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Abstract

Rupture of aortic aneurysms, is the 13th leading cause of death in the USA. An aneurysm is prevented from rupture by inserting a aortic stent graft, via open- or endovascular surgery, into the aorta. Endovascular Minimal Invasive is a fairly recent technique, but is preferred to open surgery. Faster recovery time, shorter procedure time, and smaller incisions are a few of the important advantages. But the endovascular technique is more technical and requiers a guiding catheter, inserting tools for delivering the stent graft in the aorta and imaging to locate the stent in the aorta.

When performing this technique, two major difficulties occur, namely the pre-operative selection of a stent graft and the correct placement of the stent in the aorta. The selection of a stent is a difficult task, because the stent has to be of the same dimensions (length and diameter) as the aneurysm. A stent that is too small will cause endoleak, leakage between the stent and the aorta wall. A stent that is too big will cause an irregular fluid pattern of the blood or will cause curling of the stent wall. Secondly it is important that the stent is placed in the correct position inside the aorta during surgery, which is not easy because the visual and haptic feedback are partly lost by performing endovascular surgery. An improper choice or placement of the stent can also cause endoleak, which may lead to rupture of the aortic wall.

This report focuses on the stent selection problem, i.e. how to choose a stent that will properly fit into the aorta. First the mechanical properties and behavior of the stent and aorta, and stent interaction with the aorta are discussed. Secondly a criteria is created to help to select a correct stent, based on static and hemodynamic constraints. Because this criteria is not by itself, sufficient, a 2D dynamic simulation of the expanding stent and interaction with the aorta was developed. The simulation is planned to be added to an existing software framework for surgery planning, and will use the 3D information from the 3D segmentation aorta to place the stent in the aorta. At the conclusion of this report it is discussed whether it is possible or not to help the surgeon with choosing an aortic stent and preventing endoleak.

Chapter 1

Introduction

In this first chapter the anatomy of the aorta will be examined together with the pathophysiology of the aneurysm. The factors that can cause an aneurysm as well as the consequences of a aneurysm are discussed. The current treatments to heal a aneurysm, along with their advantages and disadvantages are discussed. At the end of the chapter a suggestion will be given to create a surgery planning tool to improve the current treatment method.

1.1 Anatomy of the aorta

The aorta is a remarkable vessel with a three-layer construction (intima, media and adventitia) which allows it to absorb the impact of millions of heartbeats and carry over 200,000,000 liters of blood in an average lifetime. The aorta is not only the biggest blood vessel in the human body, but also one of the most important ones, transporting oxygen rich blood directly from the left ventricle to all the other arteries (except for the pulmonary artery, that is transporting blood from the right ventricle to the lungs). The anatomy of the aorta in the human body is shown in figure (1.1)[1], if one follows the aorta starting from the left ventricle of the heart one will see the ascending aorta, the aortic arch, the descending aorta, passing the renal arteries and finally the aorta separate into the two common iliac arteries.

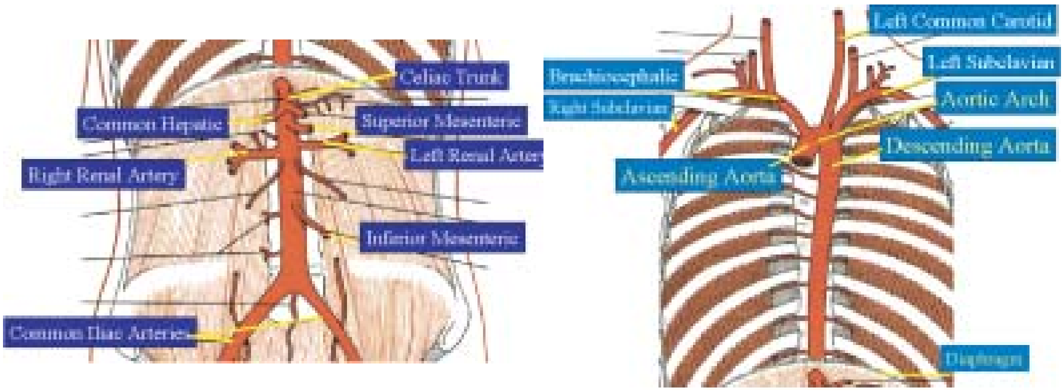


Figure 1.1: Anatomy of the normal aorta

1.1.1 Pathophysiology of the aneurysm

A aneurysm is a pathological dilatation of the normal aortic lumen, i.e. an ill aorta with a permanent increased diameter of at least 2 times the normal diameter (2 times 2.5 cm). Although it is not clear what causes an aneurysm it is assumed that it is related to a number of factors. For example, aging, atherosclerosis (hardening of the arteries), infection, inflammation, trauma, congenital anomalies, medial degeneration and smoking [2]. Research that has been conducted on this subject [3], suggests that smoking and aging are the risk-factors most strongly indicated to be associated with aneurysm. Aneurysms are classified into two groups, the first group contains the Abdominal Aorta Aneurysm (AAA), located in the lower region of the aorta. The aneurysms of this first group are commonly starting right under the left and right renal arteries and can affect the common iliac arteries. The second group of aneurysm contains the Thoracic Aorta Aneurysm (TAA), they are located above the diaphragm, for instance, in the aortic arch. In figure (1.2) on the right, a TAA is located in the aortic arch, an AAA, shown in figure (1.2) on the left, is located in the abdomen of the patient and starts just under the Renal Arteries and stops before the aorta continues in the iliac arteries. The scans are created by a X-ray angiography, a contrast product is added to shown the aorta on the image.

Figure 1.2: *Left:* A X-ray Image of an AAA. *Right:* A X-ray Image of a TAA.

The Aneurysms of the abdominal aorta are more common then the Thoracic aortic aneurysms; about 114,000 new cases are diagnosed each year in the US [10] and more than 2,000,000 are estimated to have an undiagnosed AAA . Conventionally, an abdominal aortic aneurysm measures more than 3 cm in diameter. The primary complication is rupture, which leads to 15,000 deaths per year in the US and makes abdominal aortic rupture the 13th leading cause of death in that country.

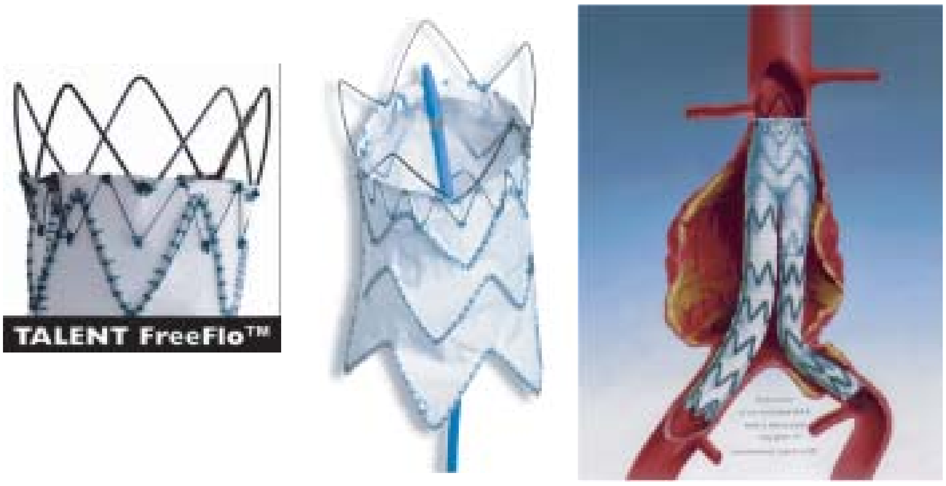


Figure 1.3: *left:* The Top spring wire of a self expanding stent *center:* A self expanding stent with catheter *right:* A schematic representation of the position of the stent in the aorta

1.2 Current treatments

1.2.1 Open surgical repair

One of the current treatments that is used for healing the aorta and preventing the aneurysm to rupture is an open surgery. During this surgical operation the part of the aorta where the aneurysm is located, is opened and a graft system is placed in between the two healthy parts of the aorta. Afterwards the aorta is wrapped and closed around the graft.

To reach the aorta, in case of a TAA or AAA, a significant incision has to be made in the thorax, and during the operation the patient is put onto a cross-clamp. The total procedure takes up to 4 hour and the hospital stay for the patient is rather long with a stay at the intensive care for at least one day and 7-14 days under normal supervision.

1.2.2 Endovascular repair

Endovascular repair, or minimally invasive repair, is the second method to treat an aneurysm. The treatment is called minimally invasive because the aneurysm is reached trough small incisions (2 to 3 cm) by a catheter, that is inserted in the Iliac Arteries and is pushed up to the location of the aneurysm. Since the surgical method is endovascular, (inside the arteries), it is not possible to locate the position of the catheter at the outside of the body or by a camera inside the body. The catheter is located by a angiography X-ray scan that shows markers that are attached to the catheter and stent. When the catheter is in the proper position a stent (figure (1.3)) is inserted and is expanded in the aorta. This procedure reveals some big advantages in respect to the open surgery. First of all, the incisions are much smaller and the patient will have smaller scars. Secondly, the procedure time is decreased as well as the risks of the operation. And third, the hospital stay and recovery time are decreased and the patient can return quicker to normal life.

Nevertheless, there are also some disadvantages joining the minimal invasive procedure. One of them is already mentioned before and is the location and placement of the stent. This is much more difficult then with the open surgery procedure, because the surgeon have tho focus on a X-ray angiography image and has no longer the classic visual and haptic feedback.

The second problem is that one has to know the exact dimensions of the healthy part of the aorta exactly above and under the aneurysm, in order to choose the correct (self) expandable stent, that will exactly fit into that position. Such that, there will be no blood flow trough the dissecting- or pseudo aneurysm, but only trough the stent. The surgeon has to make an approximation of the dimensions from a 2D CT or MRI data sets of the aorta to order the correct stent prosthesis.
The nowadays selection procedure for the stent is based upon CTA and calibrated angiogram that gives all the diameters and length that are needed to know. To select a stent the CTA and the angiogram oversized stent are needed: Usually a stent is ordered, 10 % bigger than the accurate measurements of the AAA provided by CTA and angiography. If the stent is too large in diameter, it will not expand completely and will not seal the aorta and it will make a crescent shape on axial section. When this happens a strong normal stent has to be placed inside the stent to crash the stent graft against the wall of the aorta to ensure exclusion of the AAA.

After the stent is placed, there is a risk of endoleak. Endoleak is a condition unique to grafts defined by the persistence of blood flow outside the lumen of the graft but within an aneurysm. Endoleaks are due to incomplete sealing, or exclusion of the aneurysm sac or vessel, and/or reflux of blood flow into the sac.
A distinction is made between endoleaks related to the graft device and unrelated to the graft [4].

Type I Endoleak- This type of endoleak occurs when a persistent channel of blood flow develops due to inadequate or ineffective seal at the graft ends. This type of endoleak is usually present early in the course of the treatment but may also be encountered late when blood erodes through a blood clot seal around the area of device fixation to the aortic wall.

Type II Endoleak- This is a retrograde type of endoleak. It occurs when there is persistent blood flow into the aneurysm sac due to retrograde blood flow from patent lumbar arteries, the inferior mesenteric artery, or other collateral vessels. In some circumstances when there are two or more patent vessels a situation of inflow and outflow develops creating an actively blood flow within a channel created within the aneurysm sac.

