are then moved one layer height down before the roller sweep over with a new layer of powder. Figure 5.6 on the next page shows how this process works, new powder are stored in a reservoir beneath the roller and is raised when a fresh layer is needed. The roller will then push the new powder in to the build area or powder bed. This process is repeated until the object is created. The powder bed will always be filled to the top with new powder,
this means that the excess powder which is not bound together will function as support for the rest of the object.[3]

When the object is completed it will be encased in a block of loose powder that can be removed by hand. Remaining powder is usually removed in a depowdering chamber by using compressed air to blow away the remaining powder. Excess powder will be recycled and used in the next print, this reduces the material cost of each print as well as being more environmentally friendly than other processes where support structures generates waste. In theory loose powder should also be easier to remove from the object compared to support structures from other technologies. 3D systems is one of the biggest manufacturers within binder printing and their Projet CJP series cost from around 30 000$ to 114 000$. They use a multi nozzle inkjet printhead to spray on the binder solution. This means that it is possible to use binders with different color and in that way create objects with a range of different colors in the same print.

Binder jetting offers a number of advantages over other printing technologies. First of all, there is no need for additional support structures because overhangs are supported by the loose powder surrounding the object during printing. Secondly, binder jetting is fast when it comes to print time compared to other technologies,
it also offers good accuracy and are able to print relatively thin layers. Thirdly, the cost of build materials is generally lower and there is a limited amount of energy needed to run the printer. The price per object will also be lower than with other technologies. This is related to the fact that the build material used to support the object can be recycled and used again. Finally, binder jetting printers are able to print with almost every material in powder form and is also able to print full color parts.

5.6.1 Binder jetting considerations

Parts made with binder jetting printers are basically particles glued together, this results in fragile parts with limited mechanical properties. This also limits the process to create flexible materials and binder jetting materials are usually quite rigid. When it comes to printing a heart model, the full color ability could be used to create a full heart, with different parts of the heart assigned individual colors. This could be used for educational use but you would not be able to create a flexible, hollow heart with this technology.

5.6.2 Build materials

The CJP line from 3D systems uses a proprietary gypsum based powder called VisiJet PXL. This material is so brittle that most of the objects need to undergo a post processing procedure where a chemical is sprayed or otherwise coated on the object to fill in microscopic air pockets and seal the surface. VisiJet cost around 60$ per kilo to buy and as mentioned the process uses less material then other technologies. There are also some printers that offers a powder with plastic like characteristics.[3]

5.7 Powder bed fusion

Powder bed fusion is another technology which utilize a build material in powder form. Binder jetting have it’s limitations when it comes to strength and mechanical properties of the finished objects. In applications where part strength is crucial you often turn to the powder fusion print process. This process is very similar to
5.7. POWDER BED FUSION

binder jetting, but uses a heat source to melt and bond adjacent powder granules.

Laser sintering or selective laser sintering (SLS) is the most common and widespread process within this category. Like in binder jetting, a layer of powder is rolled or swept over the powder bed. Then a laser traces out the first layer of the object. The heat from the laser causes the granulates to partially or fully melt and fuse together with adjacent granulates. This melting or fusing process is usually referred to as sintering. After the first layer the powder bed is lowered one layer down while a new layer of powder is rolled over. The process is repeated until the whole object is complete. Post processing is very much like binder jetting, after printing the part will be encased in a block of loose powder that needs to be removed. Unsintered powder can be recycled and used in the next print like the binder jetting process.

SLS is an ideal solution for producing functional products with complex geometries. The technology has very few design constraints when compared to other 3D printing technologies. This is mostly because the object gets encased in their own build material which means that the orientation and placement of the object gets irrelevant when it comes to support. SLS is capable of creating prototypes, tooling or final parts with a wide variety of engineer grade materials. Build powder can be made out of polyamide plastics, metal, ceramics, sand or wax. To ensure consistent and accurate object layers, the powder needs to be graded at a high quality. For plastic build materials this means that the granulates should have a diameter between 40 and 90 microns. If the building material is of a high standard, SLS can produce highly accurate and complex objects. It is also able to create layers at around 0.1 mm ± 0.02mm which ensures a smooth surface without too much stair stepping.[3, 40]

There is a wide range of manufacturers with SLS printer. As with other technologies, the build size is what's the biggest difference between the cheap and expensive printers. Today the average build volume is around 300 mm x 300 mm x 300 mm with the bigger machines offering a build volume of 700 mm x 380 mm x 580 mm. SLS printers usually range from 200 000$ to 300 000$, while the cheaper printers starts at 100 000$. Even though the entry price of the machine is pretty steep, SLS is as mentioned one of the most cost effective and cost per part is almost always lower then other technologies.
5.7.1 Powder bed fusion considerations

First of all the price of buying a printer might be an issue due to the high cost. Even though SLS is able to produce a consistent surface finish due to the thin layers at around 0.1 mm. SLA and material jetting printed objects usually have a much smoother and shiny surface finish compared to SLS printed object. Because the object is made out of granulates the surface appearance is a satin-like matte finish that is slightly grainy to the touch. Due to the matte finish, objects are usually not transparent and there is not materials available with transparent properties.

5.7.2 Build materials

SLS is able to print a wide range of different plastic materials. There is both a carbon filled and glass filled polyamide which enhance the stiffness and strength of the object. PEBA (TPA) is a rubber like, strong and flexible material which is available for SLS printers. As mentioned SLS is superior to other technologies when it comes to producing parts with high mechanical properties. This is mostly due to the fact that the granulates is fused together, but the fact that you are able to combine plastic granulates with other materials like aluminum, carbon and glass ensures good mechanical properties. Transparent materials are not available for SLS printers which could be a problem when it comes to printing a heart model. SLS is also not able to print multiple colors, and most of the build materials are white. Where color is needed, the objects are usually dyed as a part of the post processing.

5.8 Future technology

5.8.1 HP Multi Jet Fusion

In 2016 well known inkjet printer company HP unveiled their own 3D printing solution, the HP Jet Fusion 4200 and HP Jet Fusion 3200. The multi jet fusion technology is a crossover between different technologies and HP promises that the multi jet fusion will result in higher productivity, lower cost per part, and more reliable quality for each part. HP’s new technology is powdered based but instead
of using a laser to sinter the powder together, HP uses a fusing agent. The fusing agent is jetted where particles need to be selectively molten, and a detailing agent is jetted around the contours to improve part resolution. While lamps pass over the surface of the powder bed, the jetted material captures the heat and helps distribute it evenly. As with all other 3D printers, the model is built layer by layer until completed and the extra powder is used as support like in SLS and binder jetting.

Material science and development represents a strong backbone for every 3D printing technology. Today, most 3D printers are only able to use material from the same manufacturer. This limits the development and selection of different materials available for each 3D printer. Alongside the new multi jet fusion printers, HP has also introduced their own material development kit. HP aim to have an "open platform" when it comes to their printers and material manufacturers should be able to develop new material for the multi jet fusion printers."Open platform" in this case does not, of course, mean that you can throw any sort of powder into the MJF system and expect to have perfectly 3D printed parts. Rather, materials options include HP-branded powder (which they note provides optimal output quality) and HP-certified powder ("certified for safety and reliability of the HW"). To ensure that materials function correctly, their physical properties must be fully tested and vetted by HP's material certification lab. This open platform approach could result in more specialized materials, a wider range of different materials and cheaper material prices. Hopefully, more and more manufacturers will adopt this open platform approach which could take 3D printing to the next level.

