A QUANTITATIVE ANALYSIS TOOL FOR CARDIOVASCULAR SYSTEMS

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ABSTRACT

Coronary heart diseases are the major cause of deaths in the United States as well as in most other countries. Approximately 16.7 million people die from heart diseases every year according to estimates of the World Health Organization (WHO). Recent studies show that common methods of treatment, such as bypass surgery, do not necessarily help to avoid coronary heart disease. Consequently, there is a need for a better understanding of the functionality of the heart. Here, virtual models depicting structure and/or operation of the heart can help. In the same way, visualization is required to aid in the analysis of these virtual models. In this paper, a method for generating a virtual geometric model of a vascular tree is described. The necessary data is either based on CT scans or on a simulation using statistical methods. The software allows to explore the geometric model interactively from an external view point, where different analysis options are available. Several examples are given to prove the usefulness of the visualization system and to demonstrate how it helps scientists to quantitatively analyze their models.

KEY WORDS

biomedical visualization, geometry reconstruction, virtual exploration, cardiovascular system, coronary artery, measuring.

1 Introduction

Coronary heart diseases (CHD) are severe problems in the United States as well as in most other nations. In 2001 alone, there were 700,142 fatalities due to heart disease in the United States according to the Centers for Disease Control and Prevention (CDC) and approximately 16.7 million die from coronary heart diseases worldwide every year (WHO estimates). The risk of dying from CHD rises rapidly with increase of age as can be seen in figure 1. According to statistics, coronary heart disease is the number one killer in the United States.

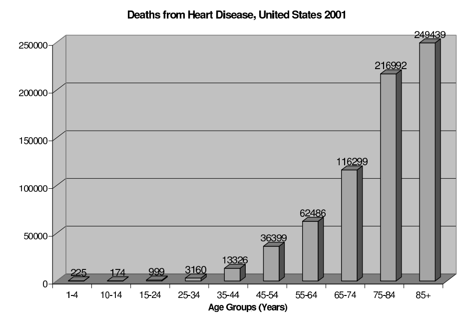

Figure 1. Deaths from heart disease in the United States in 2001, source *http://wonder.cdc.gov*.

There is common believe that heart attacks usually arise from arteries being clogged up by atherosclerotic plaque. To avoid heart attacks, popular treatments are artery-opening methods, such as angioplasty where arteries are opened up with a tiny balloon. In addition stents - wire cages that stabilize artery walls - can be used to prevent the newly stretched area from collapsing or shrinking again.

However, recent and continuing studies give reason to question whether common procedures do help avoiding heart attacks [16][17]. These studies show that a majority of heart attacks do not originate from obstructions that narrow arteries but from an area of plaque bursting and forming a clot over the area that abruptly blocks the blood flow. Therefore, a more powerful way to prevent heart attacks in high-risk patients would be to adhere rigorously to other measures, such as giving up smoking and taking drugs to control blood pressure, and driving LDL cholesterol down. All these methods can help to avoid blood clotting.

To find out more about the true reason for CHD, virtual models are necessary to get a better understanding of the way the heart actually works in detail. With such a model, scientists and surgeons are able to analyze the benefits of different treatment options and find appropriate ways to prevent coronary heart diseases. To aid in this endeavor, a geometric model of the vascular system of the heart has been developed which considers even the capillary level of the arteries. In this paper, the generation of the geometry of such a model is explained. A general approach to constructing this geometry is taken in order for the system to not only support models derived from computed tomography (CT) or magnetic resonance imaging (MRI) scans, but also simulated models where in particular the vessels at the capillary level are based on a statistical distribution rather than an actual scan [4]. Considering this requirement, the proposed method only relies on the center lines of the vessels and radius information at certain discrete points. With this information, an approximation of the whole vascular tree can be reconstructed.

One advantage of reconstructing the full geometry of a vascular tree over, for instance, direct volume visualization methods is that it allows measurement of objects in the depicted scene. Distances can be measured accurately when the geometry is known. Volume visualization methods may not have the necessary precision due to their use of a discrete grid which may have an even coarser resolution than the actual model in order to maintain interactive frame rates. In this paper, different measurement options and tools are proposed that allow the user to identify distances between arbitrary points of the vascular tree as well as other criteria, such as vessel radius or vessel volume.

The structure of this paper is as follows: initially, an overview of previous, related work is given. Subsequently, the methodology used for generating the geometric representation of vascular trees is described. Then, visualization results including various measurement and exploration methods are shown. Finally, forthcoming challenges and future work are discussed.