Type III Endoleak- This type of endoleak is related to inadequate or ineffective seal at the graft joints, between segments of overlapping graft segments, or rupture of the graft fabric. This type of endoleak may develop early, due to technical problems or late in the course of the treatment when there is displacement of one of the extensions due to aneurysm retraction or device breakdown.

Type IV Endoleak- This type of endoleak is related to the porosity and passage of blood through the fabric of the graft. Since the grafts used in endovascular devices are not preclotted most fabrics will initially leak through. With the development of thinner graft materials this type of endoleak is becoming more common.

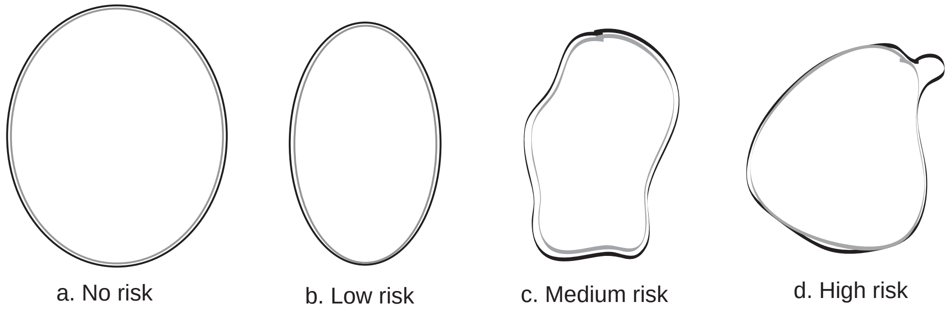


Figure 1.4: four different cases of risk on endoleak

Endoleak of Undefined Origin- This type of endoleak has an unknown cause and location, which may be eventually defined as the imaging techniques get more refined.

The major problem of repairing an aneurysm by a minimal invasive technique is the lack of acknowledge of the dimensions of the aorta which leads to insufficient sealing (TYPE I and TYPE III), this appearance of endoleak is shown schematically in figure (1.4). Where case a), b) and c) cause no endoleak, but case d) definitely higher the risk on endoleak.
The only possibility wether to check if endoleak has occurred by a patient, is to keep the patient under supervision by taking scans and check if the aneurysm diameter is de- or increasing.

This report will discuss a surgeon planning tool to help the surgeon decide what kind of stent he needs for performing an endovascular operation and to prevent situations as shown in figure (1.4) case d). By the help of a 2D CT angiography data set created 3D aorta, a proper location for the prosthesis can be chosen. With the dimensions of the landingzone for the stent known, a criterium can be formulated to select and predict whether a stent will fit or not. By this method the properties of the stent that will fit into the aorta, are pre-operative known.

1.3 Related work

The related research that is found on the topic of aneurysms, focuses the attention over a wide range. Lot of research is performed on the 3D segmentation of the aorta [5], [6], and to select a stent according to the dimensions of the aorta and aneurysm. In [7], a mechanical model for the aorta interacting with a catheter is derived. Where the aorta and catheter are reacting like deformable bodies. And in [8], the research is focussed on wave patterns and blood flow trough the aorta. Comparing this before and after placement of the stent, can show if the stent that placed is a bad match or a good one. In [9] it is suggested to create a virtual environment for surgeon training.

To prevent endoleak, a stent that will fit correctly into the aorta wall, has to be pre-operative selected. Topology, anatomy and mechanical properties of the aorta and stent, will be used to solve this problem.

Chapter 2

Characterization of aorta and stent

In this chapter the mechanical properties of the aorta and stent are retrieved from literature, a small experiment and visual information. The ratio for stiffness of stent and aorta will play an important role in our simulation.

2.1 Mechanical properties of the aneurysmal aorta

According to *MacSweeney and Young* [11] the stiffness of the aorta is very different due by criteria's like age, atherosclerosis and aneurysms. The mechanical properties of the abdominal aorta were investigated non-invasively in 41 patients, using M-mode ultrasonography. By this method the change in arterial diameter is measured and depends on pulse pressure and the elasticity of the artery. The relationship between the change in diameter and pressure is the pressure-strain elastic modulus (E_p). This modulus is defined by the arterial blood pressures at peak systole (P_s) and end diastole (P_d) and the corresponding arterial diameters (D_s and D_d) this leads to formula (2.1).

$$E_p = \frac{P_s - P_d}{\frac{D_s - D_d}{D_d}} \tag{2.1}$$

According to *MacSweeney and Young*, this resulst in the following stiffness for the aorta. An E_p of $4.0\frac{N}{cm^2}$ for a normal aorta of a 30 years old to an E_p of $14.0\frac{N}{cm^2}$ for a normal aorta in the elderly. That can increase to an E_p of $16.0\frac{N}{cm^2}$ in an aorta with atherosclerosis. Aneurysmal dilatation was associated with a significant increase in aortic stiffness, $E_p = 31.3\frac{N}{cm^2}$.

2.2 Mechanical properties of the stent

The aortic stent exists of 6 radial springs of a Shape Memory Alloy (SMA), that are placed together by a longitudinal SMA bar. The bar prevents the stent to change in length during compressing or decompressing, and gives rigidity in its longitudinal direction. The SMA is high non-linear and gives a high non-linear behavior to the stent. By using SMA, the diameter of the stent can have a big elastic deformation, which is a big advantage, but also has a big influence on the dynamic behavior of the stent.

To retrieve information about this behavior of the stent, we decided to perform a small experiment. The stent is placed in a rigid tube with a known diameter, this tube is cut into

Deformation [%]	length [m]	Force [N]	E_p [$\frac{N}{cm^2}$]	$E_{p_{metallic}}$ [$\frac{N}{cm^2}$]
10	0.12	2.0	2.1	0.87
30	0.12	6.0	2.9	
65	0.12	7.5	2.4	

Table 2.1: Experimental values for the stent stiffness

half in the longitudinal direction. A force is now added to the system to ensure that the two parts of the bar are put together. The the experimental setup, together with a schematic representation of the force play, is shown in figure (2.1). Because the initial Diameter (Diameter of the stent 46 mm) and Final Diameter (Diameter of the tube) are known and the force is measured by a dynamo-measurer. The pressure (P) wall stress (σ) relation of a thin walled tube is shown in equation (2.2).

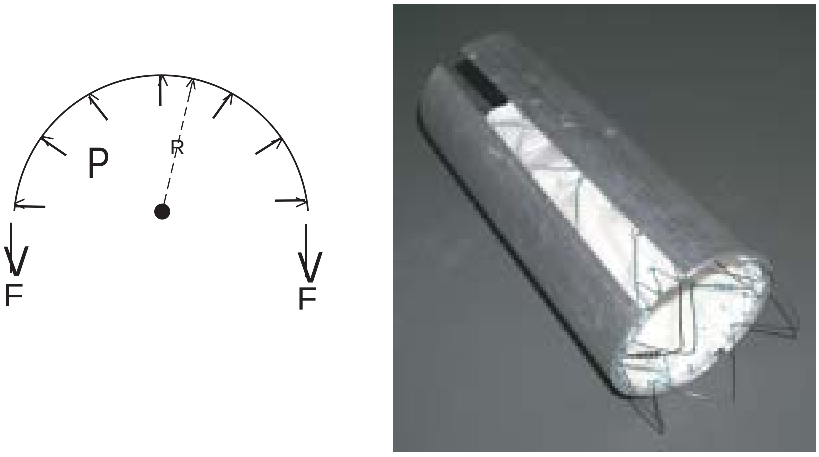


Figure 2.1: *Left:* Forces and Pressure *Right:* experimental setup

$$\sigma = \frac{F}{A} = \frac{F}{lh} = P\frac{r_v}{2h} \tag{2.2}$$

Now the pressure(P)-strain modulus can be calculated according to formula (2.3).

$$E_p = \frac{\Delta P}{\varepsilon_r} = \frac{\frac{2Fh}{lhr_v}}{\frac{D_t - D_i}{D_i}} \tag{2.3}$$

Where, F = the force acting on the tube, l = length of stent, D_t = Diameter of the tube, D_i = initial diameter of the stent, since it is a compression the force and the denumerator are negative and h the wall thickness, which can be divided in the de- and numerator. The results are given in table (2.1). Comparing the values from the experiment with values from the same experiment performed with a metallic aortic stent [12], (resp. $2.1\frac{N}{cm^2}$ to $0.87\frac{N}{cm^2}$) it is clear that the rigidity (E_p) of the metallic aortic stent is less then the rigidity of the stent graft. Nevertheless it is assumable that the Pressure - Diameter ratio will be comparable and will have more or less the same non-linear behavior. In figure (2.2) the ratio is shown (according

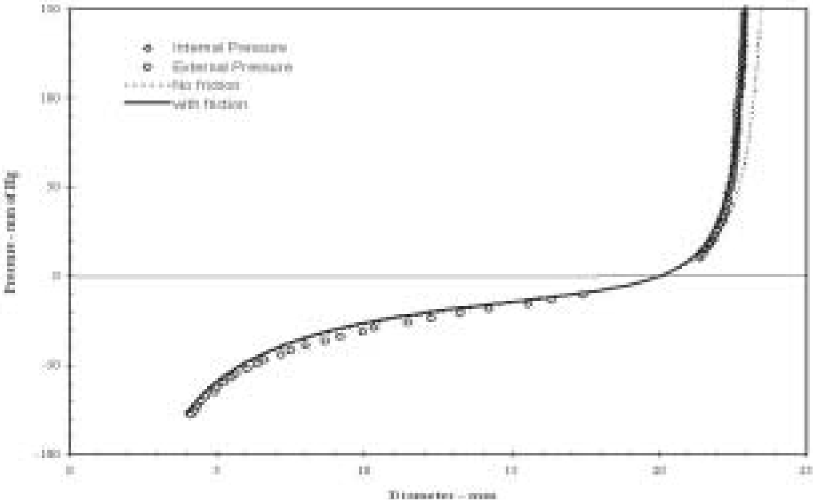


Figure 2.2: The pressure-diameter ratio of a metallic aortic stent

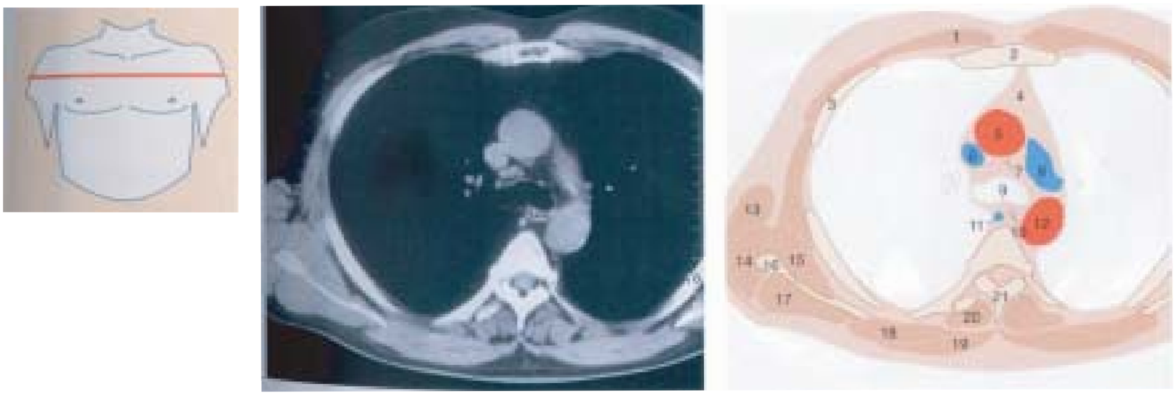
to *Wang and Ravi-Chandar*), which is clearly a high non-linear behavior. When the metallic stent is in its initial position the pressure is 0 $[mmHg]$. A positive pressure is a pressure acting from the inside of the stent and causing the stent diameter to increase. A negative pressure is a pressure acting from the outside of the stent and causing the stent diameter to decrease (comparable with the small experiment described before). The part were the stent is loaded with a positive pressure, not the springs are loaded, but much more the material that keeps the springs together. The material consists of PTFE sealed by heat and can therefor deform, but has almost no elasticity.
The behavior of the stent during suppressing is the behavior of the metallic springs of the stent and is high non-linear, especially when the stent is compressed more then 50 % of its initial diameter.