5.8.2 Bioprinting

Bioprinters are still in an experimental phase and there is no commercial options available today. Bioprinting can be used to create real tissue or blood vessels in a desired form using actual cells. Bioprinters may be constructed in various configurations. However, all bioprinters output cells from a bioprint head that moves left and right, back and forth, and up and down, in order to place the cells exactly where required. Over a period of several hours, this permits an organic object to be built up in a great many very thin layers. In the future, bioprinters could be able
to reproduce full organs like a heart. The replacement organs would be created from a culture of a patient’s own cells, which would reduce the risk of transplant organ rejection. Bioprinting could be used to create new tissue for transplantation or other applications. Models with real tissue would be the ultimate model for both education purpose and in the diagnosis and pre planning process. This technology is as mentioned still in an experimental phase but bioprinting could completely change the modern medicine in the future.[3]
Part III

Methods
Chapter 6

Testing 3D printers

6.1 Technology overview

In this chapter we will go trough the process of choosing which technology is most suited for printing organ models. We will also go trough the test models that have been printed for this project. As mentioned in the previous chapter there is a wide variety of different technologies, manufacturers, materials and proprietary names. Table 6.1 on the facing page will go trough the key points within each technology and hopefully make it easier to decide what technologies is most suited for organ model printing. Below are some clarifications of the table content.

**Dimensional accuracy**  Quantitative values from machine manufacturers and material suppliers that state the expected accuracy of parts. All tolerances stated are with respect to well designed parts on well calibrated machines.[12]

**Print speed**  Is hard to quantify due to the wide differentiations between machine price and other factors. This will therefore be a relatively general estimation based on how the technology works.
### Table 6.1: 3D printer technology comparison

<table>
<thead>
<tr>
<th>Common abbreviations</th>
<th>Material extrusion</th>
<th>Vat Photopolymerization</th>
<th>Material jetting</th>
<th>Binder jetting</th>
<th>Powder bed fusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>FDM and FFF</td>
<td>SLA, DLP and CLIP</td>
<td>Polyjet and Multijet</td>
<td>Colorjet (CJP)</td>
<td>SLS</td>
<td></td>
</tr>
<tr>
<td>Machine price</td>
<td>1000$ - 400 000$</td>
<td>3000$ - 1 000 000$</td>
<td>50 000$ - 1 000 000$</td>
<td>50 000$ - 1 400 000$</td>
<td>20 000$ - 850 000$</td>
</tr>
<tr>
<td>Surface finish</td>
<td>Fair</td>
<td>Smooth</td>
<td>Smooth</td>
<td>Griny</td>
<td>Griny</td>
</tr>
<tr>
<td>Dimensional accuracy</td>
<td>±1 mm</td>
<td>0.05 - 0.15 mm</td>
<td>±0.2 mm</td>
<td>±0.3 mm</td>
<td>±0.3 mm</td>
</tr>
<tr>
<td>Layer thickness</td>
<td>0.17 - 0.33 mm</td>
<td>0.05 - 0.15 mm</td>
<td>0.016 - 0.028 mm</td>
<td>0.1 mm</td>
<td>0.060 - 0.150 mm</td>
</tr>
<tr>
<td>Print speed</td>
<td>Slow</td>
<td>Slow (CLIP extremely fast)</td>
<td>Fast</td>
<td>Fast</td>
<td></td>
</tr>
<tr>
<td>Materials</td>
<td>Rigid and flexible</td>
<td>Rigid and flexible</td>
<td>Rigid and flexible</td>
<td>Rigid and flexible</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Translucent</td>
<td>Translucent</td>
<td>Translucent</td>
<td>Multicolor prints</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Colors available</td>
<td>One color</td>
<td>Multicolor</td>
<td>Rigid</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Multimaterial</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Support</td>
<td>Either the same build material or a soluble material</td>
<td>Same as build material</td>
<td>Soluble material</td>
<td>Encased in build material</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strengths</td>
<td>Good strength, cheap materials,</td>
<td>Surface finish, high accuracy,</td>
<td>Surface finish, high accuracy,</td>
<td>Accuracy, good strength,</td>
<td>Accuracy, good strength,</td>
</tr>
<tr>
<td></td>
<td>Ideal for desktop printing, suited for prototyping</td>
<td>wide variety of materials,</td>
<td>speed, multicolor,</td>
<td>low operational costs,</td>
<td>low operational costs,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>simple process,</td>
<td>no need for extra support</td>
<td>simple process,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>no need for extra support</td>
<td></td>
<td>no need for extra support</td>
</tr>
<tr>
<td>Weaknesses</td>
<td>Speed, surface finish</td>
<td>Speed, post processing,</td>
<td>Weak parts, high material and printer cost,</td>
<td>Weak parts, surface finish, no flexible or transparent materials</td>
<td>Large printers, surface finish,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>messy liquids, weak parts,</td>
<td></td>
<td></td>
<td>high printer cost,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>single color and material,</td>
<td></td>
<td></td>
<td>no transparent material</td>
</tr>
</tbody>
</table>
6.2 Heart model characteristics

When preparing for real world surgeries or deciding on a diagnosis, it is crucial that the CT or MRI images give an accurate and clear impression of the region of interest. The same thing applies to a 3D printed heart model, the model has to be accurate and replicate the actual heart anatomy. After some discussion within the project group at the hospital, there have been identified some model properties that the surgeons and cardiologists are looking for in a patient specific model. Firstly, they have suggested that the model should be as real to the actual heart as possible. This means that the model ideally should be made out of a flexible material with arterial tissue properties. This will give the user a more tactile feedback when handling the model. A flexible material should make it able to both cut and slice the model with normal tools as well as making it possible to test valves or physical instruments. Secondly, it could be helpful if the model was in a translucent material. This could make it easier to see anatomical structures within the model without cutting and opening the model. Finally, they wanted the whole heart to be printed in one print. This could be challenging for some technologies because it may be impossible to remove those support structures in a closed heart model.

6.3 Evaluating current technology

An evaluation of current technology will be based upon the clinicians request. Flexibility, transparency, accuracy and ability to print the whole heart in a single print are the criteria the printer should be able to fulfill. In this section we will evaluate each technology and describe why it is suited or not suited to print organ models.

6.3.1 Material extrusion

Accuracy is the criteria which you can not compromise when it comes to printing a patient specific heart model. Surgeons and clinicians are dependent on accurate models to ensure correct diagnosis and treatment. It could be a matter of life or death if the model does not represent the anatomy of the heart in the right way.
6.3. EVALUATING CURRENT TECHNOLOGY

This is why material extrusion printers are not suited for printing these types of models. The surface finish is also poor and there is usually visible layers with stair stepping. Creating a complex and large model like a heart would also take a long time using a material extrusion printer compared to other technologies. When it comes to available materials, there are some flexible materials which is also translucent. Printing a model would also require the printer to have a multi nozzle print head which enables the printer to print a soluble support material. Traditional support structures would be impossible to remove from narrow and closed parts.

Material extrusion meets many of the criteria for printing a heart model. There are multiple materials that are both flexible and translucent and support can be removed easily if a soluble material is used. On the downside it falls trough on the most important criteria which is accuracy. The accuracy is related to the nozzle size and unfortunately this has reached it’s potential. Material extrusion printers usually use a 0.4 mm nozzle size, but there are some printers that can go down to 0.2 mm. Going down in nozzle size would grant better accuracy but the print time would drastically increase. Even though a material extrusion printer is not suited to print intricate and accuracy dependent models, it still could be relevant for other applications at the hospital. Printing smaller, less intricate organs could be done with a material extrusion printer. During the project at OUS, we got a set of jaws printed with a material extrusion printer. The model where used to size a metal rail before the surgery. These types of printers also produce strong enough parts to create spare parts or prototypes for new instruments.

