Optimal catheter selection for anomalous Right Coronary Arteries (RCA)

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Abstract

During coronary artery angiography, a catheter is used to inject a contrast dye into the coronary arteries. Due to the anatomical variation of the aorta and the coronary arteries in different humans, one common catheter cannot be used for all patients. The cardiologists test different catheters for a patient and select the best catheter according to the patient's anatomy. To overcome these problems, we propose a computer-aided catheter selection procedure. In this thesis we present our approach for patient specific optimal catheter selection for the angiography of the coronary arteries with high take off. It involves segmentation of the aorta and coronary arteries, finding the centerline and computing some geometric parameters.

These parameters include computing coronary arteries curve angle (CACA), distance of the ostium from the aortic valves (DOAV) and the aorta diameter (AD) near the ostium. We then consider catheters and compute the tip angle of the catheter (CTA), catheter curve two depth (CC2D) and catheter curve two width (CC2W). We then compare CACA with CTA, DOAV with CC2D, AD with CC2W and suggest a catheter that is the closest to the patient’s arteries geometry. This solution avoids testing of many catheters during catheterization. The cardiologist already gets a recommendation about the optimal catheter for the patient prior to the intervention.
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Contents

1. Introduction .................................................................................................................................................. 9
  1.1 Angiography .............................................................................................................................................. 9
  1.2 Catheters .................................................................................................................................................. 10
  1.3 Magnetic Resonance Images ...................................................................................................................... 11
  1.4 Insight Segmentation and Registration Toolkit (ITK) .............................................................................. 13
    1.4.1 Image .................................................................................................................................................. 13
    1.4.2 Pixel Access ...................................................................................................................................... 13
    1.4.3 Reading an Image .............................................................................................................................. 13
    1.4.4 Writing an Image .............................................................................................................................. 14

2. State of the Art ............................................................................................................................................. 15
  2.1 Novel diagnostic catheter designed for angiography via the right trans-radial approach .......... 15
  2.2 Evaluation of Four versus Five French Catheters for Trans-femoral Coronary Angiography ... 16
  2.3 Use of 5 French Catheters for Cardiac Catheterization and Coronary Angiography................. 17
  2.4 Guiding catheter selection for right coronary artery angioplasty .................................................... 18
  2.5 Catheter Selection for Coronary Angiography and Intervention in Anomalous RCA ............. 19
  2.6 Patient specific optimal catheter selection for right coronary artery ............................................ 21
  2.7 Patient Specific Optimal Catheter Selection for the left coronary artery ..................................... 22

3. Procedure .................................................................................................................................................... 24
  3.1 Computing parameters from patients image data ................................................................................. 24
    3.1.1 CACA .............................................................................................................................................. 25
    3.1.2 DOAV .............................................................................................................................................. 26
    3.1.3 AD ................................................................................................................................................. 27
  3.2 Computing catheters parameters ........................................................................................................... 29
  3.3 Calculating the Radius of the RCA ......................................................................................................... 29

4. Implementation ......................................................................................................................................... 32
  4.1 Coronary Arteries Curve Angle (CACA) ............................................................................................... 32
  4.2 Aorta Diameter (AD) ............................................................................................................................. 34
  4.3 Distance of the Ostium from the Aortic Valves (DOAV) ..................................................................... 34
  4.4 Radius of RCA ....................................................................................................................................... 35

5. Experimental Results ............................................................................................................................... 38
  5.1 Patient One ............................................................................................................................................. 38
5.2 Patient Two .................................................................................................................................41
5.3 Patient Three ..............................................................................................................................44
6. Discussion ......................................................................................................................................48
6.1 Further Expected Improvement ................................................................................................48
  6.1.1 Calculating Radius of RCA ..................................................................................................48
  6.1.2 Calculating the Take off of RCA ........................................................................................48
6.2 Conclusion ..................................................................................................................................48
6.3 Future Work ................................................................................................................................49
7. References .....................................................................................................................................50
Chapter 1

Introduction

Aorta is the largest artery in the human body, originating from the left ventricle of the heart and extending down to the abdomen. The aorta distributes oxygenated blood to all parts of the body. During angiography generally the aorta is used to push the catheter inside the human body. Due to the anatomical variation in different humans, one common catheter cannot be used for all patients. Cardiologists test different kinds of catheters and use the best catheter for a specific patient. This is a time consuming and risky task. This thesis work will suggests a computer aided catheter selection procedure. This chapter will discuss introduction, basic knowledge and tools to understand the approach.

1.1 Angiography

Angiography is the inspection of the heart blood vessels, i.e., Left Coronary Artery (LCA) and Right Coronary Artery (RCA), through catheterization and Magnetic Resonance Imaging (MRI). Angiography gives doctors precise information about arteries and helps them to plan the most outstanding cure for the patient.

An angiography procedure is done and monitors by a cardiologist who specializes in minimally-invasive, targeted treatments using imaging guidance. During the angiogram, the cardiologist injects a sterile flexible tube (a catheter) into one of arteries through a very small cut in the skin. There are two ways to insert the catheter in the patient. The first one is from the arm and it enters in the aorta from the Innominate artery [10] and the second one is from lower abdomen (Fig 1.1).

![Diagram of angiography](image.png)

Fig.1.1. Catheterization from Arm and Catheterization from Abdomen [1]
The cut is too small i.e. the size of a pencil tip. For the arteries visibility, a type of dye called “Contrast agent” is then injected. The contrast agent makes the artery visible and images can be taken (Fig 1.2 (a)). The Angiogram helps doctors to investigate the disease and plan the best cure for the patient.