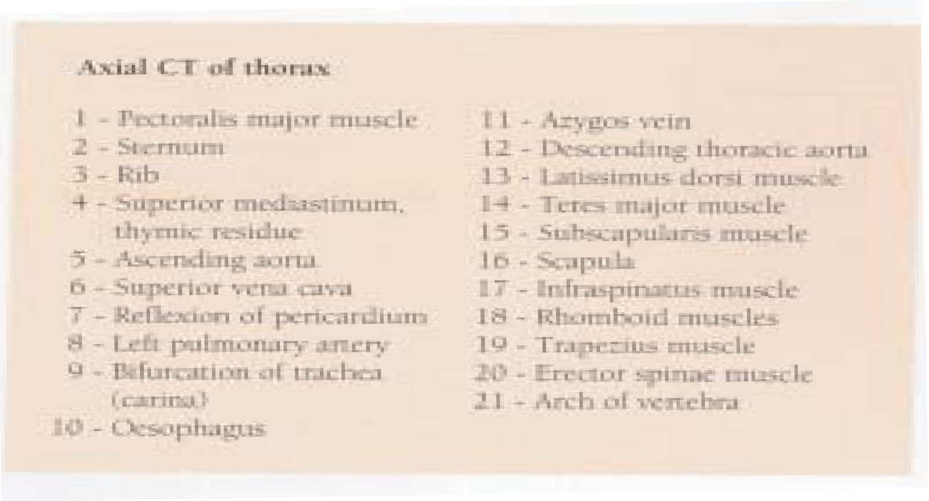
The part of interest is that part where the stent diameter is compressed by 10-20 %, because the surgeon is nowadays choosing a stent from this area. This is also the part where the behavior is not as non-linear as the rest of the graphic.

Comparing the E_p of the stent, found in the experiment,with the E_p of the aorta it seems that the stiffness of the aorta is a factor 10, or a order in magnitude, bigger then the stiffness of the stent. The expansion of the stent in the aorta will therefore not be of much influence on the change in diameter of the aorta.

2.3 Visual information interaction stent with the aorta

Another possibility to retrieve information about the mechanical properties of the stent and the aorta, are images. A nice way to compare the stiffness of the stent with the stiffness of the aorta is to compare two different states, one of the aorta without stent and one with the stent placed. These images are created by a CT angiography scan. To get some global idea from which part of the body the scans were taken, a image from an atomical atlas is added in figure(2.3) [13]. The part of interest is, of course, the artery of the aneurysm, in this case the aorta (Number 5 and 12 in figure (2.3)). It is not yet possible to insert a stent endovascular into the ascending aorta (if that is needed). One reason is the fact that the stent will close the entrance of the the number of separating arteries. The other reason is that it takes to much force to push the stent out of the catheter in or after the aortic arch, this is comparable with pushing a wire trough a curving tube.





Axial CT of thorax

1 - Pectoralis major muscle
2 - Sternum
3 - Rib
4 - Superior mediastinum, thymic residue
5 - Ascending aorta
6 - Superior vena cava
7 - Reflexion of pericardium
8 - Left pulmonary artery
9 - Bifurcation of trachea (carina)
10 - Oesophagus
11 - Azygos vein
12 - Descending thoracic aorta
13 - Latissimus dorsi muscle
14 - Teres major muscle
15 - Subscapularis muscle
16 - Scapula
17 - Infraspinatus muscle
18 - Rhomboid muscles
19 - Trapezius muscle
20 - Erector spinae muscle
21 - Arch of vertebra

Figure 2.3: CT scan with references for the anatomy

In figure (2.4) a aortic stent is inserted in the descending aorta, the two X-ray images are shown: One before the insertion and one after the insertion of the stent. The scans are comparable with the pictures shown in figure (2.3) and are taken about the same position in the thorax. Two interesting things can be conclude, while looking at those two scans.

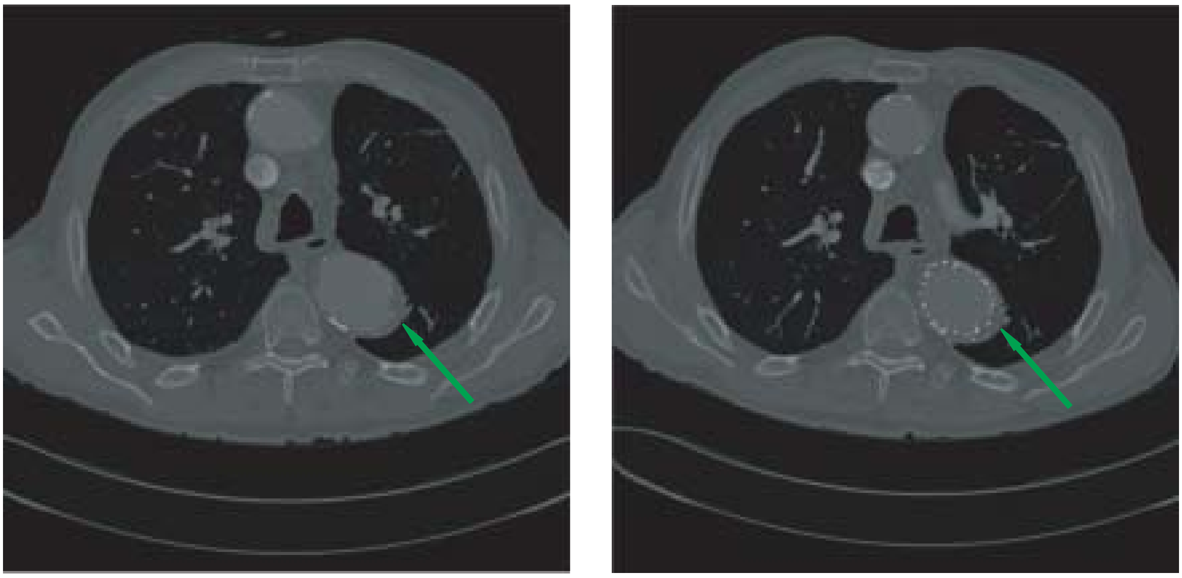


Figure 2.4: *Left:* A Scan before the placement of the stent. *Right:* A scan after the placement of the stent.

1: The diameter of the aorta is hardly changing due to the internal pressure caused by the stent. The change in diameter is less then 1%, note that it is possible that the patient is positioned different before and after placement of the stent, which can cause a small misdrawing. It seems that the stiffness of aorta and stent calculated before are right and that indeed the aorta stiffness is higher than the one of the stent.
2: On pre-op CTA of aneurysm, a amount of thrombus around the inner part of the aortic wall is located, pointed out with an arrow. Once covered by the stent graft, the thrombus is applied against the wall by the stent. The outside thrombus may shrink or remains in most of the cases if sealing is achieved. This is a remarkable effort and can only mean that the aortic stent is strong enough to put the aortic wall into a different shape.

When one combines conclusions **1** and **2** together, one can say in a plastic way, that the linear stiffness of the aortic wall is much higher then the stent stiffness, but it seems that the angular stiffness of the aortic wall (or the tissues surround it) is much lower and can not stand the pressure caused by this inserted stent.

2.4 Information about the 3D aorta

As noticed in earlier paragraph, 2D images can be created by X-ray of CT-Scans. It may also be clear that these 2D scans can be put together and form a 3D object of, for instance, the aorta. This procedure is called segmentation and reconstruction of the aorta. Segmentation and reconstruction can be performed in several difference ways and is certainly to divers to handle in this report. Nevertheless, it is of enormous importance to have a correct 3D aorta available, since all the properties like diameter, length and size of the aorta and aneurysm are displayed in the 3D image. Also the 'landing-zone' (the location where the top of the stent is placed, in case of a AAA the landing-zone is just under the renal arteries) can be examined and judged. The extra information the 3D aorta can give is an enormous effort and can help to prevent endoleak by choosing the stent with overlapping dimensions. During this report it is assumed that this 3D model of the aorta is already available.

To better understand the interaction between aorta and stent, mechanical properties of the aortic wall were found. An experiment was performed to retrieve the mechanical properties of the aortic stent. The stiffness of the aorta was found to be a ten times bigger than that of the stent, so that the circumference of the aorta wall will almost not change during the interaction with the stent.

Chapter 3

Static simulation of aorta and stent

To find a correct fit of the stent in the aorta, it may be possible to do this with the help of static solutions. The static solution could be easy without using lot of computer power. First try is to find the static solution for a spring system described in chapter (4), next a different approach is suggested by using hemodynamics equations.

3.1 Static solution by using springs

The aorta wall, as well as the aortic stent, will be represented by linear springs, connected in a radial form. In the initial position it is assumed that the spring endings of the stent make contact with the aortic spring endings. With help of the equations (4.2) it should be possible to calculate the new equilibrium, for every position of the endings of the springs. This will gives us, for $2n$ Number of springs (n for the aorta and n for the stent), $2n$ Number of forces, n Number of unknown lengths of the springs and so: n Number of equations with $\sum \overrightarrow{F} = 0$. And shows the following system:

$$[\overrightarrow{F}] = [K][\overrightarrow{l}] + [K][\overrightarrow{l_0}]) \tag{3.1}$$

Where $[\overrightarrow{F}]$ is a $[n \times 1]$ column which holds only zero values, $[K]$ is a $n \times n$ matrix, that is representing the order of connection of the springs and that holds the values for the E_p for the aorta as well as E_p of the stent are already known by paragraph (2.2). And finally the columns $[\overrightarrow{l}]$ and $[\overrightarrow{l_0}]$ that have the dimensions of $[n \times 1]$, holding resp. the unknown lengths and the relax lengths of the springs.
The first problem to encounter is the fact that it should be a 2D case instead of a 1D case where only the length of a spring is of importance, the second problem is to solve system (3.1). No global solution is found for this static case, only a very specific one and trivial one, namely that of the interaction of 2 perfectly round tubes.

The diameter of the aorta is known, according to the experiment performed in paragraph (2.2) the pressure acting on the wall by the stent will be know and with E_p of the aortic wall, the new diameter can be calculated. Noted again, that this solution is only for a perfectly round tube, something that will never happen in a real-life aorta.

3.2 Static solution by the use of length

Maybe the most simple criteria for selecting a stent in a static way is by the circumference. Where the (circumference of the complete expanded stent) > (circumference of the aorta wall). This is something that is exactly known out of the information of the 3D aorta. But in this case a criterium is created that is not complete, because a stent with no rigidity but with a bigger circumference will not fit into the aorta because there is to much interference of friction and circulation patterns of the blood. The stent will flow through the aorta like a piece of paper through a liquid. Therefore it is maybe a good idea, to solve the problem by taking the hemodynamics into account.