6.3.2 Vat photopolymerization

Is one of the most accurate technologies available today and will without a doubt produce a sufficient anatomically correct model. The surface finish will also be close to a real heart because of the smooth transitions between each layer in the model. When it comes to materials there is a wide variety of materials, both flexible and translucent materials are available for most printers with this technology. The main issue with this technology is the fact that support structures need to be created with the same material as the build material. This will make it impossible to remove support from a closed heart. A possibility would be to divide the heart
into two and print it in two sessions. Printing only half of the heart could make it easier to remove some of the support, but support inside narrow and intricate parts of the heart could be impossible to remove. Another issue is the fact that inside the heart there is structures that looks very similar to the support structures and it could be challenging to differentiate support from these structures.

When it comes to other applications within a hospital environment, they are limited compared to material extrusion. Because of the brittle nature of the end product, it is not suited for creating spare parts or prototypes. On the other hand, it would be able to create bones or jaws if they are not put through to much stress during testing. This technology could also be used to print smaller parts of the heart or parts of the cardiovascular system. It could for example be possible to print only the veins of interest when a bypass operation is needed. Printing only the area where the stent is to be inserted would make it possible to remove support structures after printing and physically test the stent size. It could also be used to create vascular models in a rigid clear plastic material. These models can be used for flow analysis, catheter motion testing and training.

6.3.3 Material jetting

Material Jetting is by far the technology that meets most of the heart model criteria. Accuracy on the same level as SLA and DLP, able to print the thinnest layers, smooth surface finish and a wide variety of materials. Some of the high end printers are able to print both rigid and flexible material in the same print, as well as multiple colors in the same print. With the right systems, it should also be fairly easy to remove the support structures, even in closed heart models. Material jetting is also one of the fastest print processes. The only downside with this technology is the high hardware price as well as high operational costs. Other medical applications would be the same as with SLA and DLP printers. The brittle nature of photopolymerized materials makes it inadequate to print spare parts for tools or machines.
6.3.4 Binder jetting

Binder jetting would produce adequately accurate models. It should also, in theory, be relatively easy to remove the support material from the inside of a closed heart. On the negative side, there is no flexible or translucent materials. The strength of printed parts are also quite weak and brittle. The only application where this process could be used is if you want to print out the blood volume of the heart. With this process you could print the blood volume in a multicolor rigid model where the different arteries, vessels and parts of the heart could be assigned different colors. These types of models could be used in education, training and patient communication.

6.3.5 Powder bed fusion

SLS would, like binder jetting, produce adequately accurate models. Removing support material should also be easier compared to other technologies due to the fact that the support is loose powder. SLS will produce models with good tear resistance and could definitely produce spare parts as well as strong bone models. There is a variety of materials and you are able to get what seems like a semi flexible material in the TPU powder. The downside is that there is currently no translucent materials available and the surface finish will feel a little grainy compared to material jetting, SLA and DLP models. Compared to material jetting, SLA and DLP operational costs inflicted by SLS are way lower. The material is cheaper as well as SLS printed objects do not need as much post processing as other technologies. On the other hand, the cost of the hardware is on the same level as material jetting printers.

6.4 Test models

From the previous section we can see that the material jetting technology and powder bed fusion is the technologies that meets most of the heart model criteria. In cooperation with this thesis and the project at OUS, four different test models have been printed to evaluate the difference between manufacturers and material. The models will then be evaluated by surgeons and cardiologists to see what
printers produce the best result for the users. Material jetting meets every criteria from the users and that is why most of the printed test models are from this technology. Of the four models printed, three of them where printed with a material jetting printer while the last was printed with a SLS machine. The material jetted models were made by Canon (3D systems), IFI (Stratasys machine) and Materialise (Stratasys). The sintered model was also made by Materialise. There will be a thorough review of each model and characteristics with each.

6.4.1 Computer test model

To get past the probable issue regarding distribution of sensitive patient data, the computer model of the heart was created with data from a Miccai segmentation challenge.[24]

The MICCAI Society is an important forum for medical image computing, computer-assisted intervention, and medical robotics. The multidisciplinary nature of these emerging fields brings together clinicians, bioscientists, computer scientists, engineers, physicists, and other researchers who are contributing to, and need to keep abreast of, advances in the methodology and applications.[33]

The MR images from the challenge was segmented by Robin Bugge, a physician working in the project at OUS. He mainly used the Mimics package from Materialise to segment and create the stl file of the heart. The patient in the miccai challenge[24] was diagnosed with VSD as well as some structural problems that restricted blood flow. VSD is as mentioned earlier a defect where there is a hole in the septum dividing the ventricles. This diagnosis made it very suited to use in an evaluation because there would be a clear area of interest and an abnormal anatomical structure.

6.4.2 Materialise sintered model

Materialise is a 3D printing service company which specialize in prototyping and medical 3D printing. They have developed medical software as well as 3D printing for medical applications. The background for printing a sintered model was that it in theory, should be easy to remove the support after printing, as well as produce
6.4. TEST MODELS

a tear resistant, strong and flexible material. The model was printed in a material called TPU 92A-1 which is specified to be flexible and tear resistant. Materialise describe the material this way:

TPU 92A-1, a thermoplastic polyurethane, is a fully-functional flexible and strong material. TPU 92A-1 is the only 3D printing material that combines the qualities of durable elasticity, high tear and abrasion resistance, high resistance to dynamic loading, snappy response and a good thermal resistance (-20°C to 80°C).[37]

Unfortunately the material is not translucent but the evaluation from the surgeons and cardiologists will show how important it is for using the model in a pre planning process. Figure 6.1 on the next page shows the whole SLS printed heart model, the dotted lines show where it should be cut before the evaluations.

When ordering from 3D printing services you only need to send the STL file and wait for the finished model to arrive. The sintered model cost 810$ to print, post process and ship. One of the reasons to print with a SLS machine was that it should be easy to remove the support material. This turned out to not be as easy as expected and Materialise actually had to cut the heart in two to remove all the support material. After they had removed all the support they glued the parts back together and it did not effect the visual appearance of the model to much. Surface finish was as expected grainy and the material was quite rigid but the thinner layers constructing the veins was more flexible. Even though some parts where flexible, the flexibility was no way near real tissue. The material quality was also good and there was no signs of tears or deformations.

Key features and first impression:

- Printer: Printed on a SLS machine at Materialise
- Material: TPU 92A-1
- Price: 810$
- Not translucent
- Semi flexible some places
- Grainy texture
- No visual tears or deformations
Figure 6.1: SLS model from Materialise
6.4.3 Materialise Heartflex model

Two of the models where ordered from Materialise and the second one was created on a material jetting machine using a proprietary material labeled Heartflex. Materialise is as mentioned one of the leading 3D printer service within the medical industry. They have many years of experience with printing these types of models and they have also developed their own material. The Heartflex material was developed to mimic the human arterial tissue properties. According to Materialise, creating a model with this material will not only offer the correct geometry of the heart, but it also mimics the material behavior of the real anatomy. These features are needed for training, accurate modeling and validation of the robotic surgical skills.[2] Figure 6.2 on the following page shows the Heartflex model, you can clearly see that the material is more translucent then the SLS model.

Due to the use of a material jetting printer and the proprietary material the model cost a total of 1733$. That is over twice the cost of producing the same model on the SLS machine in the TPU material. On the other hand, this model clearly met all the criteria form the surgeons and clinicians. The material was as flexible as expected and translucent. A smooth surface finish makes it close to a real heart. The model was printed on a Stratasys Objet machine with a soluble support material. There where some minor tears in sections with thin walls and in the end of the veins. This was glued by Materialise before we received the model. These tears probably occurred during the post processing process where water or a solution where flushed trough the model to remove support structures. The small tears had minor impact on the visual appearance and the tear resistance of the model seemed good.