2 Related Works

Several approaches exist for investigating tubular internal organs, such as vessels or colons. Many of these use the Marching Cubes algorithm as introduced by Lorensen and Cline [9] to generate geometry information based on isosurfacing. Different methods have been proposed and implemented to avoid ambiguities in the original case table of the Marching Cubes algorithm [12][10]. Examples are given, for instance, in Hong et al. [3].

Different methods have been developed for generating 3D models from 2D CT or MRI datasets. Öltze et al. use convolution surfaces with a Gauss filter in combination with preprocessing steps for external 3D tree visualizations from an external view point [13].

Other techniques include the flattening of vascular structures, as shown by Kanitasar et al. with their enhancements of curved planar reformation (CPR), where an enclosing hierarchy of vessel hulls is used to approximate the projected vessel tree. Due to the flattened layout of the structure, the complete vessel wall is visible in a single view, thus preventing occlusions by superimposed cells and allowing unobstructed views of stenoses and calcifications [5]. Puig et al. extract a symbolic model from the voxel model of cerebral blood vessels including detection of features such as bifurcations, aneurysms, and stenoses [15].

The goal of this project is to provide scientists, physicians and radiologists with exact measuring tools needed for computer aided diagnostics. In addition, statistically generated data is to be verified and appropriate tools for validation and measuring of the vascular system must be provided. The use of various measurement tools, such as distance lines, interactive rulers and angular measurements, has already been discussed by Preim et al. [14].

Using real data based on CT or MRI scans not only results in accurate geometric models. Derived models can also be used to perform a quantitative analysis of a specimen, for example computation of the volume or surface area of vessel segments and angles between different vessel segments [18]. Most of the examples in this paper are based on geometric models derived from CT scans of a pig's heart where detailed information about both the arterial [7] as well as the venous system [6] is available.

3 Methodology

When extracting geometrical information from three-dimensional volumes such as CT or MRI scans, one method to represent such pipe shaped objects is to find the center line and determine the radius at specific discrete points. This kind of information, for instance, is the output of some commercial tools, such as *Analyze*[1]. This software package implements a topology preserving erosion algorithm that shrinks down the vessels represented in a volumetric image, for example derived by a CT scanner, to a single line in 3D [8]. The remaining points can then be output as a concatenated list of points representing the vascular tree. To be compatible to this data format, the input data for the proposed approach requires a list of consecutive points and the radius information associated with these points. The point list then represents the center line of the vessels, and all segments together describe the skeleton of the vascular tree.

Due to the limited resolution of standard CT scanners (typically about 0.6 mm^3 per voxel), the points of the center line often resemble a step function rather than a smooth curve. Using this step function to construct the skeleton would restrict the angles at subsequent segments unnecessarily. To compensate for that, the points on the center line are approximated using a B-Spline [1] to get a smooth curve. More advanced methods [2][11] would allow for an even smoother result by applying a force to the end of the spline (splines under tension). But in this application, due to the limited length of the line segments, a regular B-spline already gives sufficient results.

The bifurcation points of the vascular tree always stay fixed. Only the intermediate points are allowed to slightly move in this implementation. This way, the center line of the segments between bifurcation points is smoothed, while the bifurcation points are preserved. This is important both for the intersection of vessel segments of the vascular tree. For every part of the vascular tree between two bifurcation points a cubic approximating B-Spline is created based on the points of the center line of that segment. The new positions of the intermediate points are then determined by evaluating the resulting B-Spline using the parameter values of the original points with respect to a line segment

[1] http://www.analyzedirect.com/Analyze4.0/

approximation of the center line. This results in a smoother curve and more realistic representation of the original data.

Since the radii at two neighboring points on the center line are not necessarily identical, cylinders cannot be used to graphically represent the vessel segments. Instead, frustums in the shape of truncated cones are utilized. These frustums which may have different radii at both ends are then, based on the center line and radius information, used to connect two consecutive points with the exact radii given by the data. Since two subsequent frustums share a common circle at the interface between two subsequent segments, this circle is computed only once to avoid cracks in the resulting surface representation. In addition, the circle at the end of these frustums is not necessarily orthogonal to the frustum itself. To get a smoother transition between subsequent frustums, these circles are created in such a way that the plane in which the circle resides divides the angle between the center lines of the two consecutive frustums into two equal halves. Figure 2 shows a typical example for this. With this approach, the center lines of two subsequent segments can form an angle of up to 180 degrees (reverse direction), even though the angles usually occurring in typical data sets are much smaller.