3.3 Static solution by using hemodynamics

In this paragraph a static solution is found by the use of hemodynamic equations. It is suggested that with the use of these equations, a stent can be selected that has a circumference bigger then the aorta and that can delivered enough pressure to the aortic wall to stay in the right position. The hemodynamic equation that is used is the Moens-Korteweg equation (3.2)[14],

$$c^2 = \frac{A}{\rho}\frac{\partial P}{\partial A} \tag{3.2}$$

that can provide the information that is needed to select a aortic stent. In the equation the Compliance $\frac{\partial A}{\partial P} = \frac{\text{change in cross}-\text{section area of a vessel}}{\text{change in pressure}}$ is used to find the wave speed $c[\frac{m}{s^2}]$ of a travelling wave inside the vessel. The other parameter represent the density of the fluid, in this case the density of blood ($\rho = 1.05[\frac{kg}{m^3}]$). There are some restrictions imposed the Moens-Korteweg formula, for instance, thin wall tube, isotropic homogenous, linearity elastic, inviscues fluid, straight circular tube of infinite length and therefore suggests that the formula is of limited use, but for the idee the formula will fulfill. But now the equations will be used the other way around.

The exact cross-section area A of the aorta is known at the landingzone from the 3D reconstruction model. The first step to take now, is to assume that the maximum wave speed in the aorta, c_{max}, will be 25 $[\frac{m}{s}]$, $\frac{1}{\text{compliance}}$ can be calculated and the relation between pressure and cross-area section is known. The stent that will fit correctly in the aorta, is a stent that has at the given cross-section area, a higher value of pressure then the one of the aorta. This means that the experiment performed in paragraph (2.2) turns out to be very handful and can provide the information, wether or not the stent gives enough pressure at the given cross-section. This method adds an important factor to our criterium of length, because also the pressure is taken into account. The way of using this criterium is shown in an example below.

Example (3.1)

Following from the Moens-Korteweg equation (3.2), it should not be to difficult to solve this first order degree differential equation. A rewrite will give equation (3.3)

$$-\frac{A}{\rho c^2} + \frac{\partial A}{\partial P} = 0 \tag{3.3}$$

That can be solved, with the homogenous solution for a first order DV and gives equation (3.3).

$$A(P) = A_0 \exp^{-(-\frac{1}{c^2\rho})P} \tag{3.4}$$

The constant A_0 is derived from our boundary conditions, for example: The cross area of the aorta during the pressure systole, or the cross area of the aorta during pressure zero. During this example it is assumed that the $A_0 = 0.0001$, which is the value for the aorta when there is no pressure. The solution for the DV is visually shown in figure (3.1), created with help of Matlab and the values for the parameters that were derived before. The values on the axis are converted to the dimensions of diameter and pressure mmHg (760 mgHg = 1.01325 e^5 Pa), in that case the values are easier to compare. It seems that there already is exactly a graphic in this report which is showing the relationship between the pressure en diameter for a stent, indeed figure (2.2).

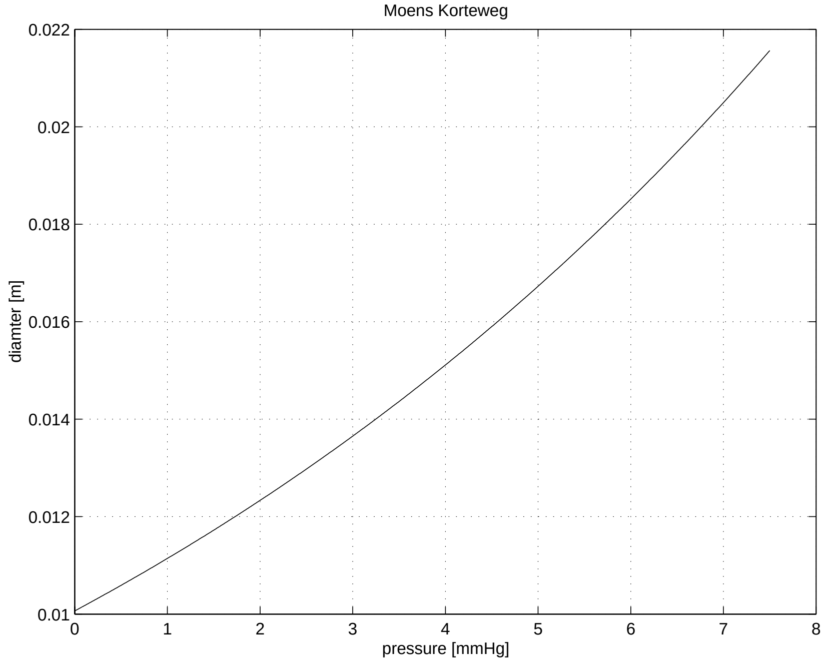


Figure 3.1: Pressure-Diameter ratio according to Moens-Korteweg

When for example, the cross area of the aorta is 0.00025 (a diameter of 18 mm), the corresponding pressure will be 5.8 mmHg. When we now look in the figure(2.2), we will see that at a diameter of 18 mm, the pressure is about 10 mmHg. And in this case the stent will act more internal pressure on the aorta then the pressure of the fluid and will therefore fit.

Nevertheless, with the criterium explained above, it is still possible to have endoleak in specific cases. If hemodynamics is used as a selecting criterium, yet the assumption has to be made that the position of placement of the stent is more or less round according to figure (1.4) cases a) and b), risk case c) and especially case d) can meet the requirements of enough internal pressure and a cross-section that is big enough, but still not prevent endoleak.

Except a different shape, it can also be possible that the aorta has some calcification. In this case the compliance of the aorta wall is not any more the same, but will be less since a higher pressure is needed to create the same deformation of the aorta wall.
In paragraph (2.3) it was shown, that it is possible for the stent to push some blob, as in figure (1.4) case d) , away. To predict such kind of behavior, a dynamic simulation of the stent interacting with the aorta is needed.

Several static methods were suggested to select an aortic stent. Hemodynamic approach seemed to be the most promising one, but does not give guaranties of complete sealing of the aorta.

Chapter 4

Dynamic simulation of a system of particles

As well the aorta as the stent are represented by a system of particles. The particles are connected by linear and angular springs and dampers. The reason for choosing a system of particles and not, for instance, a more complicated but more accurate Finite Element system, is the fact that we wanted the simulation to be almost real-time. In that case we can test a lot of different stents in a relatively short amount of time, without using big computer power. In this chapter the mechanical model for the stent and aorta will be described according to the system of particles. Next the expansion of the stent will be simulated by Euler, as well as the movement of the aorta. And the last step will be to handle the collision detection and the collision response between the stent and the aorta.

4.1 Mechanical model

A closer look is taken to the linear spring and the angular spring with its mechanical properties and physical equations.

4.1.1 Linear spring

In figure (4.1), a schematic representation of a linear spring and damper connecting 2 particles is represented. The force created by this spring and damper is represented by $F = k_{linear}(l - l_0) + b_{linear}\Delta v$ with k_{linear} and b_{linear} the linear stiffness and damping of the system. And l and l_0, the length and relaxation length of the spring.

$$\overrightarrow{F} = \begin{pmatrix} F_x = F\alpha_x \\ F_y = F\alpha_y \end{pmatrix} \tag{4.1}$$

Because the system is put into 2D, the force is acting also in 2D, according to equation (4.1), were α_x and α_y define the direction of the force.

4.1.2 Angular spring

The angular spring is connecting 3 particles and defines the angle (θ) between them (figure (4.2). The angular spring acts a momentum on M_1 according to $\overrightarrow{M} = k_{angular} * \overrightarrow{\Delta\theta}$, which

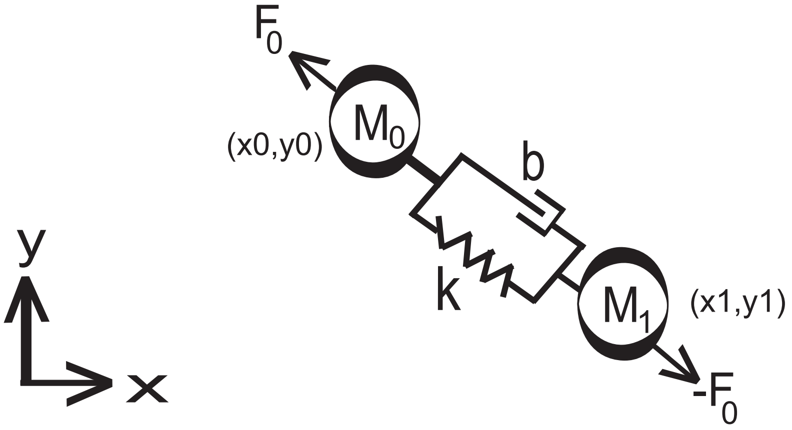


Figure 4.1: Schematic representation of 2 particles connected by a linear spring and damper

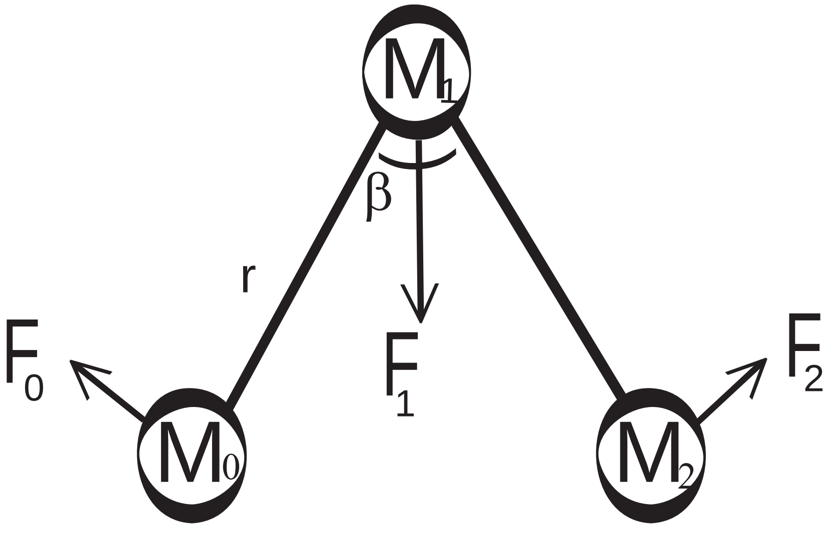


Figure 4.2: Schematic representation of 3 particles connected by an angular spring and damper

is in this 2D case in the direction out of the paper $\odot$. This gives for the forces on M_0 and M_2: $\overrightarrow{F_0} = \frac{k_{angular} * \overrightarrow{\Delta\theta}}{\| \overrightarrow{r} \|^2} \times \overrightarrow{r}$ and $\overrightarrow{F_2} = -\frac{k_{angular} * \overrightarrow{\Delta\theta}}{\| \overrightarrow{r} \|^2} \times \overrightarrow{r}$. Since in every case of a mechanical equilibrium equations (4.2)

$$\sum \overrightarrow{F} = 0 \tag{4.2}$$

$$\sum \overrightarrow{M} = 0 \tag{4.3}$$

has to be true, the reaction force on particle M_1 can be calculated and has to be the opposite resultant of $\overrightarrow{F_0}$ and $\overrightarrow{F_2}$. The forces created by the angular damper are parallel calculated, the only difference in this method is that it is generating a opposite force, to slower the particles, and it uses $\overrightarrow{M} = b_{angular} \overrightarrow{\dot{\theta}}$.