The downside with this model is that the material is proprietary and Materialise will not share details about the material composition or the printing and post processing process. This means that it will not be possible to buy the Heartflex material if the hospital establishes a on site 3D printing service. The motivation for printing this model was to see what's possible and compare the other models to this "prefect" model. The model is a good representation of the capabilities of current technology and it is important to have a model that shows the max capabilities during the evaluations.

Key features and first impression:
Figure 6.2: Heartflex model from Materialise
6.4. TEST MODELS

- Printer: Objet machine (Material jetting) at Materialise
- Material: Heartflex (proprietary material)
- Price: 1733$
- Translucent
- Flexible
- Smooth texture
- Small tears some places
- Represents the capabilities of current technology

6.4.4 3D systems model

The third model was printed on a 3D systems printer by Canon, one of 3D systems distributor in Norway. Canon printed the model as an example of what their printer could produce and this was done without charging the project at OUS. We have tried to get some more info about the cost and process but it has been hard to get in touch with the Canon representatives. The operational cost is estimated to be between 1000$ to 1300$ for a heart model at this size. Based on some material samples and the material compatibility for the material jetting printers, it is believed that the model was printed with the Projet MJP 5000 or newer successors to this printer series. VisiJet CE-NT is the name of the build material and promises to be both flexible and translucent. One of the advantages with 3D systems material jetting machines compared to Stratasys machines is that the support material is made out of wax. Removing a wax based support material only requires an oven on low heat to melt the wax and by tilting the model it should be possible to drain out the melted wax. This should be easier to remove compared to Stratasys soluble support which requires some pressure/flow system for the water or solution.

When it comes to the visual appearance, the surface finish was smooth as expected. Flexibility and translucency was on the other hand not as expected. The model felt like a lump of wax and when pressing on for example the veins, the geometry did not snap back to place but stayed at the position to some extent where it got pressed in. When it comes to translucency there was a yellow like
Figure 6.3: Canon model
color on the whole model. This may have been a result of support material not being removed properly or that the model may have been heated at too high temperature. There were no signs of tears or deformations when it arrived, but when subject to pressure, the features and model got somewhat deformed. Figure 6.3 on the preceding page shows the Canon model, you can clearly see the yellow color on the material.

Key features and first impression:

- Printer: Projet MJP 5000 or newer
- Material: VisiJet CE-NT
- Price: From 1000$ - 1300$
- Not translucent, yellow like color
- Less flexible then Heartflex but more then TPU
- Smooth texture
- No tears
- Waxy feel, easily deformed when touched

6.4.5 IFI model

The last model was printed by the ROBIN group at IFI. It was printed on a Connex 500 which is an older material jetting printer from Stratasys. TangoPlus was used as build material with Fullcure 705 as support material. TangoPlus cost around 4000 NOK which is about 475$ for a 1.44 kg cartridge. At IFI there is a pressure washer chamber to remove the support material. This limited us to only print half the heart because it would be impossible to remove the support structure from a closed heart without a circulatory system. Even when only half of the heart was printed it took many hours of tedious work to pressure wash away all the support structure. When using a pressure washer you are also exposed to tearing and deformation of thin walls and small features in the heart. In the recent years Stratasys have developed a new support material called fullcure 706 or SUP706. This can be seen as the new version of the 705 support and is even more soluble and not as hard to remove. Models printed with this support can be
soaked in warm water for some time, which softens up the solid SUP706 material. Then it’s a quick rinse to remove the softened SUP706 and the post processing is complete.

TangoPlus is both flexible and translucent, the downside is that the tear resistance is not as good as the other models. The surface finish is as expected smooth, there are some tears from the support removal and the tear resistance seems poor compared to the other models. Figure 6.4 shows the model printed at IFI, you can clearly see at the top of the model that there are some tears from the post processing or handling.

Key features and first impression:
6.5. COMPARING THE MODELS

Figure 6.5: From left to right: Canon, Heartflex, IFI and Materialise SLS

- Printer: Connex 500, printed at IFI
- Material: TangoPlus
- Price: 475$ for 1.44 kg cartridge
- Translucent, more "cloudy" than Heartflex
- Close to the same flexibility as Heartflex
- Smooth texture
- Some tears at the top of the model
- Poor tear resistance compared to the other models

6.5 Comparing the models

Figure 6.5 shows the different appearance of each model. From the image it is clear that the Canon and SLS model are the less translucent models. Translucency
6.5. COMPARING THE MODELS

in the model created at IFI is better than the Canon and SLS model, but from the
figure you can see that it is a little bit more cloudy than the Heartflex model.
With some post processing, the IFI model could have been more translucent so
it is absolutely possible to get close to the Heartflex model. When it comes to
flexibility the Heartflex is by far the best model. Close behind comes the IFI model
which is almost identical to the Heartflex model. Both the Canon and SLS model
are limited when it comes to the flexibility and is far from accurate if compared
to real arterial tissue.

When it comes to tear resistance, the SLS model is by far the best model as expec-
ted. The Canon and Heartflex was very similar, but as mentioned the Canon model
is very prone to deformations. If you press at the same point on both the Canon
and Heartflex model, the Heartflex will almost immediately snap back to place,
while the Canon model stays pressed in for some time and does not go back to its
original position. The IFI model was also as expected the worst when it comes to
the tear resistance, this may be due to the quite powerful post processing process
and the new support material SUP706 may solve this problem. Price is also an
important factor when comparing these models. Using SLS to print models will
be the cheapest alternative when it comes to the operational costs. Between 3D
systems and Stratasys operational costs there is not much difference, but it is clear
that it would be a lot cheaper in the long run to establish a 3D printer service on
site, rather than ordering from for example Materialise.

From a 3D printing perspective the Heartflex is the model that meets all the criteria
from the surgeons and clinicians. Close behind is the IFI printed model which has
good translucency, flexibility and price. On the negative side, this model is clearly
the weakest model and requires cautious handling. The Canon and SLS models
got the same insufficiencies, both are only semi flexible and thicker parts seems
rigid as well as not being translucent. Even though there is some differences
between the models there is no certainty that the initial requirements from the
surgeons and cardiologists are vital when they have the model in front of them.
It could for example turn out that most of the users would prefer a solid and tear
resistant model instead of a translucent model.
Chapter 7

Test models evaluation

This chapter describes the evaluation process where some clinicians evaluated each of the test models. It will go through some of the key points about the evaluation forms and how the evaluation was conducted.

7.1 Surgeon and cardiologists evaluation

Patient specific 3D printed organ models are first of all intended for cardiologists and surgeons to aid in setting a diagnosis and in the pre-planning process before a surgery. This is why it is important that the actual day to day users can be a part in deciding what models they think can be most valuable during diagnosing and pre planning. Both surgeons and cardiologists participated in the evaluation and we will later see if there where some difference between surgeons and cardiologists when it comes to preferred model. Evaluation was conducted with one on one interviews where the participants filled out an evaluation form for each of the models. The participants had the four models in front of them and evaluated each model on individual forms. A copy of the evaluation forms can be found in Appendix A. The evaluation will give valuable information about what features and properties are most relevant for the surgeons and cardiologists. They will in turn get a clear view of the possibilities and limitations with current 3D printing technology.
7.2 The evaluation forms

The main goal with the evaluation is to first of all figure out what material properties the users require and in turn evaluate how good each model meets these material features. Secondly, it is important to see what applications the models are suited for. If you could print a model that is good for both surgical planning, physical simulation and patient communication it would be ideal. The form used for each model consist of ten statements/questions where the participant answer on a numerical one to ten scale, where 1 is worst and 10 is the best. One question is for example to rate the flexibility of the model, if the flexibility is perfect for that specific user, they could rate it 10. The reason for using a numerical scale is to easier be able to compare the different models and make it easier for the participants to do the evaluation. The first ten questions can be divided into two parts, the first five is statements regarding material properties like flexibility, translucency and material quality. Questions about how suited the model is for specific applications make up the last five questions. Here, the participant is asked to rate how suitable the model is for sewing or valve testing for example. There is also a question with a set of applications where the participant ticks of each application they would use the model for. As well as a general feedback box and a box where they could write if there was some residue from support somewhere on the model.