Figure 2. Interface between two successive vessel segments.

After all frustums are computed, the whole cardiovascular tree can be visualized as shown in figure 3. This image shows the left anterior descending coronary artery of a pig's heart. Texture mapping and specular reflections help to get a better three-dimensional impression of the whole structure of the vascular system. By rotating, zooming, or panning the image, the user can interactively explore the structure of the vascular tree.

4 Application Examples

As mentioned before, a heart of a pig was used as a test specimen. The heart was extracted and scanned with a regular CT scanner at a resolution of 0.6 mm resulting in a three dimensional volume. Using the commercial software tool *Analyze*, the geometry of the specimen was extracted based on a topology preserving erosion process [8]. The tool generates a list of points representing the center lines of the vessels found in the 3D volume. In addition, radius information is computed by the software at these points.

The method described in section 3 results in a visualization as shown in figure 4 where the left circumflex (LCX) coronary artery of the pig's heart is displayed. In this image, a coordinate grid is included to provide a visual

Figure 3. An example of a cardiovascular tree, left anterior descending coronary artery.

aid for determining the size of the specimen. To further investigate the specimen, the user can zoom, rotate, and pan the object in real time. The user interface facilitates an interactive exploration of the entire vascular system. It also allows scientists to investigate the spatial relationship and size-related properties of the vessel segments which are especially important for simulated vascular trees based on statistical information. In addition, individual segments of the vascular tree can be picked and highlighted using the mouse. When selected, a label is attached to the chosen vessel segment showing detailed information of that segment including a segment reference as it appears in the data file or the total volume of the segment. Figure 5 gives an example of a vessel segment with annotation.

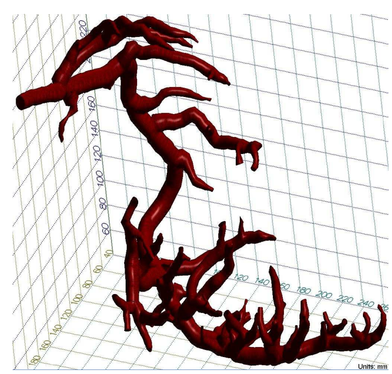

Figure 4. A cardiovascular tree (left circumflex (LCX) coronary artery) shown with a coordinate grid.

In order to achieve a more detailed generic model of a pig's heart, the scanned model can be extended based on a morphometric database. This database describes statistical information of average vessel lengths and diameters. Then, a geometric model can be extended by growing vessels starting at the terminal vessels of the existing model. This can be continued down to the capillary levels as shown by Kaimovitz et al. [4].

Since such a simulated vascular tree is not limited by

Figure 5. Part of the cardiovascular tree (left circumflex (LCX) coronary artery) with detailed information of one particular segment.

the resolution of a scanner and therefore may also contain smaller vessels on the capillary level, the number of vessels in such a model can be tremendously high. Figures 6 and 7 show examples for such a simulated vascular tree depicting the left circumflex (LCX) artery. The results show a very detailed representation of a network of smaller vessels even in this close-up view where the user already has zoomed in. The data set contains 1.4 million vessel segments which are all shown in this example. Even with such a high number of segments the algorithm is still able to render an image at a rate of approximately one frame per second, still allowing an exploration of the model at reasonably interactive frame rates. For this test a commodity PC was used featuring a Pentium 4 processor running at 2.66 GHz, and equipped with an NVidia Quadro4 980 XGL graphics card and 1 GB of RAM.

Especially since the geometric model was based on statistical information, it was important to the scientists to analyze the results of their simulation. Only by exploring the model interactively, they are able to check efficiently if the simulation was correct. The developed software tool greatly helped for instance, to visually check for self-intersections in the model which would have meant that there was an error in the simulation code.

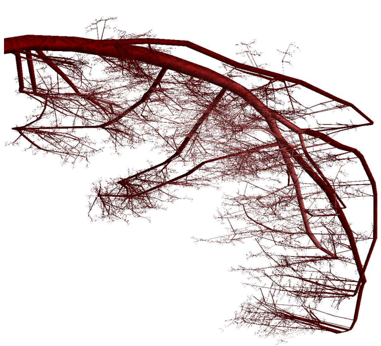

Figure 6. Overview of a simulated vascular tree based on statistical information, left circumflex (LCX) coronary artery.