4.1.3 Initial model

The initial model is separated in the initial model for the stent and the initial model for the aorta. In the initial position the aorta will be in complete rest, the flow pattern or change in diameter caused by the beating of the heart is neglected even as the frictions and gravity will be zero. The aorta wall exists of particles connected by linear and radial springs in radial direction. The initial position of the particles can be derived from, for example the information from the CT-scans. The stent in its initial position is far from its relax state, it is put together into the delivering device and is not more then a small round on the position of the catheter. The stent will be represented by 10 particles, this is because one radial spring of the stent shaped as 10 points connected triangular to each other (figure (1.3)).

4.2 Dynamical simulation

The dynamic simulation is used to see the evolution of physical model toward its equilibrium position. To find some nice simulations on the web look for [15] and [16].

According to Newton's Law

$$\sum \overrightarrow{F} = m\overrightarrow{\ddot{x}} \tag{4.4}$$

and

$$\sum \overrightarrow{M} = J\overrightarrow{\ddot{\theta}} \tag{4.5}$$

by these equations the acceleration can be derived from the total force acting on a particle. The forces are known according to the previous sections of linear and angular springs.
The particles are assumed to be point masses and therefor the angular velocity is neglected in the future and the attention will be focused on the forces acting on the particles.

Since our model is not too sophisticated Euler's method (equation (4.6)) can be used to find and simulate the movement of the particles. Note that the equation is for the simulation in a discrete time domain, instead of a continuous time domain.

$$\overrightarrow{x_{t+1}} = x_t + \overrightarrow{\dot{x}_t}dt + \frac{1}{2}\overrightarrow{\ddot{x}}\,dt^2 \tag{4.6}$$

$$\overrightarrow{\dot{x}_{t+1}} = \overrightarrow{\dot{x}_t} + \overrightarrow{\ddot{x}}\,dt \tag{4.7}$$

This simple integration method can lead to unstable states which will make the simulation to blow up. This situation occurs when the forces are to big in respect to the integration time (Δt), or when the velocity of a particle become too high.

$$K_{max} \sim \frac{M}{\pi^2(\Delta t)^2} \tag{4.8}$$

The relationship between the Maximum stiffness K_{max} and the integration time step Δt, is as formula (4.8) [17]. The two situations can be prevented by choosing a small integration time step and not to high values for stiffness and damping factors.

4.3 Collision detection

At curtain point during the simulation, the stent will make contact with the aorta. To know whether there is a contact or collision between the two objects a 'collision detection' is needed. There are lots of possibilities to write a collision detection algorithm and it is certainly slowing down the program if there are a lot of points. Since our model is 2D and does not contain more then 100 particles (including stent and aorta), there is no need for a very sophisticated collision detection algorithm, for instance the method which uses bounding-box. The situation before and after the collision is shown in figure (4.3). The first step in our collision detection is to calculate the signed distance from a point of the stent (M_0) to all the lines between two points of the aorta (M_1 and M_2), according to equation (4.9) and equation (4.10).

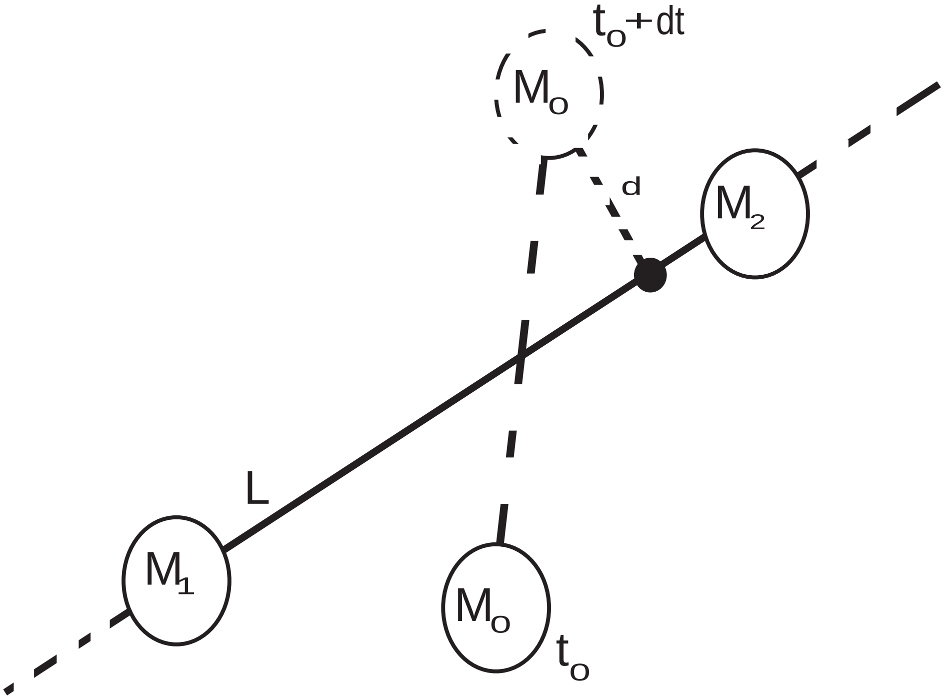


Figure 4.3: collision detection

$$\overrightarrow{n} \cdot (\overrightarrow{Q} - \overrightarrow{0}) + d = signed\ distance \tag{4.9}$$

with $\overrightarrow{n}$ is the normal of the line, $\overrightarrow{Q}$ is the point M_0 and d is the shortest distance from the line to the origin according to equation (4.10)

$$d = \overrightarrow{P} \cdot \overrightarrow{n} \tag{4.10}$$

where $\overrightarrow{P}$ a random point on the line, for instance M_1. Let us now imaging the three possible cases:
Case 1: signed distance == 0, gives the position of M_0 exactly on the line.
Case 2: signed distance $<$ 0, gives the position of M_0 under the line.
Case 3: signed distance $>$ 0, gives the position M_0 above the line.

Note that Case 2 and Case 3 can be inverted when the normal of the line is inverted.

Next thing that has to be checked is whether the point M_0 crosses the line between the two point (M_1 and M_2), since the line does not stop at these two points. This is done by a simple mathematic relation, shown in equation (4.11).

$$R = \frac{(Q-P)\cdot(M_2-M_1)}{(M_2-M_1)^2} \tag{4.11}$$

In case $0 < R < 1$ the point Q is between the two points M_1 and M_2. It may come clear while looking at figure (4.3), that the assumption $dt << 1$ and $d << l$ are necessary for a good collision detection.

Now the collision detection is finished and the collision for one point is detected, the algorithm is applied on all the points according to schema show below.

1. find signed distance from particle stent to all the lines of the aorta
2. if signed distance < 0 and $0 < R < 1$ there is a collision
3. take next particle of the stent and repeat steps 1 and 2
4. if all the particles of the stent are checked use step 1,2 and 3 to do the same for the particles of the aorta.

4.4 Collision response

Now the collision is detected, the two bodies have to be prevented to penetrating each other. This prevention will be the collision response.

4.4.1 Simple collision response

The simple collision response is really a simple collision response and has not a complete physical background. When the collision between a particle of the stent and a bar or the aorta is detected, the velocity of the particle of the stent and the velocity of the particle of the aorta that is the nearest to the collision point, are changed in sign. In this case the direction of movement of the particle after the collision is the same as before the collision but exactly inverted. To improve the real like behavior of the collision response an other approach is needed.

4.4.2 Rigid collision response

Rigid collision response, handles the collision response between 2 rigid bodies, according to [18], which is called "Newton's Law of Restitution for Instantaneous Collisions with No Friction". Since this is a very nice physical grounded approach a closer look is given in the physics.

When the collision is detected, according to paragraph (4.3), the situation looks like figure (4.4). With:

M_1, M_2 the particles of the aorta
M_0 the particle of the stent
$\overrightarrow{v_1}, \overrightarrow{v_2}$ the velocities of M_1, M_2
$\overrightarrow{v_0}$ the velocity of M_0
CM the Center of Mass of M_1, M_2
$\overrightarrow{n}$ the normal of the line between M_1, M_2

Since this method handles a

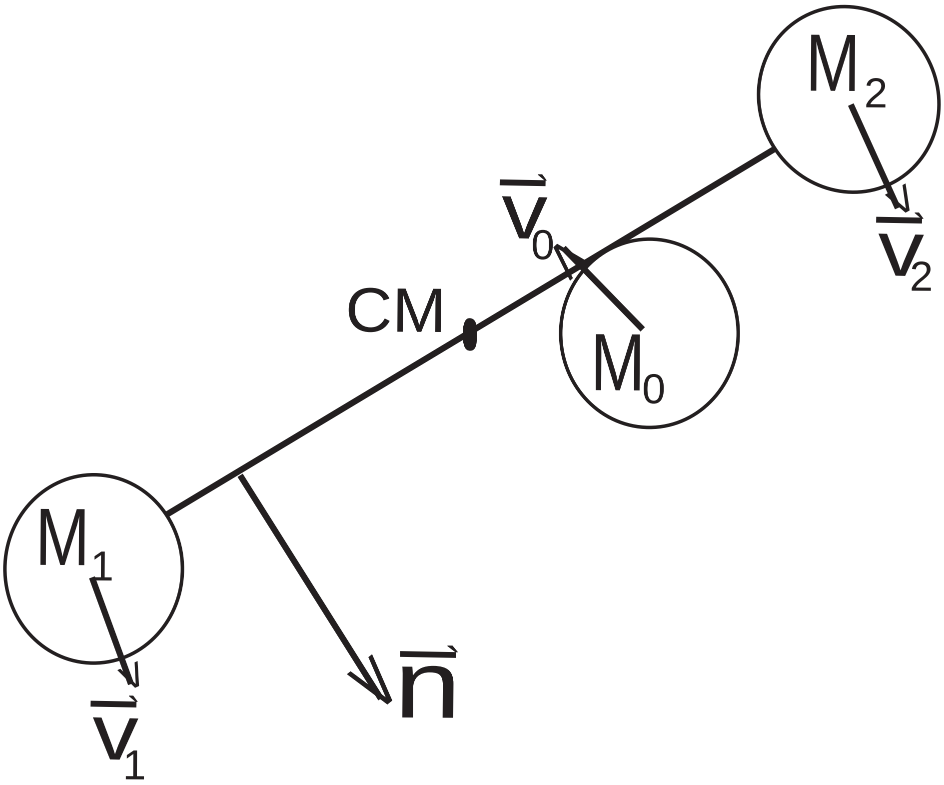


Figure 4.4: Situation when collision is detected

collision of two rigid bodies the first assumption is made that the initial angular velocities are equal to zero and that $\overrightarrow{v_{cm}} = (\overrightarrow{v_1} + \overrightarrow{v_2})/2$. A relative normal velocity can be defined (equation (4.12)) and a third check wether there is a real collision or not, can be performed.

$$\overrightarrow{v_{rel}} \cdot \overrightarrow{n} = (\overrightarrow{v_0} - \overrightarrow{v_{cm}}) \cdot \overrightarrow{n} \tag{4.12}$$

If equation (4.12) is greater than 0, then the points are leaving and there is no collision, if equation (4.12) is equal to zero the points are neither leaving nor colliding, if equation (4.12) is smaller then zero the particles are smashing into each other, and there has to be done something to prevent them to penetrating.
This prevention will be the collision response, that is handled with help of the 'impulse' (j). Since velocities can not change initially but only by forces through integration, the impulse is used to put the particles, that take part in the collision, in the correct direction after the collision. To do so, the impulse has to be calculated and put in the proper equations to calculate the new velocity and velocity direction of the particle. The following equations will show how to calculate the new velocities and impulse.