After evaluating the different models the participants where asked to fill out a secondary form also found in Appendix A. This form is more on a general basis and the goal is to provide a better understanding of which features and material properties the users rates the most. In the form there is six questions regarding their view on patient specific organ models and some questions to cover other possibilities that was not printed. They answered with a scale ranging from «strongly disagree» to «strongly agree». The questions were about how important flexibility and translucency is for them as well as asking if multicolor or multi material models could be more helpful then the test models. They also had to choose whether or not they would like the whole heart to be printed or only a section of the area of interest in a real case. Lastly they where asked to range the four test models from best to worst.
7.3 Evaluation participants

The participants that helped out with the evaluations are all surgeons or cardiologists at Rikshospitalet. A total of seven participants, four cardiologists and three surgeons responded to the interview request. The interviews were all done at the intervention center at Rikshospitalet from March up until mid May 2017. The participants were generally positive to the models and the opportunities they create. The models were labeled and evaluated as follow:

1. SLS model
2. Canon model
3. IFI model
4. Heartflex
Part IV

Results and conclusion
Chapter 8

Results

8.1 Results from the evaluation

<table>
<thead>
<tr>
<th></th>
<th>SLS model(1)</th>
<th>Canon model(2)</th>
<th>IFI model(3)</th>
<th>Heartflex model(4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Handling the model</td>
<td>6.86</td>
<td>6.29</td>
<td>5.29</td>
<td>6.14</td>
</tr>
<tr>
<td>Thickness of the walls</td>
<td>5.14</td>
<td>6.29</td>
<td>7.0</td>
<td>8.14</td>
</tr>
<tr>
<td>Rate the flexibility of the model</td>
<td>2.57</td>
<td>6.14</td>
<td>6.57</td>
<td>8.71</td>
</tr>
<tr>
<td>Is the translucency adequate?</td>
<td>1.86</td>
<td>3.71</td>
<td>7.14</td>
<td>8.71</td>
</tr>
<tr>
<td>Quality of the material (tear resistance)</td>
<td>7.86</td>
<td>6.0</td>
<td>3.86</td>
<td>8.86</td>
</tr>
<tr>
<td>Suitable for valve testing?</td>
<td>1.86</td>
<td>5.0</td>
<td>4.57</td>
<td>7.0</td>
</tr>
<tr>
<td>Suitable for sewing?</td>
<td>2.29</td>
<td>5.71</td>
<td>6.14</td>
<td>7.71</td>
</tr>
<tr>
<td>Suitable for patient communication?</td>
<td>7.0</td>
<td>6.29</td>
<td>6.14</td>
<td>7.71</td>
</tr>
<tr>
<td>Ability to show the region of interest</td>
<td>4.86</td>
<td>6.71</td>
<td>7.00</td>
<td>8.14</td>
</tr>
<tr>
<td>Would the model aid in the pre planning process?</td>
<td>6.14</td>
<td>6.86</td>
<td>7.43</td>
<td>8.0</td>
</tr>
<tr>
<td>Average score overall</td>
<td>4.64</td>
<td>5.9</td>
<td>6.11</td>
<td>7.91</td>
</tr>
</tbody>
</table>

Table 8.1: Average rating between all participants for each model

From table 8.1 it is clear that the heartflex model scores the best on a majority of the questions. There is also a big gap between the heartflex model and the other models when it comes to the overall average score. The model created at IFI scores very similar on all the questions except the quality of the material and the valve testing question which reduce the overall score a bit. Only a few points behind the IFI model we have the Canon printed model. Like the IFI model it scores fairly even between each question, but scores very low on the translucency question. The SLS model got the lowest overall score, this is due to the low scores of flexibility and translucency as well as low score on valve testing and suitability.
for sewing. Overall the scores reflect the initial assessment of the models with no unexpected surprises.

<table>
<thead>
<tr>
<th></th>
<th>SLS model(1)</th>
<th>Canon model(2)</th>
<th>IFI model(3)</th>
<th>Heartflex model(4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material properties average (First five questions)</td>
<td>4.86</td>
<td>5.69</td>
<td>5.97</td>
<td>8.11</td>
</tr>
<tr>
<td>Physical use average (Last five questions)</td>
<td>4.43</td>
<td>6.11</td>
<td>6.26</td>
<td>7.71</td>
</tr>
</tbody>
</table>

Table 8.2: Average rating when differentiating between material properties and application questions

Table 8.2 shows the overall score of the questions if divided into material properties and physical use. The first five questions of the form concerns material properties like flexibility and tear resistance while the last five is about how suitable the model is for physical testing and use. As you can see the models are still scored in the same positions as in table 8.1. Worth noticing is the fact that better material properties does not automatically means that it is more suited for physical use. Both the Canon and the IFI models scores better on the physical use then on the material properties. While the heartflex and the SLS model scores better on material properties then the physical use questions. The physical use score difference between the IFI and heartflex model is also lower then the material properties score difference. This shows that the Canon and IFI model is not that far behind the heartflex model when it comes to real life applications.
Table 8.3: Feedback from the general evaluation. 1-4 cardiologists, 5-7 surgeons.

<table>
<thead>
<tr>
<th>Participant</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>The material need to be translucent</td>
<td>Strongly agree</td>
<td>Neutral</td>
<td>Neutral</td>
<td>Agree</td>
<td>Strongly agree</td>
<td>Strongly disagree</td>
<td>Agree</td>
</tr>
<tr>
<td>The model need to be flexible</td>
<td>Agree</td>
<td>Strongly agree</td>
<td>Strongly agree</td>
<td>Disagree</td>
<td>Strongly agree</td>
<td>Agree</td>
<td>Strongly agree</td>
</tr>
<tr>
<td>Multimaterial model would be more helpful</td>
<td>Neutral</td>
<td>Strongly disagree</td>
<td>Strongly disagree</td>
<td>Agree</td>
<td>Strongly agree</td>
<td>Disagree</td>
<td>Neutral</td>
</tr>
<tr>
<td>Multicolor model would be more helpful</td>
<td>Agree</td>
<td>Strongly disagree</td>
<td>Strongly disagree</td>
<td>Agree</td>
<td>Neutral</td>
<td>Disagree</td>
<td>Only for educational use</td>
</tr>
<tr>
<td>Tear resistance is important</td>
<td>Agree</td>
<td>Neutral</td>
<td>Strongly agree</td>
<td>Agree</td>
<td>Agree</td>
<td>Agree</td>
<td>Strongly agree</td>
</tr>
<tr>
<td>3D models are better then computer models</td>
<td>Strongly agree</td>
<td>Neutral</td>
<td>Agree</td>
<td>Agreement</td>
<td>Agreement</td>
<td>Agreement</td>
<td>Agreement</td>
</tr>
<tr>
<td>Print whole heart or only part</td>
<td>Whole heart</td>
<td>Only area of interest</td>
<td>Whole heart</td>
<td>Whole heart</td>
<td>Whole heart</td>
<td>Area of interest</td>
<td>Area of interest</td>
</tr>
<tr>
<td>Rate the test models from best to worst</td>
<td>4, 3, 1, 2</td>
<td>3, 4, 1, 2</td>
<td>4, 3, 2, 1</td>
<td>4, 2, 1, 3</td>
<td>4, 2, 3, 1</td>
<td>3, 2, 4, 1</td>
<td>4, 3, 2, 1</td>
</tr>
</tbody>
</table>