![Angiogram Image](image)

Fig.1.2. Coronary Arteries, after injecting contrast (a), Aorta with complete ending (b) [2]

### 1.2 Catheters

A catheter is a pipe which is inserted into the human body. Catheter permits drainage and direction of fluids like blood and urine. The process of inserting a catheter is called catheterization. Mostly, a catheter is a thin, flexible pipe, though sometimes, it is a larger, solid catheter. A catheter which is left inside the body, either temporarily or permanently may be referred to as an indwelling (implanted) catheter.

Catheters are made of different varieties of polymers which include silicone rubber, latex, and thermoplastic elastomers. Because of the silicone static property is widely used polymer. It is not harmful to body fluids and a series of medical fluids with which it might appear into contact. While, the polymer is not strong, catheters can face breakages.

For the selection of catheter, careful guidance is very necessary. There are too many kinds of catheters available in the market. Each of them has different angle, length and curve. Some of them have multiple curves too. For example, for the angiography of LCA usually left judkins catheter is used. According to the regions in left artery other catheters are used e.g. Amplatz catheter is required for superior or posterior angioplasty of LCA. There is a problem in the angioplasty of RCA because of the unpredictable nature of proximal segment and origin of RCA. In this case choice of catheter to be used becomes more challenging. Height of RCA varies due to the aortic shapes, degree of orientation of posterior or anterior of aorta and arteries and severity of anomalous but the most important factor which affect the selection of catheter are the origin and the curve angle of RCA [18] as well as take off of the coronary arteries.

Choice of suitable catheter in different situation is the key point for the success of coronary angiography. Coaxial and stable position between the proximal segment and aorta is achieved only when suitable catheter is used. Some types of catheters are shown in Fig 1.3.
1.3 Magnetic Resonance Images

Human body needs oxygenated blood. Heart is the organ which supplies the fresh oxygenated blood to the whole body. Lungs take de-oxygenated blood from heart and returns back the oxygenated blood. Heart can be divided into four parts as its functions; Right ventricle, left ventricle, right atrium and left atrium (Fig 1.4).

Right atrium receives de-oxygenated blood from the body and right ventricle pumps blood into the lungs while Left atrium receives oxygenated blood from the lungs and left ventricle pumps blood to the body.

If there is any kind of interruption in the flow of blood, then it is very necessary to examine the function of the heart. For this problem, doctors advise for angiography, which is done using MRI. MRI is an imaging method which uses powerful radio waves and magnet waves to produce the detailed and rich information of heart tissue’s and muscle’s images. This is a medical imaging method, which provides the three dimensional (3-D) data [6].

These MR Images contains too much information and data in them. Even for a technical person it is too difficult to understand and locate the aorta, RCA, LCA etc. So, for this purpose, to extract the desirable information and data from MR Images; image segmentation process is performed. This process is to locate the objects and boundaries in the image. For the suggestion of the catheter, geometrical model of the aorta must be known.
An MRI data contains many two dimensional (2-D) images to express 3-D organ. These 2-D images are basically in a form of slices (Fig 1.5).

MR images have very large applications in medical computing to diagnose and surgery planning. These images provide information for the doctors to analyze the heart and related functioning.
1.4 Insight Segmentation and Registration Toolkit (ITK)

The Insight Segmentation and Registration Toolkit (ITK) is a C++ class library which is cross platform and is open-source. This library is for registering and segmenting and analyzing the image. This C++ class library includes the image processing of multidimensional medical data or images. It has the same mechanism for garbage collection, a garbage collector in it, for efficient use of memory. ITK also uses smart pointer [4].

1.4.1 Image

Every image in ITK has its own information about size, dimensions, origin and number of pixels.

1.4.2 Pixel Access

Pixels of particular image can be accessed by the following ways:

- Direct Access to a Pixel
  ImageName.GetPixel ([index])
  Although this approach is very slow because it is time consuming to access each pixel. But sometime this approach is very helpful, if the exact index is known.
- The Pixel is accessed by Image Iterator
  This is an iteration connected to the image, and each pixel of the image can be accessed (Fig 1.7).

1.4.3 Reading an Image

Before processing any image, it is necessary first to load that image in some variables and/or in memory. For reading an image it is necessary to define the dimensions and the pixel type of the image. (Note: this code is only for understanding the image reading code format; this will not run as it is.)

Type def itk:: Image <char Pixel Type, int Dimension> Image Type;
Type def itk:: Image File Reader <Image Type> Reader Type;

![Fig.1.7. Image Iteration method in ITK::Image](image-url)
Create a reader pointer and object of Reader Type, to read the image:

```cpp
Reader Type:: Pointer reader = Reader Image:: New ();
Reader->SetFileName(char *inputFilePath);
Here inputFilePath is the complete path of the image.
```

```cpp
Reader. Update ();
Image Type:: Pointer image = reader-> GetOutput ();
```

1.4.4 Writing an Image

Writing method is same as the reading method, but the main difference is to tell the method complete name with path. (Note: this code for understanding the image writing code format; this will not run as it is.)

```cpp
Typedef itk:: Image <char Pixel Type, int Dimensions> Image Type;
Typedef itk:: image file writer <Image Type> writer type;
```

Create a write pointer and object of write Type, to write the image:

```cpp
WriterType::Pointer writer = WriterType::New();
typedef itk::ImageFileWriter<ImageType> WriterType;
writer->SetFileName( outputFileName );
```

output file name is the complete name with path.

```cpp
writer->SetInput(inputImage);
writer->Update();
```
Chapter 2

State of the Art

Angiography is used to investigate the blood vessels by the help of a contrast agent, which is injected into the arteries through a catheter. In this method, MR Images of the blood vessels are produced.