First

$$\overrightarrow{v_{2_{t+\Delta t}}} = \overrightarrow{v_{cm_{t+\Delta t}}} + \overrightarrow{\omega_{cm_{t+\Delta t}}} r_{\perp} \tag{4.13}$$

with $\overrightarrow{r_{\perp}}$ as the perpendicular distance from CM to the point which new velocity is calculated. By changing the 2 by a 1 the new velocity of $\overrightarrow{v_{1_{t+\Delta t}}}$ can be calculated. The $\overrightarrow{v_{0_{t+\Delta t}}}$ is simplified because the $\overrightarrow{r_\perp}$ is equal to 0 in this case.

$$\overrightarrow{v_{cm_{t+\Delta t}}} = \overrightarrow{v_{cm_t}} - \frac{j}{M_{cm}}\overrightarrow{n} \tag{4.14}$$

$$\overrightarrow{\omega_{cm_{t+\Delta t}}} = \overrightarrow{\omega_{cm_t}} - \frac{\overrightarrow{r_\perp} \cdot j\overrightarrow{n}}{I_{cm}} \tag{4.15}$$

putting equations (4.14) and (4.15) back in (4.13) gives the new velocities according to the impulse. The one thing left to do is to calculate the correct impulse, this is done with the help of equation (4.16).

$$\overrightarrow{v_{rel_{t+\Delta t}}} \cdot \overrightarrow{n} = -\epsilon\overrightarrow{v_{rel_t}} \cdot \overrightarrow{n} \tag{4.16}$$

Equation (4.16) introduces yet another new quantity, the 'coefficient of restitution' (ϵ), that has no dimension and is a factor of elasticity. For example, $\epsilon = 1$ means a complete elastic collision and a total plastic collision for $\epsilon = 0$. Since the $\overrightarrow{v_{rel_t}}$ and the equation for $\overrightarrow{v_{rel_{t+\Delta t}}}$ are known by equations (4.12) and (4.13) they can plugged into (4.16) which leads to equation (4.17) for the impulse.

$$j = \frac{-(1+\epsilon)\overrightarrow{v_{rel}} \cdot \overrightarrow{n}}{\overrightarrow{n} \cdot \overrightarrow{n}(\frac{1}{M_{cm}} + \frac{1}{M_0}) + \frac{(\overrightarrow{r_{\perp CM \to M_0}} \cdot \overrightarrow{n})^2}{I_{cm}} + \frac{(\overrightarrow{r_{\perp M_0 \to M_0}} \cdot \overrightarrow{n})^2}{I_0}} \tag{4.17}$$

Now the impulse is known, it can put into the first equation so the new linear and angular velocities and their correct direction are calculated.

Although the result of the collision response is much better then the simple collision response, some modifications had to be made. The system of the collision between a bar and one mass is rigid, but the total system of aorta and stent is not rigid at all, therefore a third collision response is suggested.

4.4.3 Non-rigid collision response

Non-rigid collision response, handles a collision response between to non-rigid bodies . When a collision is detected, the forces of body 1 are applied on body 2 and visa versa. Since, as is mentioned before in paragraph (4.4.2), velocities can not change instantaneous by applying a different force but only by integrating over time, we will not prevent the two bodies to penetrate each other. Therefore it is necessary that the particle that is penetrating the bar is projected on the bar. In this case the particle has time to change his velocity and there will be a different resulting force acted on both the bodies which will cause a displacement. A nice example is show in [19]. With this method it may also be possible to include friction between the stent and aorta in the model.

As well the simple collision as the rigid collision response are implemented, with a real-like behavior of collision response for the rigid collision response. The simple collision shows some strange behavior, the mass is bouncing back in the same direction as it came from, something that will never happen in reality. The behavior that is created with the rigid collision response, neglects forces by friction and therefore it will be less accurate. Also it may not be able to simulate some states in which the stent and aorta are in an equilibrium. For instance, with the rigid collision response the springs of the stent are all of the same length during equilibrium. In reality it is possible to have an equilibrium where the lengths of the spring are not the same. But a simulation with a rigid collision response does show a good interaction, where the masses of the stent bounce in the right direction with the correct velocity. And a great advantage is that the factor of elasticity can be defined, to create a more or a less elastic collision. Nevertheless it may be useful to implement the non-rigid collision in future research and include friction into the model to increase the accuracy of the model, research at this subject is on this moment performed at MECOBIO [20].

A dynamic simulation model using a system of particles is presented. Different methods to simulate the collision response between stent and aorta are presented. None of them were fully realistic, but showed a real-like behavior. A demonstration of this statement is part of the next chapter.

Chapter 5

The stent planning tool

The total program exits of a catheter insertion, a location for stent placing selection (that are discussed in paragraph 5.5) and a testing environment for the dynamical simulation. Figure (5.1) shows the interface of the testing environment. There are several possibilities to perform in the program, the options will be discussed below.

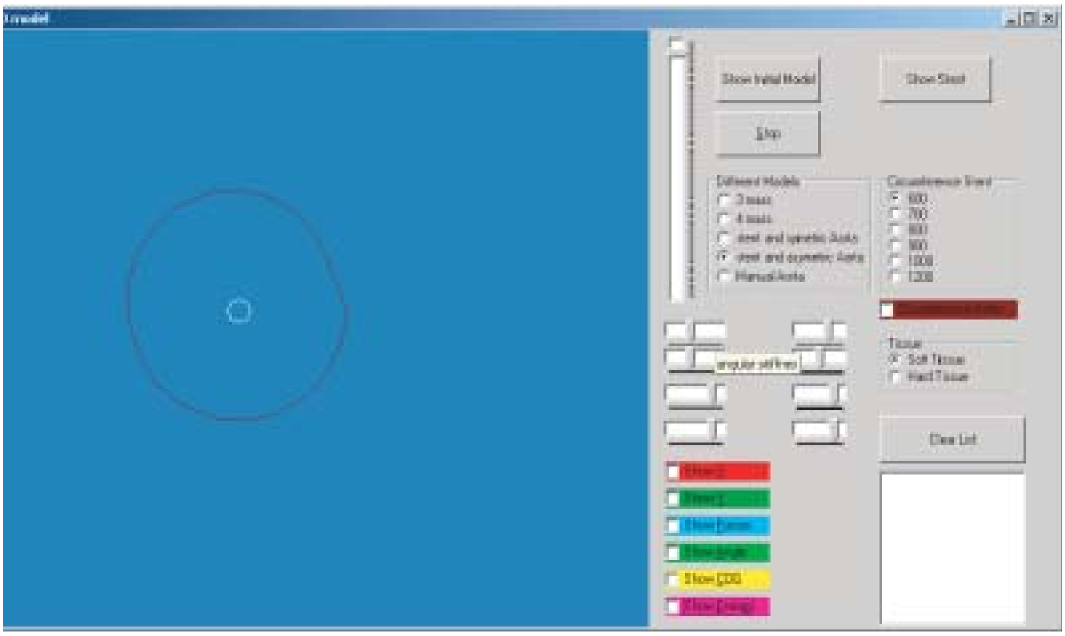


Figure 5.1: The 2D test environment.

5.1 2D test environment

5.1.1 Pre-shaped aorta

There are several preshaped aorta's and stents programmed in the program, two triangles, two rectangular boxes, a perfectly symmetric aorta and an asymmetric aorta. In the last two cases the stent circumference can be varied. In all the cases, first the Model has to be initialized by pushing the 'Initial Model' button. Afterwards the parameters for stiffness can

$k_{linear_{Stent}}$	0.0-0.1 $[\frac{N}{m}]$	$k_{linear_{Aorta}}$	0.0-0.2 $[\frac{N}{m}]$
$b_{linear_{Stent}}$	0.0-0.1 $[\frac{Ns}{m}]$	$b_{linear_{Aorta}}$	0.0-0.1$[\frac{Ns}{m}]$
$k_{angular_{Stent}}$	0.0-100 $[\frac{N}{rad}]$	$k_{angular_{Aorta}}$	0.0-100 $[\frac{N}{rad}]$
$b_{angular_{Stent}}$	0.0-10 $[\frac{Ns}{rad}]$	$b_{angular_{Aorta}}$	0.0-10 $[\frac{Ns}{rad}]$
$k_{Soft_{Tissue}}$	0.0 $[\frac{N}{m}]$	$k_{Hard_{Tissue}}$	1.0 $[\frac{N}{m}]$
$b_{Soft_{Tissue}}$	0.02 $[\frac{Ns}{m}]$	$b_{Hard_{Tissue}}$	1.0 $[\frac{Ns}{m}]$
$m_{particle_{Stent}}$	0.1$[kg]$	$m_{particle_{Aorta}}$	0.1$[m]$
$I_{Bar_{Stent}}$	$\frac{1}{12}mL^2[\frac{kg}{m^2}]$	$I_{Bar_{Aorta}}$	$\frac{1}{12}mL^2[\frac{kg}{m^2}]$
ϵ	0.9 [-]		

Table 5.1: The different tuned parameters of the dynamical model

be initialized by changing the track-bars and the simulation can be started by clicking the 'start simulation' button.

5.1.2 Manual created aorta

There is also the option to create some more sophisticated aorta shape, by the 'manual aorta' in the 'different models' group. By drawing only the stent and by adding points in the image your own aorta will be created.

5.1.3 Soft or hard surrounding tissue

A choice can be made in the simulation of different tissue surrounding the aorta. Although this has almost infinitive possibilities, only two possibilities are programmed.

5.2 Tuning the parameters

It seems possible to create almost every dynamical behavior one can think of. The main goal is to create a dynamical behavior that can represent the interaction of the stent with the aorta. There are 12 parameters that can be tuned, and they are shown in table (5.1), with their corresponding values. Choosing this parameters, gives a highly damped, in-elastic behavior, where the aorta and stent are evaluating in time as discussed in paragraph (2.3). The parameters for the spring stiffness can still vary, in that case it is possible to see different responses in the testing environment. By choosing a *mass* the total of parameters are scaled up or down, because by Newton's law, this should be kept in mind when handling with parameters in the future.