The material need to be translucent | Strongly agree | Neutral | Neutral | Agree | Strongly agree | Strongly disagree | Agree |
The model need to be flexible | Agree | Strongly agree | Strongly agree | Disagree | Strongly agree | Agree | Strongly agree |
Multimaterial model would be more helpful | Neutral | Strongly disagree | Strongly disagree | Agree | Strongly agree | Disagree | Neutral |
Multicolor model would be more helpful | Agree | Strongly disagree | Strongly disagree | Agree | Neutral | Disagree | Only for educational use |
Tear resistance is important | Agree | Neutral | Strongly agree | Agree | Agree | Agree | Strongly agree |
3D models are better than computer models | Strongly agree | Neutral | Agree | Agreement | Agreement | Agreement | Agreement |
Print whole heart or only part | Whole heart | Only area of interest | Whole heart | Whole heart | Whole heart | Area of interest | Area of interest |
Rate the test models from best to worst | 4, 3, 1, 2 | 3, 4, 1, 2 | 4, 3, 2, 1 | 4, 2, 1, 3 | 4, 2, 3, 1 | 3, 2, 4, 1 | 4, 3, 2, 1 |
8.2. RESULTS BETWEEN SURGEONS AND CARDIOLOGISTS

Table 8.3 shows how each of the participants answered the general evaluation form. There are some variations in the answers but when it comes to translucency, flexibility and tear resistance, the majority of the participants thinks that it is important that the model got these material properties. When it comes to multicolor and multimaterial printing there is a wide diversity in the answers. This makes it hard to conclude whether or not this could be useful features or not. A majority of the participants also finds 3D printed models more useful than 3D computer images. Participants are divided when it comes to whether or not they would like the whole heart or only the area of interest. This means that a printer and post processing process should be able to produce parts of the heart as well as the full heart. Participants where also asked to rate the models from best to worst and overall the heartflex model was most liked with the IFI model on a second place. Between the Canon model and the SLS model the Canon model was placed higher overall.

In table 8.3 participant 1-4 are cardiologists and 5-7 are surgeons. There are no obvious differences between the cardiologists and the surgeons answers, there is also some variations within each of the groups. From the general evaluation, looks like personal taste reflects the answers more than the expertise area.

### 8.2 Results between surgeons and cardiologists

#### Table 8.4: SLS model

<table>
<thead>
<tr>
<th></th>
<th>Model average</th>
<th>Material properties average</th>
<th>Physical testing properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surgeons</td>
<td>3.97</td>
<td>4.33</td>
<td>3.6</td>
</tr>
<tr>
<td>Cardiologists</td>
<td>5.15</td>
<td>5.25</td>
<td>5.05</td>
</tr>
</tbody>
</table>

#### Table 8.5: Canon model

<table>
<thead>
<tr>
<th></th>
<th>Model average</th>
<th>Material properties average</th>
<th>Physical testing properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surgeons</td>
<td>5.47</td>
<td>5.47</td>
<td>5.47</td>
</tr>
<tr>
<td>Cardiologists</td>
<td>6.23</td>
<td>5.85</td>
<td>6.6</td>
</tr>
</tbody>
</table>
### Table 8.6: IFI model

<table>
<thead>
<tr>
<th></th>
<th>Model average</th>
<th>Material properties average</th>
<th>Physical testing properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surgeons</td>
<td>5.63</td>
<td>5.20</td>
<td>6.07</td>
</tr>
<tr>
<td>Cardiologists</td>
<td>6.48</td>
<td>6.55</td>
<td>6.4</td>
</tr>
</tbody>
</table>

### Table 8.7: Heartflex model

<table>
<thead>
<tr>
<th></th>
<th>Model average</th>
<th>Material properties average</th>
<th>Physical testing properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surgeons</td>
<td>7.43</td>
<td>7.53</td>
<td>7.33</td>
</tr>
<tr>
<td>Cardiologists</td>
<td>8.28</td>
<td>8.55</td>
<td>8</td>
</tr>
</tbody>
</table>

Overall the cardiologists rate the models higher than the surgeons. On the other hand, this has no effect on the model scores and the heartflex model is still the highest rated model within each group. The IFI model still comes in on second place, but the cardiologists actually prefer the Canon model for physical testing. This may be due to the brittle IFI model that had some tears during the evaluation. The Canon model and SLS model are the lowest scoring models within each group. When it comes to the SLS model we can see that this is the model with the largest score difference between the surgeons and cardiologists. This may be due to the fact that cardiologists are more interested in the anatomy while surgeons are more interested in physical testing and therefore requires a flexible model.
Chapter 9

Discussion

All the test models printed was able to sufficiently display the area of interest and give the clinicians an extra tool to help set the diagnosis. The test models looked anatomically accurate and displayed features and distinctions in a good way. Distance and size between anatomical structures and features on the models have not been measured and tested with the real heart. Therefore it cannot be concluded that the models made a 100 percent anatomically accurate model. As mentioned earlier when going through the segmentation process, discrepancies between a 3D printed model and the real heart is usually a result of segmentation process or CT/MRI process. The printers used to create the test models, all print at a very high accuracy which means that there should be minimal difference between the computer 3D model and the finished print.

The four test models were printed with SLS technology and material jetting technology. This was decided after considering all available technology as well as the clinicians criteria for the models. Broadly speaking, the clinicians wanted a flexible, transparent and tear resistant model as well as the ability to get a full heart model. Printing the full heart immediately excluded SLS/DLP because support material would be impossible to remove from a full heart. Material extrusion was deemed to inaccurate, poor surface finish as well as slow print speed. A full heart printed on a semi professional printer like the fortus 250mc, would take up to 56 hours to complete.

At IFI there has previously been printed some other heart models on the Connex 500. The experience from these previous prints was that removing support was
tedious and time consuming work as well as the danger of damaging thin walls and small features. It was therefore important to test technology which could make it easier and less time consuming to remove support material. SLS was the standout technology when it came to support removal. In theory the loose powder should be easy to remove by using compressed air to blast out support from a full heart. SLS also offered a flexible material with good tear resistance and it was decided to try this technology with one test model.

Material jetting was from the start the technology that stood out and met most of the clinicians criteria. Three of the test models was created with different printers within material jetting and this was mainly due to availability. The IFI printed model was created with only material cost and the Canon model was a part of a sales pitch from Canon so this was free of charge. Getting a print from both 3D systems and Stratasys machines made it possible to directly compare the result from the leading 3D printer manufacturers. The main difference between the printers is that 3D systems printers use a wax like support material which should be easier to remove then the support used at IFI. The heartflex model created by Materialise was printed to see the best possible solution. Even though this material and process are not commercially available it is important to see if available material and printers can match the heartflex model.

One of the main considerations when deciding how to print the models where as mentioned the support removal process. The IFI model had some support residue and we where not able to remove all because of the narrow and tight anatomical structure. The Canon model also had some residue and the outside and inside of the model felt a bit waxy. Surprisingly enough, the SLS model printed by Materialise had to be cut in half to remove all the support material before they glued the parts back together. The heartflex model had no support residue and probably used the more soluble support material SUP706 instead of the SUP705 material used at IFI.

As expected the heartflex model scored the best from the clinicians. Even though there where some distance between the heartflex model and the IFI model, most of the clinicians seemed to like the IFI model. The biggest issue with the IFI model was the tears and poor material strength. This may be a result of the fact that this model was created some time before the other models, while the heartflex and SLS model was created right before the evaluations started. As mentioned earlier,
models created with a light source are prone to deterioration from normal light. The IFI model had also been handled by multiple people before the evaluations and many of the tears where not present right after it was printed. If the model was printed right before the evaluations it may not have been scored that low on material quality.