There are geometrical variations in the aorta and coronary arteries of different humans and one common catheter cannot be used for all patients. The cardiologists test different catheters for a given patient and select the best one with respect to the anatomy and geometry of the patient.

This process is taking too much time and there is a slight chance of cancer [23] from excessive radiations. After this whole procedure there is also a possibility that a selected catheter mismatched with the geometry of the aorta and coronary arteries leads towards internal bleeding.

Literature related to optimal catheter selection discusses general concepts of the aorta and the coronary arteries shapes but it lacks the patient’s specific catheter selection.

2.1 Novel diagnostic catheter designed for angiography via the right trans-radial approach.

Trans-radial method is the method of catheterization using the radial artery from the wrist to approach the heart and coronary arteries (see Fig 2.1). This approach is becoming the alternative approach for angiography.

Campeau [7] in 1989 took some initial steps and did some trans-radial attempts for catheterization. This patient friendly method was refined by Kiemeneij and Laarman [8, 9]. Kim [10] discusses about the novel catheter (5F Tiger-II by Terumo Co., Tokyo, Japan) in Fig 2.2, which is manufactured for engaging left and right arteries from the right trans-radial artery approach. This Tiger-II and standard judkins was applied on 160 patients randomly by making two groups. One of Tiger-II and second one were of judkins group. Judgment points were the duration of procedures, the quality of image and catheters performance. Patient’s resume activity was noticeable after the procedure and was appreciated as this evades the long bed rest. There was noticeable difference in both groups. Tiger-II took 40% less time in x-ray imaging time and 33% less in total procedure time.
This angiography was done by the arm, where wrist was next of hip and upward. Approach was right radial and it was cannulated with twenty gauge needle, and 0.021’ guide wire was passed through the needle. Then 11cm long 6F radial cover was inserted. Also 3-mg of dinitrate and 3-mf verapamil was introduced in it to prevent contraction of arterial mussels [10]. Here Fig 2.3 shows the procedure, how to operate this kind of catheter.

Out of 160 patients just 7 were failed by tiger-II and judkins left catheters took pace to complete the task. It observed that patients feel pain with judkins specially at replacing time. Careful and gentle rotation from left artery to right artery is needed. For RCA it took 40% less procedure time and 33% less x-ray time. Tiger-II provides 100% better right coronary angiograms. As it completed 100% right coronary angiograms and randomized catheters completed 95% of them. For the left coronary angiography there was no considerable difference 91% from Tiger-II and 98% from randomized judkins. The tiger-II catheter is mainly useful for those who are conscious about the procedure time and also having the concern about the experiencing the radiation. As the tiger-II catheter took less procedural and x-raying time.

2.2 Evaluation of Four versus Five French Catheters for Trans-femoral Coronary Angiography

The French gauge (Fr) system is frequently used to measure the diameter of the catheter. Larger Fr number means a larger diameter catheter (see Table 2.1). The conversion from Fr system to System International (SI), unit millimeter (mm) has the following mathematical relation:

\[
Diameter \ (mm) = Fr/3 \quad (2.1)
\]
<table>
<thead>
<tr>
<th>Fr number</th>
<th>Diameter mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>1.35</td>
</tr>
<tr>
<td>5</td>
<td>1.67</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 2.1 Mathematical relationship between Fr and SI unit system

For coronary angiography, use of small catheters has been increased in order to prevent complications and saving the cost [11]. Because of the coronary Ostia, dislodgement frequency 4Fr catheters are seem to be difficult to use hence making the usage procedure long and increase the fluoroscopy time [12]. This is the reason for preferring 5Fr diagnostic catheters. But the fact is that the quality of coronary opacification in 5Fr catheter is not that much good as in 4 Fr catheters [13].

Most of the coronary angiography can be done by a 4Fr catheter. For attaining complete procedures size, catheters above than 5Fr were not necessary. For both of the catheters (4Fr and 5Fr) relative feasibility issue of coronary angiography was considerable. Usually fluoroscopy time does not vary for two catheters; crossover exchange was required in both groups for obtaining sufficient coronary Ostia intubation in LCA with 4Fr group and of right coronary artery in 5Fr group. During procedure no remarkable raise in streaming or Ostium dislodgment is observed in the 4Fr group as compared with the 5Fr group. No significant difference was noticed during the avoidance of local vascular complications between catheter sizes, but this study had no statistical power. However, difference in ecchymosis occurrence had been observed. A decrease in hemorrhage compression time was noticed during the comparison of 4Fr and 6Fr catheters [13]. While this noticeable advantage becomes uncertain when compared with 5Fr size catheters. These factors made both 4Fr and 5Fr size catheters compatible with outpatient coronary angiography when joint with 4 hour or less of bed rest post procedure.

No difference is observed in reliability, feasibility and efficiency of catheter size about vascular complication rates with both 4Fr or 5Fr diagnostic catheters and no considerable distinction was verified regarding procedural characteristics, coronary contrast quality, or local vascular damage. Though, one patient passed by in the 5Fr group and two in the 4Fr group.