5.3 Data flow during the simulation

It was explained in chapter (4), how the forces, velocities, accelerations and new positions can be calculated. How to take care of collisions and what kind of collision responses can be simulated. With all this information it is possible to run the simulation, but the functions has to be performed in the correct order and both for the stent and the aorta. The data flow and calculation order is shown in figure (5.2), this is meanwhile the same construction of the (in

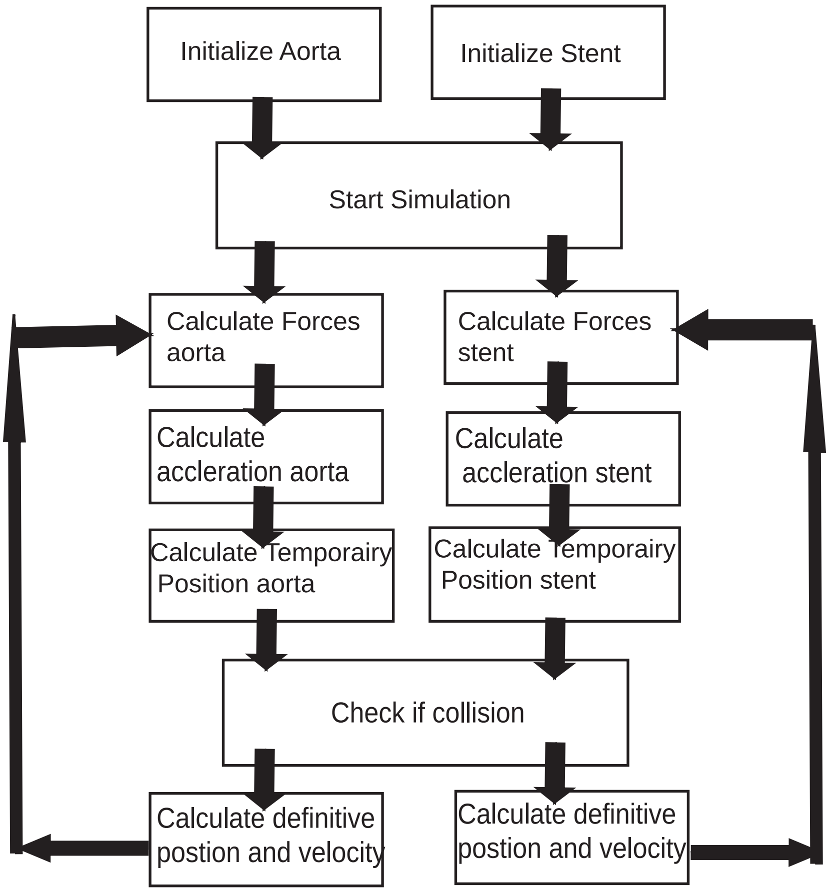


Figure 5.2: A schema of the dataflow during the simulation

C++ programmed) 2D simulation program. First step is to initialize the stent and aorta, in this initialization the relaxation lengths and angles of the springs are given even as the initial position of the both bodies. When the aorta and the stent are initialized, the simulation can be started.
The first step during this simulation is to calculate all the forces acting on the particles, this can be done because the initial position is already known. When the forces are found, the acceleration is calculated according to Newton. After this the new temporarily position of the particles can be found by Euler. This is the temporarily position and not the final because a collision can occur, if so the particle will bounce and will get another position. By performing the collision detection and a collision response, the new final position (of that time step) is located. With the new position of the particles known, the new forces according to that position can be calculated, until the simulation is stopped.

5.4 The final position

The main question, is of course, if it is predictable whether the stent will fit into a blob in the aorta wall, something that was not possible to predict with a static simulation. Therefore a

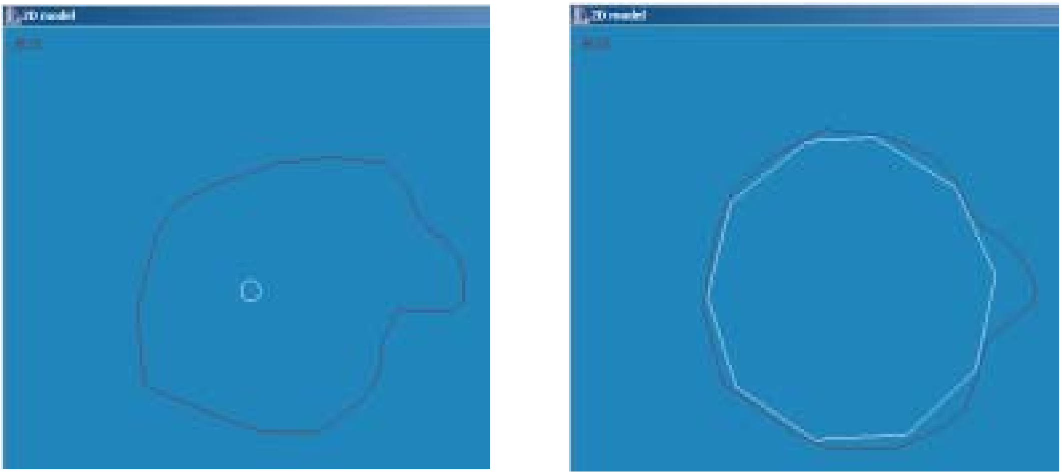


Figure 5.3: *Left:* The initial position of 2D stent and aorta. *Right:* The final position of 2D stent and aorta.

manual aorta is created with a blob (note that this may be not the ideal position to place the stent) and different stents with different diameters are expanded in that location. The aorta is roughly drawn as shown in figure (2.3). In this particular case the circumference of the aorta was $96[mm]$ and we choose circumference of $100[mm]$ for the stent. The initial position of the stent and aorta is shown in figure(5.3) on the left side, whit the stent in white and the aorta in the dark color. It is chosen to model the stent by 10 angular and linear springs and 10 particles. The number of particles is 10, because when one takes a virtual slice of the stent the slice will cross on 10 points the SMA spring. The number of particles of the aorta is chosen to be at least 20, to create a good behavior. The stent is expanded to the final position in figure (5.3) on the right. As it is shown in the final position, the stent will not be able to push completely through the blob and therefore, the stent will not completely seal the aorta. Instead of what we expected with a static simulation, the internal pressure of this stent is not high enough in respect to the aorta wall. Of course there is a remark to this simulation, the parameters can be tuned different so the stent will fit into the aorta. The parameters in this case are tuned as described before, high angular and low linear stiffness stent, low angular and high linear stiffness for the aorta.

The final result shown in figure (2.3), was different then the result in figure (5.3). The first reason for this is the fact, mentioned above, of wrong parameter tuning. Which is quite unlikely, because the linear stiffness of the aorta >> linear stiffness of the stent and the angular stiffness of the aorta was low. The second reason that can make a difference is the choice of a stent, maybe the stent in the reality had a relatively bigger diameter then the one used in this experiment. And therefore could develop more pressure to the inside aorta wall. Of course the experiment can be repeated with different stents to find the same final position of the stent as in figure (2.3), what is done in figure (5.4). Another remark of the simulation is that it is 2D and that eventual 3D torsion effects of the spring are not taken in to account and the constraints are slice related.

Since every aorta is different, and so the parameters of the aorta can be tuned different

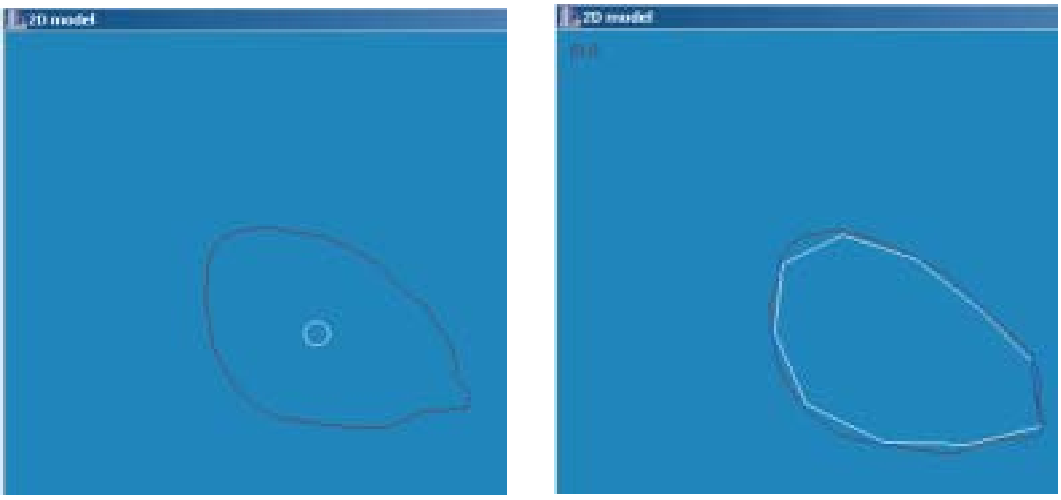


Figure 5.4: *Left:* The initial position of 2D stent and aorta. *Right:* The final position according to reality.

in every case, it is not possible to assure that the simulation is the evolution of stent and aorta during a real-life insertion. It only shows that the insertion of a stent is such a kind of aorta cause extra risk of endoleak. It may be very useful for a surgeon to perform such experiments with different stent and in this way to assure that, knowing the risk caused by the shape of the aorta, he will choose the best possible stent to seal the aorta.

5.5 The total program

The total program consists of a existing program, created by Brian Jacobs (CMV) , and was adjusted and modified by Micaël Rochat (EPFL). The experimental environment was later integrated with this program. A interface of the planning tool is shown in figure(5.5), and shows the 3D aorta and the different sheets. The tab sheets are divided in Catheter, Stent, Debug and Simulation. Some of the sheets will be explained in paragraph 5.5.1, 5.5.2 and 5.5.3. The program is completely created to make it more easy for a surgeon to select a landingzone, with the according dimensions. And next to that to run a dynamical test simulation of the interaction between the stent and the aorta.

5.5.1 Catheter sheet

In the catheter environment, a catheter can be inserted in the 3D aorta (figure (5.6) on the left). The rigidity of the catheter can be changed, as well as the diameter of the catheter. The insertion of the catheter adds a nice visual effect, for the physical background of this insertion Micaël Rochat (EPFL), should be contacted.

5.5.2 Stent sheet

The landing zone, in other words the position were the top of the stent has to placed, can be selected in this feature. Also the position where the bottom of the stent is located can be

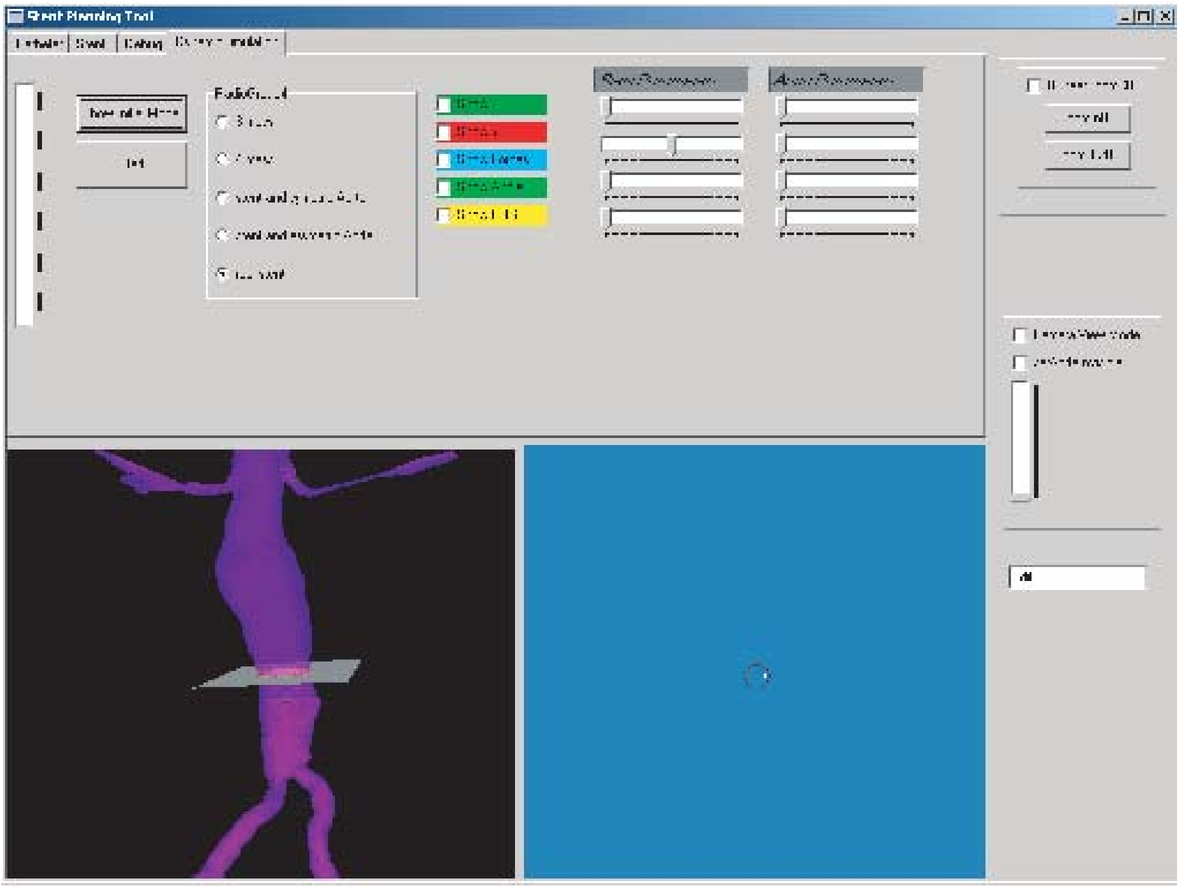


Figure 5.5: The interface of the planning tool.