The SLS model scored very well when it came to the tear resistance and material quality. Unfortunately the model was not as flexible as expected and the thickness of the walls made it feel almost solid. It was only when pressing at the veins that you could feel that the material was somewhat flexible. The surface finish was not realistic and felt pebble like. Overall the clinicians found this model to have limited applications and would not be very useful compared to other options. Sintered models are also not watertight, this means that it would not be possible to use this print technology to create models for flow analyses.

The Canon model was not as flexible as expected and the material got easily deformed. Clinicians noted that it felt like a compact wax lump and that the material was not translucent enough due to the yellow color. The flexibility was no way near real life tissue and the model actually got more rigid as the weeks passed. Before the last evaluation the model was almost as rigid as the SLS model. This may be due to the wax residue from the support hardened or that the build material itself gets more rigid when exposed to air and light.

The IFI model met most of the criteria from the clinicians and was generally well liked. Almost all the participant noted that the material quality was bad and that it looked cheap. As mentioned this may have been a result of the fact that it was created some time before the other models. A model straight from the print might not have been perceived the same way. Some also noted that the model was a little bit to cloudy, with some post processing work the model could have been more transparent. Overall, the results show that this printer and material could be a useful and viable option for printing patient specific models. Some improvements regarding the print process and post process could produce models close to the heartflex material. First of all the new SUP706 support material could be used to make it easier to remove the support structures. This would also reduce the stress put on the actual model and could result in a more solid and tear resistant model. The model could also be a bit more translucent with some additional post processing.
As expected the heartflex model was most liked by the clinicians. The biggest difference is the quality of the material compared to the IFI model and the translucency. Even though the heartflex model scored the best, the issue is that it is a proprietary material and process created by Materialise. If the hospital should establish an on site 3D printing service they would not be able to produce models like this. We know that the model was created on a Stratasys Objet machine and the material was very similar to the Tango Plus material used on the IFI model. Most likely Materialise have used the Tango Plus in combination with some other materials to enhance the material quality and tear resistance.

From the results it is clear that the material jetting technology is the most suited technology for printing full hearts. Within the material jetting technology machines and material from Stratasys seems to give the best results. This is based on the fact that the Canon model from a 3D systems machine was to rigid, not translucent and prone to deformation. It is also very limited what type of material you are able to print on each printer and the rubber like material used on the test model is only available on the high end printer which is very expensive. Stratasys machines are more versatile and there is a larger selection of printers able to create translucent and flexible models. The downside with Material jetting printers is the cost, it is expensive compared to other technologies to purchase the actual printer and the operational costs are high. Under the general evaluation the participants where asked to rate how useful they think it would be to be able to print models with different colors and materials. A majority of the participants did not see a real value with these features when it comes to printing heart models. This means that you don’t necessarily need to invest in one of the top printers and should be able to print models on printers that only print one color and material at a time. This will drastically reduce the printer price.

Support material removal have been one of the key criteria when evaluating each technology on how suited it is for creating full heart models. Experiences from IFI suggest that the SUP705 material from Stratasys is hard to remove without damaging the actual model. This means that only based on the test models and known support materials used, the Canon model with wax material was the easiest to remove support from. This is much due to the fact that Materialise had to divide the SLS model to remove all the support. On the other hand we know that the heartflex model was created on a Stratasys machine and would most likely have
used the SUP706 material. The heartflex model had no visible support residue and there where minimal tears in the actual model. Unlike the wax like feel of the Canon model, it seems that the SUP706 material did not affect the model in the same way. Even though a material jetting printer would be able to print a full heart in one print, it would be less time consuming, both in print and post processing time, to print the heart in two halves and then glue it back together after support is removed. This would make it easier to remove support with limited negative impact on the final model.

In this thesis it has been a criteria that the printer should be able to print a full heart in one print. Not all cases requires a full heart and you could only use parts of the heart or cardiovascular system to test or plan a surgery. Printers able to print the whole heart is of course also able to print only parts of the heart with the same accuracy, but if only parts of the heart where to be printed, it should in theory be possible to use a SLA, DLP or Clip printer for smaller or less intricate parts. If the parts are somewhat open and not to narrow and intricate it should not be a problem to remove the support structures created with this print process. These printers are able to create translucent models with a flexible material and it could be used to print artery network before stent operations. It could also be used to for example print only one of the atriums in the heart for sizing and fitting valves. SLA and DLP printers can be relatively cheap, both when purchasing the actual machine and the operational costs. Thats why it could be a good idea to start out with a reasonable priced printer and use it to see what it could produce. At the same time, the hospital would be able to assess the value of 3D printed models without using a lot of money on one expensive machines.

An on site 3D printer service at the hospital should also be able to print other organs or parts of the body. Again, printers able to print the whole heart are also able to print other organs. A less expensive alternative would be an material extrusion printer, smaller parts would be able to be printed within a reasonable time. Even though the material extrusion printer may not be able to produce the wanted accuracy for a heart, things like bones, jaws or less intricate organs should in theory be adequately accurate enough with this technology. Patient specific bones printed in a hard plastic material could be used to size and fit metal shins or screws before surgeries. Another benefit with material extrusion is that the material strength is a lot better than with material jetting and SLA/DLP. This
would make it possible to print spare parts for machines and prototypes for tools with good material strength. As with SLA and DLP machines, it is possible to purchase desktop material extrusion printers for around 5000$. The operational costs is also relatively low on material extrusion printers. This would again help the hospital to assess the value of 3D printed parts without spending to much at a time.

A thing to note is that desktop SLA, DLP and FDM printers usually require some manual adjusting from the user. If there only is a few people operating the printers, it should not be a problem, but if several people use the machine without the right knowledge, it could easily mess up the printers. This usually applies for desktop printers and by going up one level in cost, you usually get printers that are more suited for "plug and play" use. These printers usually cost from 10 000$ to 15 000$. If an on site 3D printing service was to be set up at the OUS, it could be a good idea to start out with some less expensive printers and evaluate the value the 3D printed models give. Some examples of suitable material extrusion printers could be the Ultimaker desktop printers or the Stratasys F123 series. When it comes to SLA printers, Formlabs desktop printers and 3D systems Projet series are good alternatives. A 3D printer service with a material extrusion printer and a SLA printer should be able to produce spare parts, prototypes, simple flexible models and bone models. It would on the other hand, not be able to produce intricate models like a full heart.

Even though the 3D printer technology is constantly in development like all other technology. Minor changes have happened the past five years when it comes to elastic or rubber like materials. There are only minor differences between the TangoPlus material used on the IFI model and the proprietary heartflex material. The lack of improvement may be a result of low demand on rubber like flexible material, but if more and more medical institutions starts to use patient specific organ models, the development of more suited materials will increase. HP's open source material solution is a giant step towards an increased development rate of more specialized materials. This will enable medical institutions to work together and create specialized materials for a wide range of applications. From materials specialized for bone structures to a specialized, flexible and translucent material for heart models.
Chapter 10

Conclusion

Using 3D printed organ specific models would clearly aid the clinicians when finding a diagnosis or in a pre planning process. This research mainly focuses on 3D printing of full heart models. This led to certain criteria such as material properties like flexibility, translucency and tear resistance. Printing a full heart also requires the support material to be easily remove without damaging the actual model. The reason for printing a full heart was to really test the 3D printers capabilities and limitations. If the machine is able to print a full model of such an intricate organ like the heart, it should be able to print almost all other desired organs or body parts. The initial criteria was set by the clinicians that is a part of the project at OUS, they represent the actual users and had valuable input on what they wanted from a 3D printed model.

After evaluating present 3D printer technologies with these criteria, material jetting and SLS stood out as the printers that in theory should produce the best models. This was mainly due to the support removal process and 3D printer technologies like material extrusion and SLA/DLP where concluded to not be suited due to the support structures and long print time on material extrusion printers. SLA/DLP use the actual build material to construct support structures and it would be impossible to remove these structures from a full heart. Material extrusion would first of all use to long time to print a full heart. Secondly the accuracy and surface finish on these models are not good enough for a heart model which require high accuracy and precision.