2.3 Use of 5 French Catheters for Cardiac Catheterization and Coronary Angiography

Many centers tried using the 5 French catheters and mentioned that: “the smaller arterial puncture site may decrease both recovery time and the number of complications” [14, 15].

In most cases they were of equal quality to those found with larger catheters, where rate of complication for small size production was very low and could assist former ambulation. Some technical problems related to these catheters were found but was certainly overcome where no problem found in large catheters. The post-catheterization recovery time was reduced by 1 hour from routine of 8 hours. The
study concludes that 5 French catheters are ideal for most heart catheterization and are now used regularly in casual cardiac catheterization [22].

2.4 Guiding catheter selection for right coronary artery angioplasty

Judkins catheters have designed in such a way that they have a noticeable longevity and are still dominating. Some modifications have been done according to the requirement of treatment in angioplasty so for the selection of catheter, careful guidance is very necessary. For the angioplasty of LCA, usually left judkins catheter is used [16]. According to the regions in left artery other catheters are used e.g. amplatz catheter is required for superior or posterior angioplasty of LCA. There is a problem for the angioplasty of right RCA because of the unpredictable nature of paroximal segment and origin of RCA. In this case choice of catheter to be used becomes more challenging. There are variations in the width and shape of the aorta from the ascending side. Most useful angle for proximal segment of RCA is the left anterior oblique (LAO) radiographic view. Following angles types in proximal RCA has been observed [17].

**Type 1:** 90° angle from the aorta (Horizontal angle), in this type RCA comes out of the aorta by making horizontal angle from the right sinus of the Valsalva as in Fig 2.4 (a). For this type judkin curve catheter with the distal tip is horizontally aimed at meeting of RCA orifice.

![Fig.2.4. (a) Horizontal angle, (b) Upward angle, (c) Downward angle, (d) Anomalous origin of RCA [17]](image)

**Type 2:** Less than 90° degree angle from aorta (upward angle): noticeable upward angle during this type is seen as in Fig 2.4 (b). Angle between RCA to the proximal segment and RCA origin is a challenge for passing the catheter and guide wire through the RCA. A range of guiding catheters may lead to direct tip orientation on RCA engagement, in a result of this coaxial alignment of catheter tip and proximal vessel segment is achieved.

**Type 3:** Greater than 90° angle from aorta (downward angle): This downward angle of RCA is a less common and may create a trouble for right judkins catheters (Fig 2.4 (c)). For the angioplasty of this type catheters with directed tips, such as right venous bypass, multipurpose are used. Coaxial association with the proximal vessel segment is achieved successfully with amplatz or stertzer catheters as with judkins curve.

**Type 4:** Anomalous origins: Long horizontal proximal segment in LAO projection of RCA may show an angle of proximal vessel orientation positive for use of judkins curve, but this long vessel usually
symbolize an ectopic origin, valued more readily in an RAO projection (Fig 2.4 (d)). Amplatz, stertzer, venous bypass or king configuration catheters are the best recommendations in this type of situation. Noticeable proximal RCA tortousity have impact on selection of guiding catheter. Visible twisted origin of RCA has a major effect for selecting guiding catheter. This twisted origin requires additional backup to proper insert in the coronary. This provides stability but position of steno-sis affects the choice of guiding catheter. Severe steno-sis in tortuous artery needs optimal coaxial arrangement of guiding catheter. For this case balloon catheter with low profile is used [17] and many catheters are present with side holes. These holes allow ante grade flow into artery through the catheter. Failure of contrast injection through side holes and low reliability in pressure measurement during angioplasty are the disadvantages of side holes catheters [19, 20]. For angioplasty choice use of hardware is based on many criteria e.g. for tortuous artery, traceable catheter is required. Choice of suitable catheter in different situation is the key point for the success of coronary angioplasty. Coaxial and stable position between the proximal segment and aorta is achieved only when suitable catheter is used [16]. Lumen guiding catheter is newly introduced; these catheters increase the flow rates and contrast volume for the visualization of angioplasty. These catheters have a soft tip to allow safe deep arterial engagement.

2.5 Catheter Selection for Coronary Angiography and Intervention in Anomalous RCA

Sarkar [21] found that about 20% of the heart patients has the problem in anomalous origin of the RCA. The selection of the right catheter is very critical for the successful angiography. In this method cardiologist divides the gathered 24 angiograms data into four parts. An imaginary line has drawn from the top of the left coronary to the top of the right coronary arteries. This line divides the aorta horizontally. One more line drawn parallel to the first one but passing from lower corner of the ventricle outflow tract. This line divides the aorta from the ventricular outflow tract. Then third and last line drawn from the top of the aorta till the end of the aorta, this divides the aorta vertically. Based on these line locations of four points of anomalous vessel are described [21] (Fig 2.5):

- A. Origin from the aorta above the Sino-tubular plane
- B. Origin just below the ostium of the left LCA.
- C. Origin below the Sino-tubular plane between the midline and the LCA.
- D. Origin along the midline.
More than forty thousand operations among which more than eight thousand Percutaneous Coronary Intervention (PCI) were performed at hospital in 4.5 years. Information of 24 patients is as follows [21]:

Type A was found in four patients, that is above the left Sino-tubular plane. For three of them Forward Take off Judkins (FL) catheter successfully used and one patient required Femoral Curved Left (FCL). Type B was in five patients, this is below the origin of LCA. In four cases among five, FCL3.0 or 3.5 was successful. Type C was common and it was in nine patients, in which RCA originating from between the LCA and the midline. At this originating point Voda Left (VL) was successful in eight cases out of nine. Type D was in just six cases, where anomalous RCA originating in or from the midline of first and third lines. In this type of anomalous RCAs; Amplatz Left 1 (AL1), Amplatz Left 2 (AL2) and Amplatz Left 3 (AL3) were used in three, one and one patients respectively [21].

