Visual Exploartion in Sugery Planning of Balloon Dilitations

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ABSTRACT

Cardiovascular diseases, mainly caused by an accumulation of lipids accumulating within the vessel wall creating plaque, are one of the leading cause of death in modern society. In advanced cases, surgery is required to avoid strokes or heart attacks.

Therefore the aim is to assist in the planning stage of the surgery in order to indentify risks and discuss options. Unfortunately, the state of the art slice-by-sclice reviewing method lacks in the ability to visual explore CT (Computertomographie) scans, as it only shows a single slice of the raw CT scan at a certain time.

This paper presents a tool to insert visual exploration to the surgery planning process. Therefore, an interactive linked view system process is introduced that contains a standardized tree view of the coronary arteries and additional supporting view to orient in space and in the recorded CT scan.

This technique provides the ability to visual explore a recorded CT scan to plan the process of a surgery. As the visualization is derived as part of the medical workflow it addresses the users needs and opens the black box of vessel visualization to obtain user approval.

1 INTRODUCTION

As, studies show, cardiovascular diseases are one of the leading causes of death in modern society [21]. Most of these are caused by an accumulation of plaque in the coronary arterial system resulting in reduced blood flow or blockage, especially if the afflicted area ruptures. This process is continuous and the more advance it is the more dangerous it becomes. At a later stage of these diseases, the only viable option often is to surgically open narrowed parts of the vascular system.

As surgeries on a beating heart come with a high risk the overall aim is a reliable virtual endoscopy system that is capable to simulate the surgery process. An important step of the virtual endoscopy is *planning* [18]. As a survey showed, surgery planning is a promising tool for medical doctors to enhance: **(1)** Assessment of surgery **(2)** Teaching for future doctors **(3)** Safety during surgery and **(4)** Patient information [10].

To achieve these aims a useful visualization of the recorded images is required. State of the art in CT scan reviewing is a slice-by-slice approach where doctors scroll through the CT-scanned slices and build a three dimensional image. During long education doctors learn to create a three-dimensional image in their mind. Although this method is very accurate as it displays the raw CT scan it is very slow and not as useful in case of surgery planning as it does not allow measurements or annotations. Additionally, the learning curve is very flat.

Advanced visualization techniques can be adapted to the surgery planning workflow, but most of them lack in a possibility to let the user prove the image generation process. As medical decisions can

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have a huge influence on patients health, a suitable visualization needs to provide doctors with the possibility to prove its correctness. If this is not the case, medical users reject new visualization methods and stay with the slice-by-slice technique.

In this paper, an open-box approach to plan surgeries of balloon dilations with CT-scanned heart vessel data is introduced. Therefore, the coronary arterial tree is projected to a plane and important features can be displayed and annotated interactively. To give the user the ability to relate the visualization to the state of the art slice-by-slice reviewing method and to provide a spatial context a linked view system was created. This allows a robust, easy to understand and trustworthy visualization for the surgery planning process.

2 RELATED WORK

The following section will discuss the state of the art in vessel visualization and their application to surgery plannings.

CPR (curved planar reformation) relates to the flattening of a vessel along its centerline by sampling the vessel cross-sections [1]. The quality of the resulting planar grey-scale images are highly dependent on the chosen sampling strategies. In addition, the visualization of several vessels raise the question of their arrangement in a plane [9, 13]. The application of CPR is a basic tool in surgery planning [23] as medical users are trained to understand grey-scale images. Unfortunately, it is not able to provide spatial context.

In contrast to planar visualization approaches volume rendering can be used to create a three-dimensional visualization of the monitored heart. The main problem for this class of visualization is the applied transfer function. Especially in medical datasets they can be hard to find. Several approaches use additional knowledge obtained from cardiovascular modeling or simulations to create suitable and more accurate transfer functions [12, 5, 7]. Volume rendering can be applied to surgery planning [6, 20, 2, 14] by rendering the raw CT scan or segmented structures as isosurfaces and provide interaction methods to navigate through the volume. Besides the induced occlusion problems of this techniques volume rendering approaches do not directly display the original dataset and the color-scheme usually used in the medical field.

To combine the benefits of volume rendering and CPR hybrid methods, such as focus & context [16, 22] or linked views [11], are available in vessel visualization. The suitability of hybrid methods highly depend on the methods used and the fashion of their connectivity. A suitable combination of techniques for the scenario of surgery planning is not provided so far.

3 APPLICATION AND DATA

The following section will give a short introduction to balloon diliations and their process, questions that need to be answered in advance and the available data in this application.