A 3D heart model segmented from a dataset used in a segmentation competition
hosted by the MICCAI society was used for printing test models. This was primarily due to the high quality dataset, as well as not having to be concerned of patient data being distributed outside the hospital. Even though the data could be anonymous, one could still argue that it could be possible to identify a person based on their anatomy. This has to be taken into consideration before establishing an on site 3D printer service and the right approvals need to be in place.

In total, four models was printed, two was printed by a Materialise, one was printed at IFI and one was printed by Canon. One of the Materialise models was printed with an SLS machine, while the rest of the models where printed with different material jetting printers. The material jetting model created by Materialise used a proprietary material called heartflex which promises to mimic real arterial tissue when it comes to the flexibility. The heartflex model was printed to have a best possible model for the clinicians. This made it possible to compare the other models with the best possible solution available and see what the other models lacked.

As expected the heartflex model was rated highest by the clinicians participating in the evaluation. Five out of the seven participants placed the heartflex model as the best model. The IFI model was close behind and the main issues with this model was the poor tear resistance. Other properties like flexibility and translucency was close to the heartflex model. The other models did not turn out exactly as expected. The Canon model felt like a dense wax lump and instead of being translucent it had a yellow/orange like color. Flexibility was not as expected and the model was prone to deformation. The SLS model was printed in the belief that the powder like support material would be easy to remove. It turned out that Materialise had to cut and open the heart to remove all the support. This model was also not translucent and not as flexible as desired, thick parts felt rigid.

From this study we can conclude that material jetting printers offers the best possibilities to create a full patient specific heart model, as well as offering suitable materials. Even though material jetting technology is the most suited, this study found that there is a large difference between the 3D printers that is based on material jetting. It found that the materials available on the 3D systems machines where not as translucent as expected, nor as flexible as wanted. The model made with Stratasys Tangoplus material had good flexibility and translucency, but lacked the tear resistance the clinicians wanted. From the results we can also see
that the clinicians liked the material from Stratasys better than the 3D systems material. This means that the Polyjet printers from Stratasys with the TangPlus material and SUP706 support material would be the best choice for printing full patient specific heart models.

The ideal solution for an on site 3D printing service, would be one printer that had the capabilities to produce models for all the applications at the hospital. Unfortunately, 3D printers today all have a variety of strengths and weaknesses and to be able to create usable models for all the applications at a hospital, you would need several printers and technologies to do so. By starting out with some low to mid range material extrusion and SLA or DLP printers. You would be able to print models for a majority of the applications at a hospital. The operational costs of both technologies are relatively cheap compared to other technologies and it would be helpful to first of all get some experience with 3D printing, as well as be able to evaluate the value such 3D printed models would bring to the day to day operations without spending too much money. With these printers you would unfortunately not be able to produce intricate models like a full heart, but you should be able to produce anatomically simpler parts of the heart.

There is no doubt that the clinicians participating in the evaluation sees the value of 3D printing patient specific organ models. Other studies have tried to quantify the value 3D printed model gives. The problem with many of the studies is the few cases evaluated, that’s why the OP heart 3D print study with over 400 patients can be very important to quantify and show the benefits of using 3D printed models. Even though the outcome of the OP heart study could impact the view on 3D printed models. There have not been found any other studies that evaluate different printer technologies and materials like this study. The majority of studies tries to quantify the benefits of 3D printed models and some studies have tested how well 3D printed models was able to replicate the actual anatomy. This study has shown that to print full heart models, a material jetting printer is best suited for this particular application. We have also seen that support material plays an important role when it comes to 3D printing. Providing clinicians with excellent 3D printed patient specific models, could hopefully lead to improved surgery, improved outcomes and result in lower treatment costs.
Chapter 11

Future work

This study has focused on printing a full heart and future work within this area could for example be to print some multicolor or multimaterial models that could be evaluated. From the general evaluation the clinicians seemed to not see any real advantages with multicolor and multimaterial models, but this could change if they got a test model in front of them. Future work could also include trying to print simpler parts of the heart with a SLA machine or a FDM machine and see whether or not it is possible to remove the support structures. Trying to print bones for physical testing and evaluating how good pre surgical testing matched the final result could also be an interesting and important for clinicians and the medical industry. This would also apply to printing parts of the cardiovascular system as well as single atrium’s to size valves or stents before surgery and see how they matched the final result.

The most time consuming parts before printing the actual model is to acquire image data from the patients via CT or MRI and the whole segmentation process to create the 3D computer model. Making it less time consuming and easier available for the clinicians to acquire the image data and 3D model, should make the process more worth while and make it easier to 3D print patient specific models. One way could be to use echocardiogram. Echocardiogram is used to visualize the heart, aorta, and other blood vessels. An echocardiogram is essentially a Doppler ultrasound tool. The device emits sound waves, which bounce off the heart’s structures, creating an image of the heart and/or blood vessels under examination. It could be very interesting to see whether or not this process could be able
to produce accurate 3D models faster than using CT or MRI.
Appendices
Appendix A

Evaluation forms
## Figure A.1: Evaluation form for the test models

<table>
<thead>
<tr>
<th>Model number: Rate the model from 1 to 10.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (Worst)</td>
</tr>
<tr>
<td>Handling the model, consider the smell and solvent residue.</td>
</tr>
<tr>
<td>Thickness of the wall.</td>
</tr>
<tr>
<td>Rate the flexibility of the model.</td>
</tr>
<tr>
<td>Is the translucency adequate?</td>
</tr>
<tr>
<td>Quality of the material, consider the tear resistance.</td>
</tr>
<tr>
<td>How suitable is the model for valve testing?</td>
</tr>
<tr>
<td>Is the material suitable for sewing?</td>
</tr>
<tr>
<td>Rate how suitable the model is for patient communication.</td>
</tr>
<tr>
<td>Ability to show the region of interest</td>
</tr>
<tr>
<td>Would the model aid in the pre planning process?</td>
</tr>
</tbody>
</table>

### Select how the model would be used.
- Plan surgery
- Physical testing on the model
- Practice surgery
- Educational use
- Communication with patients

### Any signs of residue from the support material used during printing?

### General feedback.
## Evaluering 2

### General evaluation

<table>
<thead>
<tr>
<th>Statement</th>
<th>Strongly disagree</th>
<th>Disagree</th>
<th>Neutral</th>
<th>Agree</th>
<th>Strongly agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>The material need to be somewhat translucent?</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>The model need to be flexible?</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>It would help if the model was made with both flexible and hard materials.</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>A multi-color model would be better than a model that is only translucent.</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>It is important that the model got good tear resistance.</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>3D models are superior to 3D computer models and could be an important tool in pre-operative planning</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
</tbody>
</table>

### 3D model

- The model can be printed as the whole heart or just a part of the heart. For most cases, what would you like to get.
  - ○ The whole heart
  - ○ Part with the area of interest

### Range the evaluated models from best to worst.

- 

### Name and title/department

- 

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Figure A.2: The general evaluation form
Bibliography


white_paper_mimics_ct_heart_tool_validation_study.pdf (visited on 17/03/2017).


[29] *Material Extrusion | Additive Manufacturing Research Group | Loughborough University*. URL: http://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/materialextrusion/ (visited on 02/05/2017).


[38] Ultimaker PVA | Ultimaker. URL: https://ultimaker.com/en/products/materials/pva (visited on 02/05/2017).


[40] What is 3D Printing? The definitive guide. URL: https://www.3dhubs.com/what-is-3d-printing (visited on 06/06/2017).