Forward take off judkins (FL) was successful to engage the anomalous RCA, having origin above the LCA and moving lower to the right. FCL catheter was most successful to engage the Type-B RCA. For the RCA’s whose origins are below the LCA; enhanced FCL curve catheters were best for them. Finally for the RCA’s having origin between the midline and left coronary sinus and just below the Sino-tubular plane; Voda (VL) catheter was best to provide the backup. Some common guiding catheters are as in Fig 2.6.
2.6 Patient specific optimal catheter selection for right coronary artery

Rahman and others [23] are the first to provide solution for catheter selection based on patient’s image data. They consider the RCA curve length and curve angles as well as catheter’s curve length and curve angle and suggest an optimal catheter for the RCA based on these computations (Fig 2.7).

Fig.2.7. (a) Original Catheter, Digitizing, drawing vectors and calculation Angle at point P [23]

However the above mentioned algorithm provides solution only for the RCA with normal origin and shape of artery. Abnormal origin of RCA may have many kinds of problems. Like take off of the abnormal RCA, angle of RCA and diameter of artery etc.
2.7 Patient Specific Optimal Catheter Selection for the left coronary artery

Rahman and others [24] present an approach for the catheter selection of the LCA. Their approach involves segmentation of the aorta and coronary arteries from the MR Images, then finding the middle line and calculating different geometric parameters like curve angle of LCA, LCA opposite side wall curve angle and Aorta Cavity Length (ACL). These parameters are shown in Fig 2.9. Then they compute the catheters parameters. Finally by comparing both parameters they suggest a catheter which is approximately have same parameters as patient’s aorta has. This whole system avoids testing of different catheters during catheter selection process. So cardiologist already gets a recommendation about the optimal catheter for the patient prior to the selection process.

To the best of our knowledge no one has suggested patient specific optimal catheter selection for the coronary arteries with high take off.
Chapter 3

Procedure

In this chapter approach for patient specific optimal catheter selection for the angiography of the coronary arteries with high take off is presented. It involves segmentation of the aorta and coronary arteries, finding the centerline and computing some geometric parameters. These parameters include computing coronary arteries curve angle (CACA), distance of the ostium from the aortic valves (DOAV) and the aorta diameter (AD) near the ostium (Fig 3.1). Consider catheters and compute the tip angle of the catheter (CTA), catheter curve two depth (CC2D) and catheter curve two width (CC2W) (see Fig 3.2). Then compare CACA with CTA, DOAV with CC2D, AD with CC2W and suggest a catheter that is the closest to the patient’s arteries geometry.

![Fig.3.1. Naming parameters of aorta and coronary arteries, these are necessary in the catheter selection process](image)

In the next sections explanation of computing these parameters is available.

3.1 Computing parameters from patients image data

3.1.1 Coronary Arteries Curve Angle (CACA).
3.1.2 Distance of the Ostium from the Aortic Valves (DOAV).
3.1.3 Aorta Diameter (AD).
3.1.1 Coronary Arteries Curve Angle (CACA)

There are four points (dots on yellow curve line A, B, C and D) starting and ending points are already known by computing RCA curve using the concept given in [23]. Tangent line is calculated by using the known RCA curve. Mathematically, to draw a straight line minimum two points are required, so considering the first two blue dots in aorta (point A and B) and draw a straight line towards the bottom (line AE in Fig 3.3). Then considering the next two points (point D and C) and draws a line in the direction of the LCA (line DF in Fig 3.3). These lines intersect each other at point P (Fig 3.3). Now it is easy to calculate required RCA angle by three points (\( \angle DPE \)).
3.1.2 Distance of the Ostium from the Aortic Valves (DOAV)

The coronary arteries take off depends on the distance between the ostium (branching point) and the aortic valves.

<table>
<thead>
<tr>
<th>Take off</th>
<th>Distance from aortic valves</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal take off</td>
<td>1 - 1.5 cm</td>
</tr>
<tr>
<td>High take off</td>
<td>&gt;1.5 cm</td>
</tr>
<tr>
<td>Low take off</td>
<td>&lt; 1cm</td>
</tr>
</tbody>
</table>

Table. 1. Take off of the coronary arteries

There are three types of origins for coronary arteries (Table 1). Further this report will provide all the necessary information for both take offs i.e. for high take off and for low take off (abnormal origin of RCA) and select the optimal catheter for arteries with high take off. In high take off, catheter gets back-up from the aortic valves (Fig 3.3).
In these abnormal takeoffs different kind of information is required. The first one is the angle of the RCA; this is the angle from the end of aorta to the start of RCA. This can be seen more clearly in Fig 3.3, a green curve line. Here yellow line is the RCA curve and green line in Fig 3.3 is showing the required angle for the RCA curve angle. To calculate the DOAV, a line is drawn using two points A and B towards the aortic valves. Then computing the last non-zero pixel on the line, line EA (Fig 3.3). DOAV calculated using distance formula for the line PE (Fig 3.3). Here P is the intersection of the line AE and line DF.