3.1 Balloon Diliation

As mentioned before, a massive calcification can only be resolved by surgery. Therefore the narrowed part of the aretry needs to be dilated. This can be mainly done via two options. Either the narrowed part can be stretched by an inflatable balloon or the insertion of a stent, a small pipe holding the vessel opened [19]. In both cases, a catheter with a certain diameter (usually 1.5 cm to 4 cm in total [8]) is inserted in the vessel to guide the ballon or stent to its destination.

In order to plan this procedure several questions are desirable to be answered in advance. First, the *location of calcification* needs to be known exactly. This is defined as the focal point of the surgery. After that, possible *entrance points* for the catheter need to be identified, that are close to the focal point. During the process of planning, the best suited candidates for these points need to be found. An entrance point in combination with the focal point result in the next task of determining a *surgery path*. To choose such a path several parameters needs to be taken into account. The most important are:

- risk factors (narrowed parts and branches)
- requested diameter of surgery tool (dependent on the diameter of the vessel that needs to be enlarged)

To answer this questions a suitable visualization needs to be devised that is able to work with the available datasets in clinical daily routine.

3.2 Available Data

The following section will list the datasets available in this application and discuss their origin.

CT-Scans CT datasets are acquired by X-ray based scanners resulting in a volume containing a scalar value for each voxel. The intensity values are typically calibrated using the Hounsfield unit (HU). Though CT scans are widely available and used in the medical domain, diagnosis of cardiovascular issues can be difficult as the images can contain several artifacts and inaccuracies due to, e.g., low resolution, motion, or image artifacts [17].

In this paper the CT scans have a resolution of 512x512 pixel per slice and around 200 slices in summary. Each resulting voxel has a resolution of 0.6x0.6x1.0mm.

The images are captured from pig hearts of previously surgically extracted hearts. A detailed description of the data acquisition can be found in the essay of Huo et al. [25].

Centerline After recording the raw CT scan, features embedded within the volumetric image can be extracted. This paper will focus on centerline data. The data available in this case was extracted with an algorithm presented by [24].

The centerline is a topological line-representation of the vascular system that is located in the center of the vessels [3]. This means that the centerline covers all branches and connects continuous components.

For centerline extractions there are multiple classes of algorithms available. Cornea et al. [4] provide an overview.

The algorithm used in the presented case is geometry-based and utilizes boundary information of the vessels as an input to calculate a Delauney tetrahedrization of the vessel interior. Normal vectors of the boundary are used to generate a vector field in the vessel interior. For the resulting vector field extreme points, i.e. singularities, are identified. For each of these points, the extraction algorithm follows the vector field direction and checks if it can be connected with other points to a line.

This paper refers to a arbitrary centerline point as c_i with its values $c_i.xyz$, the location of the point in space, and $c_i.radius$ the vessel radius at the examined point.

4 VISUALIZATION TECHNIQUES

According to the special needs of the medical user and the defined tasks in surgery planning the resulting framework is designed as an interactive linked view system to capture the benefits of planar as well as 3D approaches. Therefore three views are provided. First, a tree-view visualizing the coronary arteries projected onto a plane to examine the complete vascular system. Second, a slice view referring to the state of the art slice-by-slice technique and at last a 3D view that shows the volume rendered heart.
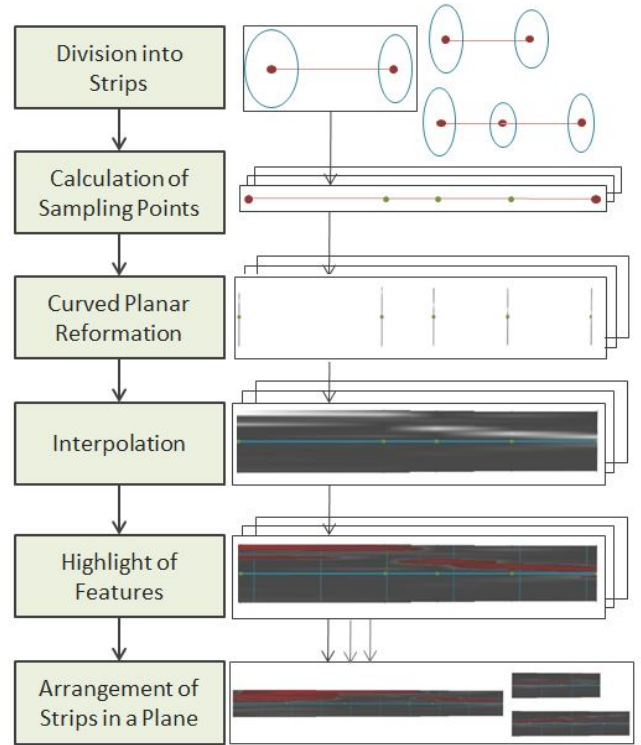

Figure 1: The computational steps to create the presented tree-view of the visualization.