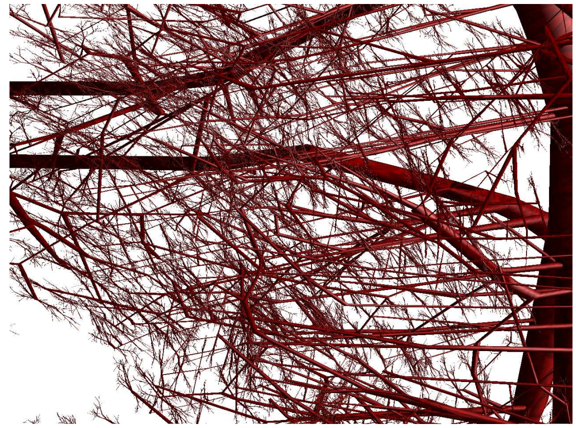

Figure 7. Detailed view of a simulated vascular tree based on statistical information, left circumflex (LCX) coronary artery.

5 Measuring Toolkit

Usually, medical doctors and biomedical engineers are not only interested in visualizing the data but also in precise measuring. Distances between two vascular branches can be important, especially when considering changes due to movement of the surrounding tissue. A coordinate grid gives a rough overview of the size but lacks precision when the user attempts to read distances from a projection on the grid. Therefore, a digital measuring toolkit was implemented that allows precise measuring based on the extracted geometry of the object. In analogy to a real physical object that can be measured with a tape measure, a ruler tool was added to the user interface which can be individually placed at any position in the scene. This tool, which is easy and intuitive to use, allows the user to measure distances between any two points in the scene. Figure 8 shows the ruler and a part of the vessel tree. The ruler is placed such that it connects two points on individual branches where the user is interested in the distance. As opposed to a real ruler, which cannot intersect an object, the virtual ruler can be placed anywhere in the scene and even intersect the specimen.

In addition to the ruler, a second measuring option is available where the user can determine the distance between two arbitrary points on the specimen. After clicking on any point in the scene, the z-buffer of OpenGL™ is used to calculate the real world coordinate of the selected point. The user can then drag the mouse to select a second point while the distance between the selection is always displayed in the lower left corner of the window until the user releases this function. Figure 9 illustrates this feature. The line connecting the two points which the user selected is shown and circled in this image while the distance between the two points is shown in the lower left corner. This gives the user a precise and flexible measurement option that is very intuitive to use.

Figure 8. A cardiovascular tree (left circumflex (LCX) coronary artery) shown with a ruler used for measuring distances.

Figure 9. Measuring distances in a cardiovascular tree, left circumflex (LCX) coronary artery.

6 Conclusions and Future Work

In this paper, a visualization system for vascular trees was presented where the data can be explored interactively. Analysis and measuring tools allow precise determination of, for instance, distances between different vessel segments, the length of such segments, and angles at bifurcation points.

It was shown that the system can handle even large amounts of data. Commercially available software packages were not able to render such enormous amounts of data, and without this software it would not have been possible for the research team to analyze the data set and to verify the correctness of the simulation.

The existing quantitative analysis tool could benefit from a future extension to support immersive virtual environment systems that facilitate a tabletop metaphor, such as the ImmersaDesk™ or Responsive Workbench, since these systems allow the application of virtual measurement and analysis tools in the same way as corresponding tools are handled in the real world, thus bringing computer-aided diagnosis closer to real-world surgery environments.

In addition, hierarchical methods would be helpful to cope with larger datasets as they usually occur in simulated cardiovascular systems that include structures as small as the capillary vessels. A vascular tree modeled in such detail can contain several million vessel segments when all three main branches of the arteries supporting the human heart are considered (the current data set contained only one of these three branches). A region of interest could be specified and zoom functions based on subtrees might be able to enable handling of such enormous amounts of data.

7 Acknowledgments

This work was sponsored in part by the National Institute of Mental Health (NIMH) through a subcontract with the Center for Neuroscience at the University of California, Davis (award no. 5 P20 MH60975), by the National Partnership for Advanced Computational Infrastructure (NPACI), Interaction Environments (IE) Thrust (award no. 10195430 00120410), and by the Department of Electrical Engineering and Computer Science in the Henry Samueli School of Engineering at the University of California, Irvine.

The authors gratefully acknowledge Ghassan S. Kassab and Benjamin Kaimovitz of the Cardiovascular Biomechanics Laboratory at the University of California, Irvine, for providing the data sets the demonstrated visualization results are based on. Also, their helpful comments were very much appreciated.

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