3.1.3 Aorta Diameter (AD)

Aorta diameter is also an important parameter for optimal catheter selection.
The idea is to calculate the slope of the line AB (black line in Fig 3.7). By using two points, point A and point B, slope of line AB can be calculated by using following slope formula;

\[ m = \frac{x - x'}{y - y'} \]  \hspace{1cm} (3.1)

Where \((x, y)\) coordinates are of point A and \((x', y')\) coordinates are of point B. From these points, calculating the slope of the line, perpendicular to line AB. Mathematically perpendicular line has following relation of slope;

\[ m = \frac{-1}{m'} \]  \hspace{1cm} (3.2)

Here \(m\) is the slope of the line AB and \(m'\) is the slope of perpendicular line \(OO'\). By using slope of line \(OO'\) (\perp \text{ to } AB\) following conditions has to be satisfied as in Fig 3.7;

\[ (x - x') = m' (y - y') \]  \hspace{1cm} (3.3)

Basically the requirement is to search a perpendicular line (\perp) on the point \(A\). Slope \(m'\) will be the slope of line \(OO'\) and point A’s coordinates will become \((x, y)\). Two times, two finite loops calculate the non-zero location in binary image. One is for point and another one is for point \(O'\).
3.2 Computing catheters parameters

In Fig 3.2 the catheters parameters are shown. The catheter tip angle is shown by the red curve. The catheter curve two width CC2W is represented by green line and the curve two depths is represented by the blue line. These parameters are computed for all the catheters.

Radius of RCA is also computed which can be used for optimal catheter selection in future work.

3.3 Calculating the Radius of the RCA

First task was to calculate the radius of the RCA. For this purpose, there is ITK gradient image filter to get the gradient images Fig 3.8 (b).
Calculation starts from point B in Fig 2.8 (c) or point B in Fig 3.8 (b). For every point of centerline image (center of gradient or binary image) algorithm is calculating the line of equation, using the second next pixel. Let’s say a point D is the second next pixel of point B. Then equation 1 can give the slope (m) of the small line;

$$x - x' = m(y - y')$$  \hspace{1cm} (3.4)

Here (x,y) is the location of point B and (x',y') location is of point D. Basically nearest pixel is needed, but if nearest pixel is found then possibility of wrong selection is high.

For correct pixel, slope of perpendicular line of point B (in any direction) is needed. Mathematically if two lines are perpendicular to each other, then relation between slopes can be defined as;

$$m = -\frac{1}{m'}$$  \hspace{1cm} (3.5)

Here $m'$ is the slope of perpendicular line. Now any pixel location$(x',y')$, which will satisfy the following equation, will be the nearest and perpendicular to that specific pixel;

$$\text{point B (}(x) - x' = \frac{1}{m}(\text{point B (}(y) - y')$$  \hspace{1cm} (3.6)

Or

$$m'\{\text{point B (}(x) - x'\} - \text{point B (}(y) + y' = 0 \hspace{1cm} (3.7)$$

By using above equation, form point B to point B’, all distances calculated from yellow line of Fig 2.8 (C) till gradient line of Fig 3.8 (b). Finally the minimum distance is the radius of the RCA. Here in equations, point B(x) means x-coordinates of point B and point B(y) means y-coordinates of point B location.

Finally, by using above strategies, these final pictures are ready to represent the angle approximations in Fig 3.9. Above all methods are explained according to the aorta, but in Fig 3.9 (a, b) every parameter is
shown from the catheter perspective. CACA approximation can be seen in Fig 3.9 (a), DOAV and AD are in figure 3.9 (b).

Fig 3.9. Pictorial representation of CACA approximation (a), Pictorial representation of DOAV and AD (b)
Chapter 4

Implementation

MRI data is used in this thesis work or experiments. The data is provided by the hospital “Uniklinikum Würzburg”. Fast Marching Method is used for segmentation of given data [25]. Then obtained the skeleton of the aorta and coronary arteries using the technique described in [23]. Centerline (thin image) images are created from the segmented images using the binary thinning image filter [23].

4.1 Coronary Arteries Curve Angle (CACA)

For calculating CACA, two lines AE and DF are required (Fig 3.3). Information regarding the points A, B, D and C are already known [24]. Using two points A and B, draw a line AE (Fig 3.3). Then calculating the last point inside the aorta of calculated line. Similarly using points D and C and draws a line. Then calculating the last index in the aorta by using following lines of code.

Calculating the non-zero point on the line by

```c++
for (int i = 0; i < line.size(); i++)
    if (!binaryImage->GetPixel(line[i]) = = 0))
        return line[i];
```

Till now point F and E are calculated. So now angle at point P is required (Fig 3.3), but for this step 3-D image considered. This means that there is a chance that these lines will never intersect each other. So, first step is to project these lines on 2-D plane.

**Projection:** Three points are required to create a plane. Here in this case, our reference projection plane is the RCA curve points (start point, mid-point and end point).

Here is the idea how to set the projection plane and how does it works:

Selecting projection plane

LineB plane is now projected on the plane of RCA curve. Here are some lines of code to understand the working of projection function;

```c++
gmVector3 projectedPoint;
gmVector3 normal = cross((index 1-index 0), (index 2 – index 0));
Here gmVector3 is a class representing a 3D vector and the vector operations.

    normal.normalize();
    distance = dot(normal,(point-index 0));
    projectedPoint = point - (distance * normal);
    return projectedPoint;
```
Above lines gives the projected point but projected indexes are needed, so these points are converted into indexes by using following lines;

```c
ImageType::IndexType index;
Index [0] = point [0];
Index [1] = point [1];
Index [2] = point [2];
```

After projecting both lines on single plane, calculating the intersection point of both lines by using the following method.