4.1 Tree-View

As Figure 1 shows, the generation of the tree-view consists of several steps that will be discussed in the following.

Division of Centerline into Strips The input dataset can contain several subtrees of the vascular system as well as unconnected components resulting from the centerline extraction algorithm. Additionally, there is user input required to determine the root of each tree.

After the root node is selected, the algorithm follows its neighborhood information to capture all points that are connected in this subtree. While doing this, the points are clustered into *Strips*. Two centerline points c_i, c_j belong to one *Strip* if there is a path from c_i to c_j and the number of neighbors for each point on this path is not higher than two. With this separation it is possible to perform the following calculation steps without involving special cases in the graph.

Each *Strip* with n points consists of $n-1$ Segments *Seg*. A Segment describes the two neighbored centerline points of a strip and holds information about the applied sampling points, length ($Strip_{i,j}.length$) and the segment direction ($Seg_i.dir$). The calculation of this information will be shown in the following.

Calculation of Sampling Points In many cases the extracted centerline is not dense enough to be used as sampling points solely. Consequently, there are additional sampling points required. Although a constant sampling rate assignment would be straight forward it lacks in the ability to adjust the number of points to the length of the segment what would result in unequally sampled strips. To solve this problem a distance-based rate assignment was used in this case. This means that the rate of a segment is higher if the segment is longer. More formal, this can be formulated as: $Seg_i.rate = fac * Seg_{i,j}.length * \frac{1}{sumStripLength}$ with $Seg_{i,j}.length$ as the current length of the segment and *sumStripLength* as the sum of
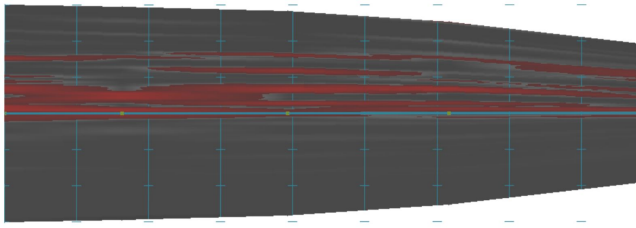
Figure 2: Features, that can be added to the CPR. Red: highlighted calcification. Green: sampling point. Blue: Scale

all segment length. The calculated rate can be controlled by a global scaling factor fac. As a result, the longer a segment is the more sampling points will be assigned. Each segment will be equally divided by its number of rate.

Curved Planar Reformation   For each centerline point and sampling point the cross-sectional area can be defined. This area is the plane in space that intersects the sampling point and has the direction $Seg_i.dir$ as its normal vector. For each cross-section the algorithm performs a CPR that samples the CT volume.

To create a direction independent sampling, a circular approach can be used [15]. In this case circles with increasing size surrounding the center point are sampled and the maximum calculated. To avoid different sampling rates on circles with different sizes the sampling points are set with a user-defined distance on the circles.

As the circular approach reduces each circle to a point (the maximum) sampling information is lost. To solve this problem, the CPR is mirrored at the middle line and displayed again with the mean value of the sampled circle. This covers a wider range of values and gives a better impression of the cross-sectional area.

Interpolation   After the CPR is calculated for each sampling point the resulting image pieces are arranged in a line, depending on their position in the segment. The gaps between the sampled lines are interpolated by their position in the trapezoid formed by the previous and following sampled values.

Highlight of features   To highlight interesting features for surgery planning several visualizations can be added to the strips. First, it is possible to add a scale to each strip starting from the root and marking the distance to it. The diameter is shown on this scale as well what can be seen in Figure 2 with the blue lines. The calculated sampling points can be visualized with green dots on the middle line.

Additionally, to highlight calcification, the user is able to choose an isovalue. All grey scale values on the resulting visualization that are higher then the depicted isovalue will be colored in red with a opacity value depending on the grey-scale value. This results in darker red colored voxels the higher the grey-scale value 2.

Furthermore, it is possible to blind out parts of the image. The user can depict a certain diameter. This diameter is given by the catheter that the doctor wants to use for the surgery. After choosing the diameter, the algorithms follwing the tree and checks for every centerline point if the radius is higher then the depicted value. If not, the subtree followed by the centerline point will be blacked out. Additionally, it is possible to cut all displayed vessels after the depicted value is reached, which can be seen in Figure 2.