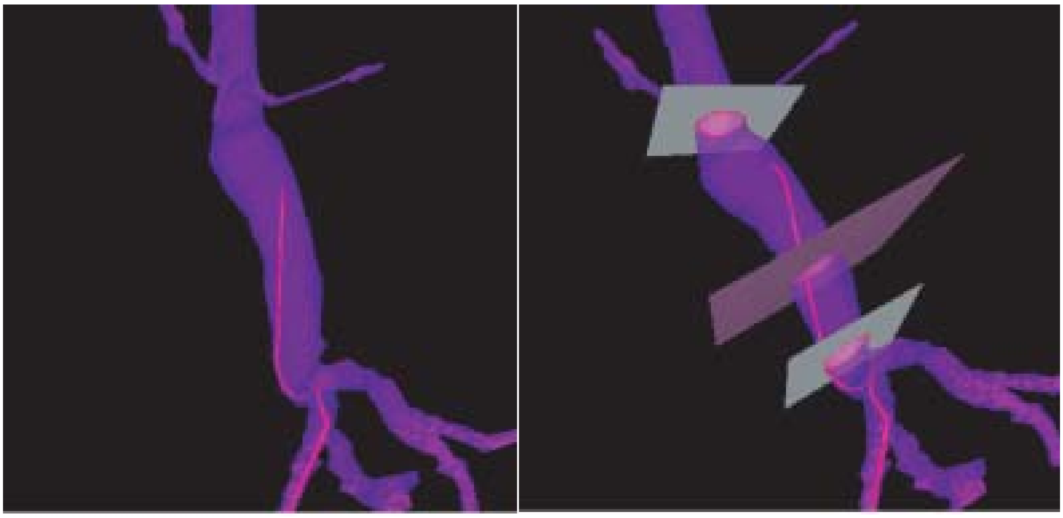


Figure 5.6: *Left:* The 3D aorta with catheter. *Right:* The 3D aorta with the 3 layers.

selected by another plane, see figure (5.6). In the image next to the 3D aorta, a 2D picture is given of the third plane intersection with stent and aorta. This image can provide exact information about the circumference of the aorta/aneurysm. The exact circumference of the aorta will be used for the simulation. As the points of the aorta wall will form the initial model of the aorta.
It is also possible in the stent sheet, to automatically select a stent. The automatically selection is based on the distance between the layer of the top of the stent and the layer of the bottom of the stent. And based on the circumference of the aorta at the position of these layers. The link between the selection of the stent and the initial position of the stent in the dynamical simulation is not yet connected, but may be future work.

5.5.3 Simulation sheet

When the position of placement for the stent is selected in the 'catheter-sheet' in the program, one can continue to the 'dynamic simulation-sheet' and one should be able to run the simulation as shown in paragraph (5.1 t/m 5.4). In this way the both programs can be integrated into each other. At this moment this feature is not 100 % working and it is highly recommended to make this connection between the two programs in future work.

The dynamic simulation is presented and the results of the system behavior are discussed. It seems that a good tuning of the dynamic parameters is hard to handle. The results after tuning were confirmed with a real case study, that validates the theoretic model. At the end of the chapter, the integration of the dynamic simulation and the landing-zone selection is shown, this gives a first impulse to create a complete stent selection program.

Chapter 6

Conclusion and future work

At first anatomy and pathology of the aneurysm were examined. It was show that the classes of aortic aneurysm can be divided in two groups, Thoracic and Abdominal Aorta Aneurysm. Aneurysm can lead to rupture of the aorta and therefore lead to the death of a patient. Two surgical procedures were discussed with their positives and negatives, it was clear that a endovascular surgery of the aorta is preferred to open-surgery. The big disadvantage that occurs with this method is Endoleak. The four types of endoleak were discussed and it was shown that the primary reasons that can cause endoleak are : First, the insertion of a stent with dimensions that did not overlap with the dimensions of the aorta. Secondly, a bad placement of the stent in the aorta. To help the surgeon to choose that stent that will have the same dimensions of the dimensions of the aneurysm (diameter, length), it was suggested to create a surgery planning tool.

To create this planning tool at first a closer look was taken to the aorta and stent. A small **experiment** with rigid tubes was performed to find the **pressure-circumference ratio E_p of the stent**. And it is show that this ratio is an order 10 smaller than that of the aorta and a factor 2 bigger than that of a metallic aortic stent (performed by *MacSweeney and Young*). This was also confirmed by the visual information of scans before and after placement of the stent. From the 3D reconstruction it is possible to retrieve information about the aneurysm (length, diameter) to select a stent.

Because the mechanical properties of both the stent and aorta were retrieved, a static criterium is formulated for the selection of a stent. The **first criterium** that is suggested is the interaction of two perfectly round tubes. By the **formula of radial expansion of a tube and the internal pressure acting on the aorta by the stent**, it will be known if a stent will fit. The **second criterium** to select a stent was derived by the **hemodynamic equation of Moens-Korteweg** and gave a criterium taken care of the circumference of stent and aorta and the internal pressures of both caused by the wave speed. With this method the relationship between pressure and circumference of the aorta was calculated and the pressure-circumference relation from the experiment was used for the stent. At a known circumference of the aneurysm (from the scans), a stent is chosen that has a higher internal pressure than the aorta, at that circumference. The conclusion of both the selection procedures, is that they are sufficient for selection a stent in a aneurysm shaped more or less round. If the assumption is made that the circumference of the aorta where the stent will be placed is more or less round and there is no calcification, this criterium is certainly worth using. Nevertheless in cases were the aorta wall is strangely shaped it gives no guaranty that the stent will seal the aorta and will prevent endoleak. **Because it is needed to known wether the stent will seal the aorta, a dynamic simulation is created that will show the evolution of the expansion of the stent inside the aorta.**

The stent and aorta in the dynamical simulation are represented by a 2D system of particles, connected by angular and linear spring. Although this may not be the most accurate way of simulating the both, it certainly gives the possibility to run the simulation real-time. The collision response is handled by a rigid collision and is therefor semi-rigid. A improvement of the model will be to handle the collision as a collision between two deformable bodies. The next suggestion to improve the model is to simulate the model in a 3D space, the 3D information is completely lost. Since the landingzone of the stent is most of the time not very long (1 cm) and does not change in diameter at that position, the 3D information will add a nice visual effect, but may not give much more information about the sealing of the aorta.
It is also shown, that the dynamic simulation gives a different result of stent selection then the static criterium, when the circumference of the aneurysm is strangely curved.
It is also clear that it is possible to create almost every kind of dynamic behavior in the simulation. The question is: 'What is the correct behavior for the stent interaction with the aorta'. To solve this question, not only 2 static images of the aorta with and without stent, are needed. But a complete movie of the enpension of the stent has to be used. And even when there is that kind of reference material, still the problem consists that every aorta will react different on the impact of a stent.
Nevertheless, the program can help selecting a landingzone for the stent and simulate the expension. Maybe not to assure the stent will seal the aorta, but certainly to add some sort of risk factor (a value for 'goodness' of fit), to every stent and choose that one with the lowest risk factor. This factorization can be performed in the static solution as well as the dynamic solution, in that case the two solutions can be combined.

During the introduction of this report, it came forward that not only the selection procedure of the stent, but also a bad placement of the stent in the aorta can lead to endoleak. To solve the problem of endoleak, the placement procedure of the stent should be improved. Possible ways to do this are, for instance, a better tracing method for the position of the stent in respect to the aorta. This can be achieved by creating a sort of Virtual Environment, or by better imaging techniques. Or one can think of a guiding device that will lead the stent to the correct position.

It may not be possible to predict in every case wether a stent will seal the complete aorta without endoleak, it is important to minimize the risk and help the surgeon as much as possible to select a correct stent. And using mechanical background, can help to prevent a lot of problems.

Bibliography

[1] Gerard J. Tortora, *Principles of Human Anatomy*, Third Edition, ISBN: 0-471-38728-2.

[2] *Metronic, surgery training slides*

[3] *http://www.acponline.org/annals/15mar97/abdomin.htm*, Annals of Internal Medicine 15 March 1997. 126:441-449.

[4] *http://www.musc.edu/radiology/interventional/index.htm*

[5] Gerritsen Frans A., Breeuwer Marcel et al. *Image-Guided Surgery the EASI project European Applications in Surgical Interventions*, PHILPS Medical Systems Nederland BV.

[6] Rochat Micaël *Systèm de Navigation pour la Pose d'Endoprothèses Aortiques*, Département de Microtechnique, EPFL, Switserland.

[7] Alderliesten et al *Simulation of Guide Wire Motion and Deformation for Minimally Invasive Vascular Interventions* (2001)University Medical Center Utrecht, The Netherlands.

[8] Taylor Charles A. Draney Mary T et al. *Predictive Medicine: Computational Techniques in Therapeutic Decision-Making* Stanford University, Stanford, California, USA

[9] http://www.comp.leeds.ac.uk/vis/nuha/websim/el-khalilinh.html

[10] *http://www.rjmatthewsmd.com/Definitions/aneurysm.htm*

[11] S.T.R. MacSweeney, G. Young, R, et al. *Mechanical Properties of the aneurysmal aorta*, British Journal of Surgery (1992) pp. 1281-1284.

[12] Renjun Wang and Krishnaswamy Ravi-Chandar, *Mechanical response of a metallic aortic stent*, The University of Texas at Austin. (2001) http://www.ae.utexas.edu/research/mssm/Stent.html

[13] A. CSillag, *Anatomy of the living human*, ISBN: 3f-8290-4264-7

[14] Y.C.Fung *Biomechanics, Mechanical Properties of Living Tissues*, chapter 8, ISBN: 3-540-97947-6 (Berlin)

[15] *http://www.myphysicslab.com/index.html*

[16] *http://www.sodaplay.com/constructor/index.htm*

[17] J.-C. Latombe, et al *A Stereoscopic Palpable and Deformable Model: Lucy 2.5* University of Stanford, (2000).

[18] Hecker C., http://www.d6.com/users/checker *Physics, part 3: collision response.*

[19] *http://www.cs.unc.edu/ geom/collide/videos.shtml*

[20] MECABIO - ECOLE SUPERIEURE DE MECANIQUE DE MARSEILLE http://www.technopole-marseille.com/site/servin.htm

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