**Line intersection:** This method is to calculate the intersection of two lines, like two lines AE and DF in Fig 3.3 having intersection point P.

Here four points from line A and line B are in consideration. One is starting point of line A, one is last point of line A then same for line B. These four points are in vector form and stored in q1, a2, p1 and p2.

```
Setting line A and line B
lInter.set (lineA, lineB);
gmVector3 c1, c2;
float s, t;
gmVector3 d1 = q1 - p1;
gmVector3 d2 = q2 - p2;
gmVector3 r = p1 - p2;
float a = dot(d1, d1);
float e = dot(d2, d2);
float f = dot(d2, r);
float c = dot(d1, r);
float b = dot(d1, d2);
float denom =  a * e - b * b; // Always nonnegative
```

This denom will always be nonnegative number. If segments not parallel, it will compute closest point on line A to line B.

```c
if (denom != 0.0f)
  s = (b * f - c * e) / denom;
else
  s = 0.0f;
  t = (b * s + f) / e;
c1 = p1 + d1 * s;
c2 = p2 + d2 * t;
return c1;
```

At this stage all indexes, points and lines are calculated. Now angle on the point P, zDPE (Fig 3.3) is needed.

**Angle Calculation:** This method needs three indexes to calculate the angle. Angle will be calculated on index B.

Sending three point to the function.
```
findAngle (index A, index B, index C);
```

Now creating vector points of index A, B and C
**4.2 Aorta Diameter (AD)**

For this parameter, already calculated RCA curve is used. Considering the last index and then a second index that was five indexes away from first one.

```cpp
gmVector3 point1 (line1 [0], line1 [1], line1 [2]);
gmVector3 point2 (line2 [0], line2 [1], line2 [2]);
gmVector3 point3 (line3 [0], line3 [1], line3 [2]);

dot ((point2 - point1), (point2 - point3));
dotResult = dot(vecV1, vecV2);
length = (point2 - point1).length() * (point2 - point3).length();
return acos(dotResult/length)*180/3.14;
```

**4.3 Distance of the Ostium from the Aortic Valves (DOAV)**

DOAV is the distance from point P to point E. So the 3-D distance between these points is calculated by using the following line of codes. This code is taking two index points and then calculates the distance between them.

```cpp
gmVector3 vec_one (index_one [0], index_one [1], index_one [2]);
gmVector3 vec_two (index_two [0], index_two [1], index_two [2]);
gmVector3 disVec = vec_one - vec_two;
```
\[ disVec[0] = disVec[0] \times 0.787; \]
\[ disVec[1] = disVec[1] \times 0.787; \]
\[ disVec[2] = disVec[2] \times 0.787; \]

Now “disVec” variable contains the distance between index_one and index_two and in this particular case this variable contains the DOAV.

### 4.4 Radius of RCA

This procedure takes the input of Start_of_Thin_Line and Get_Start_Index_RCA. Start_of_Thin_Line is the first point of thin line image in axial view. This line then follows the aorta and then arteries of image. Get_Start_Index_RCA is the first point of the RCA and then this point continues the whole aorta till the Start_of_Thin_Line.

For implementation and ease of calculation, it is necessary to take the gradient of each image. In our particular case, gradient image of aorta is hollow aorta. This image just has boundary, no pixel exists inside of the aorta or arteries as in Fig.3.8 (b). Here are some brief lines of codes about gradient filter.

```cpp
typedef itk::GradientMagnitudeImageFilter<InputImageType,OutputImageType> FilterType;
FilterType::Pointer filter = FilterType::New();
filter -> SetInput(inputImage);
filter -> Update();
write(filter -> GetOutput(),"Complete name with path");
return filter -> GetOutput();
```

So for every patient three images considered i.e. thin line image, binary image and gradient image. Starting point (of descending aorta (see Fig 1.2)) of thin image and starting point of RCA are calculated. After defining a vector it has to be clear from the garbage values and then neighbors are calculated by using “push_back” new values in “desiredCurve” vector, this will continue until neighbors will finish and last index comes by using the following line.

To clear the vector

```
desiredCurve.clear();
```

Inserting the value of startIndex in desiredCurve vector

```
desiredCurve.push_back(startIndex);
```

Now moving forward, by calculating the neighbor index in thin image of current index (cIndex)

```
vNeighbors = getNeighbors(cIndex);
```

Last index value means vNeighbors.size( ) == 0, no more neighbors exist in the thin image so break the condition;

```
if ( vNeighbors.size( ) == 0 )
```
While finding the neighbors and starting from the descending aorta there are three arteries Left Common Carotid, Left Subclavian and Brachiocephalic artery in the way of ascending aorta (see Fig 1.2). Calculating the minimum of both ends, that are x-axis and y-axis. This will assure that next neighbor will be from ascending aorta.

```
cIndex = getMinXY(vNeighbors);
thinImage -> SetPixel (cIndex, 0);
desiredCurve.push_back (cIndex);
```

At this stage point B of Fig 3.8 (b) is approached, from where the distance from center line to the gradient image, i.e. the outer side of the artery. This distance is calculating by the same method as used in the DOVA. The smallest distance is our actual and required distance.

Experimental results are in the next chapter.
Chapter 5

Experimental Results

For each case a 3-D image of the aorta (containing the LCA and RCA too) is taken and computed the center line of the image. These both images are input to our algorithm and then different parameters are calculated.