At last, the system allows the user to make annotations, thus the doctor can mark parts of interest and note some important findings from the planning.

Arrangement of Strips in a Plane   Once all single $Strips$ are calculated they need to be arranged in a two-dimensional plane. In contrast to other cases, this visualization requires the preservation of the edge length. To obtain a better impression of the vessel length a parallel view is chosen.

For parallel alignment the algorithm starts by assigning a box to each strip, starting with the root. For each leaf the height of the corresponding image will be defined as its box. After that, the box of each node will be obtained from the sum of widths from all of its children. After all strips have an assigned box they can be arranged in the plane starting from the root. Each strip will be placed in the middle of its assigned box followed by recursively drawing its children by dividing its size to the child strips.

4.2   Supporting Views

During the process of tree-view generation, spatial information is lost as well as not all sampled points can be displayed. Therefore, two additional views are added to restore this information.
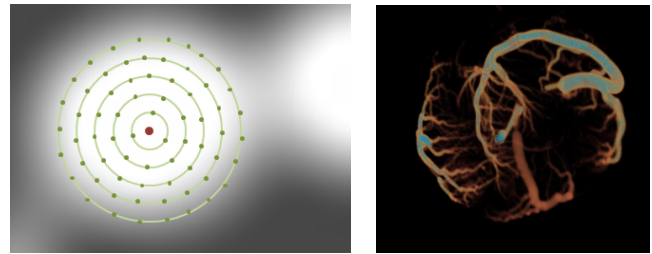

Figure 3: Left: A depicted slice of the tree view. The crosssectional area is shown with the grey scale values of the CT scan and the centerline point, sampling points and dimater are shown. Right: Volume rendering of the CT scan.

Volume View   The volume view aims to add the spatial context that is lost in the tree view during the sampling process. In this view, the CT scan is rendered with a one-dimensional transfer function. To see the surgery path in space, the selected start and end point as well as their connecting path can be displayed.

The volume view is able to point to the corresponding location in space selected by the user in the tree view. This helps the user to get a feel for the geometric arrangement of the vasculature within the tree view.

Slice View   The slice view is an additional option to help the user to follow the workflow of the algorithm. It shows the cross-sectional area of a depicted centerline point in the CT volume. As doctors are used to reviewing the gray scale slices this provides a correlation of the tree view to their previous used reviewing method.

Additionally, for the selected cross-section the centerline point, sampling points, and radius will be added to show how the cross-section is sampled. This allows the user to control the CPR settings and see if the vessel is covered properly. Additionally, it allows an insight into the CPR process.

5   RESULTS

In the following, a potential real world example will be discussed to prove the applicability of the presented system. Figure 4 shows the presented visualization to the right coronary arteries of a pig that is affected by calcification. Branching vessels are connected by a blue bar. The scale is enabled, which can be seen by the blue lines. Grey scale values with a higher value then 90 are highlighted with the red colorscheme to identify calcification.