Three set of patient’s images are used, detail is given below.

5.1 Patient One

The image has a resolution of 200×200×200. Followings are the results and images:
DOAV of this patient is (from U to U’) is approximately 13 mm (green thick line). CACA is approximately 90° (red curve in Fig.5.1) and radius of RCA of this patient is measured as 1.75 mm.

![Fig.5.1. Calculating the DOAV and CACA of patient one](image)
Required ACA angle is $\angle RU'R'$ (green curve). But approximation of this angle is done by taking $2 \times \angle RU'U$ (red curve). This half ACA is $57^\circ$ so ACA is $114^\circ$ (see Fig.5.2) and width is calculated as 43 mm from R to R' (Fig.5.2).

![Fig.5.2. Calculating the ACHA of the patient one](image)
Calculating AD was a critical task. The problem in this task was the orientation of the aorta. Like in Fig.5.3 (green line) the normal aorta diameter (AD) is 30 mm. To solve this problem, calculating the orientation of the aorta by taking point B, this point is five pixels away from point A (Fig.5.3 red line). This orientation calculates the slope of the line AB and gives the orientation (slope) of the aorta. Using this slope information, the AD is approximately 28 mm. In Fig.5.4 red thin line is showing the error in calculation and green thick line showing exact diameter of an aorta.

Fig.5.3. Calculating the slope of line AB and then diameter (green line)
5.2 Patient Two

The image of patient has a resolution of 200×200×200. Followings are the results and images: DOAV of patient (from U to U’) is 17 mm (green thick line). CACA is approximately 105° (red line in Fig.5.4) and radius of RCA is measured as 1.11 mm.

Fig.5.4. Calculating the DOAV and CACA Angle of patient two
Required ACA $\angle RU'R'$ (green curve). This angle is approximated by taking $2 \times \angle RU'U$ (red curve). This half ACA is approximately $54^\circ$ so ACA is approximately $108^\circ$ (Fig.5.5 green curve) and catheter width from R to R' (Fig.5.5) is calculated as 35 mm.

Fig.5.5. Calculating ACHA of patient two
In Fig. 5.6 the normal aorta diameter (AD) is 34. But after calculating the orientation of the aorta and calculating the slope of the line AB this diameter is now approximately 28 mm. In Fig. 5.6 red thin line is showing the error in calculation and green thick line showing AD.

Fig. 5.6. Calculating the slope of line AB and then AD (green line)
5.3 Patient Three

This image has the resolution of 200×200×200. Followings are the results and images: DOAV of this patient (from U to U’) is approximately 11 mm (green thick line). CACA is approximately 101° (red line in Fig.5.7) and radius of RCA of patient is measured as 0.79 mm.

Fig.5.7. Calculating the DOAV and CACA of patient three
Required ACA $\angle RU'R'$ (green thin curve). This angle is approximated by taking $2 \times \angle RU'U$ (red curve). This half ACA is approximately $48^\circ$ so ACA is approximately $96^\circ$ (see Fig.5.8) and catheter width from R to R' (Fig.5.8) is calculated as 39 mm.

![Fig.5.8. Calculating ACA Angle of patient three](image)
In Fig. 5.9 the normal aorta diameter (AD) is 35 mm. But after calculating the orientation of the aorta and calculating the slope of the line AB this diameter is now approximately 32 mm. In Fig. 5.9 red thin line is showing the error in calculation and green thick line showing exact AD.
Chapter 6

Discussion

This thesis work approach includes segmentation of the aorta and both arteries, calculating the middle line of the aorta, computing coronary arteries curve angle (CACA), distance of the ostium from the aortic valves (DOAV) and the aorta diameter (AD) near the ostium. Considering catheters and computing the tip angle of the catheter (CTA), catheter curve two depth (CC2D) and catheter curve two width (CC2W). Then comparing CACA with CTA, DOAV with CC2D, AD with CC2W and suggesting a catheter that is the closest to the patient’s arteries geometry. This solution avoids testing of many catheters during catheterization. The cardiologist already gets a recommendation about the optimal catheter for the patient prior to the intervention.

6.1 Further Expected Improvement

6.1.1 Calculating Radius of RCA

In this work “thin line” image is used to calculate the radius of RCA. Calculating the radius is depending on the thin line, this is not confirm that the thin line will penetrate into the RCA for each 3-D image.

6.1.2 Calculating the Take off of RCA

Take off of RCA is always depending on the line AA’ (Fig.5.8). This line should pass through the mid of the aorta root (see Fig. 1.2 (b)). Different RCA curve lengths are used in this thesis work to resolve this issue. This can be improved by more accurate curve calculation.

6.2 Conclusion

Solution for the high take off of RCA along with some basic necessary parameters calculation is presented. This work introduced some basic parameters and their calculations, which can identify the origin of RCA. These parameters are calculated by the aorta root calculation. The result of this thesis work will help in the selection of catheter.
6.3 Future Work

The work can be extended to cases where the RCA has anterior origin. The cases where the aorta itself is not normal can be investigated. If there are lesions in the aorta then the existing techniques will need some modification. In this work only 2-D centerline considered, but aorta and coronary arteries diameter also play a role in the best catheter selection. There are also 3-D catheters which are interesting for future work. The deformable nature of catheters is also needed to be considered and the investigation of the variability of catheter positioning inside the patient's arteries will be interesting.
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