Figure 4 c) shows a depicted calcification that needs to be removed. Therefore a balloon catheter with a diameter of 1.5 cm needs to reach this point. The aim is to strectch this point to a diameter of 2.5. There are two possible entrance points (see Figure 4 1 and 2). Both points have their benefits and drawbacks. On the one
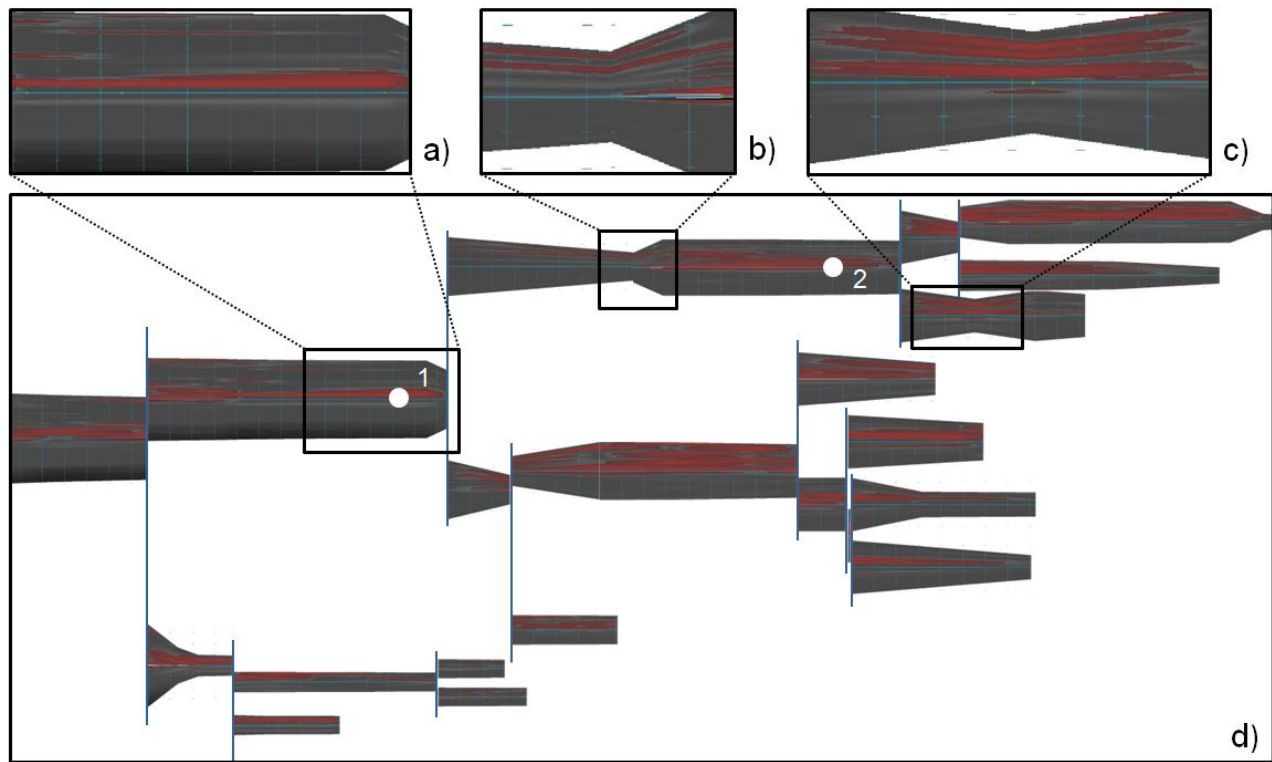
Figure 4: An real world example visualized with the presented system. d) The left coronary tree of a pig. a) possible entry point for the balloon diliation b) narrowed vessel c) aim point for the balloon deliation.

hand, point 1 is better situated as there is a low calcification around it (see Fig 4 a) which makes it more suitable as an entrance point. On the other hand it located at a large distance to the focal point and there is a narrowed area on the path to the focal point (see Fig 4 b)). For point 2 the distance is smaller, but unfortunately the environment is affected by calcification. With this visualization medical doctors can now discuss the benefits and drawbacks and see which option will be performed.

6 DISCUSSION

As mentioned before, planning in virtual surgery aims at enhancing several aspects. The *assessment of surgery* and *increase of complications* can be enhanced with the presented visualization. As the example showed it is possible to visually explore the calcification in the arteries of the heart. Additionally, possible entrance points can be defined. With the filtering tool, all parts of the visualization that exceed a certain diameter can be skipped. This allows the medicaldoctor to try several scenarios of different surgical tools and entrance points. The technique is well suited for the medical use as it links to the state of the art technique which is very accurate. Thus, the image generation process can be controlled and therefore the black box issue of visualization is resolved. With the additional 3D view, the spatial context of the selected points is ensured.

The *Teaching of future doctors* and *Patient Information* have a different target group. Here, the addressed users are not strongly related to the state of the art visualization technique, but need a quick and easy to understand overview over the planned process. For future doctors, the visualization can be used to setup a database with performed and recorded surgeries. With this database medical students can be taught frequently occuring problems during surgery or the general process of planning.

To obtain a higher acceptance for the planned procedure, proper patient information is required. With the presented visualization it is possible to show the patient the planned procedure and inform him or her about the risks and planned stages in the surgery.

7 CONCLUSION AND FUTURE WORK

In this paper we presented an interactive, standardized linked view visualization for surgery planning using balloon dilation. As the design of the visualization follows the workflow of the medical user and related to the state of the art technique, this work presents an open-box approach.

Therefore this work contributes new insights in CT scans and their features and allow the enhancement of the surgery planning workflow with existing knowledge.

The presented example shows how important the study of the addressed user is to create suitable visualization and obtain user acceptance.

As future work it is planned to extend the presented visualization to further applications in vascular visualization and provide a general framework that is able to go beyond current datasets, such as simulated pressure values of the coronary arterial tree. Additionally, the clinical applicability will be tested in a formal user study.

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