Visualizing Morphometric Data of Vasculatures

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Abstract—Volume visualization is a common, very well-established visualization technique for volumetric data sets. Numerous advancements have been proposed and sophisticated improvements have been implemented to produce elaborated renderings that are capable of enhancing details within the volume. However, volume visualization alone is often not sufficient for the application domain. Often times, researchers are interested in accurate measurements extracted from volumetric data to gain further insight of the specimen. These extracted measurements can then be used to generate and visualize a geometric reconstruction of the specimen. The visualization can incorporate additional tools that allow researchers to determine additional measurements of the specimen to help in the analysis. This paper describes such a software system which is capable of accurately extracting measurements from volumetric data, reconstructing the geometric properties of the specimen, and interactively visualizing the results, thereby allowing researcher to further investigate the geometric configuration of the specimen.

Index Terms—Morphometric measurements, geometric reconstruction, visualization of vascular structures.

1 INTRODUCTION

The analysis of spatial perfusion of any organ requires detailed morphometry on the geometry (diameters, lengths, number of vessels, etc.) and branching pattern (3-D angles, connectivity of vessels, etc.). It is therefore of great importance to provide suitable visualization tools that are capable of extracting such morphometric knowledge from volumetric data and presenting the data to the user in a suitable fashion. A statistical analysis of the morphometric knowledge alone may not be useful without the context it refers to. Hence, it is necessary to put the knowledge into context as performed by Doleisch et al. [2]. This paper describes a system that is capable of extracting morphometric knowledge of the vasculature from volumetric data and visualizing a geometric reconstruction based on center lines and radii as well as presenting additional morphometric data, such as vessel volume and bifurcation angles, within its context.

Several approaches exist for investigating tubular internal organs, such as vessels, esophagi, or colons. The datasets mainly differ in size and resolution. Many of these methods use the Marching Cubes algorithm as introduced by Lorensen and Cline [3] to generate geometry information based on iso-surfacing. Different methods have been proposed and implemented to avoid ambiguities in the original case table of the Marching Cubes algorithm [4][5]. Examples are given, for instance, in Hong et al. [6].

Different methods have been developed for generating 3D models from 2D CT or MRI datasets. Őltze et al. [9] use convolution surfaces with a Gauss filter in combination with pre-processing steps for external 3D tree visualizations from an external view point.

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 [7]. 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 [10].

For extracting morphometric measurements from volumetric data, a center line algorithm is used. Several approaches for extracting center lines or medial axis can be found in the literature. A very good overview of available techniques can be found in the paper by Cornea et al. [1]. Another algorithm for extracting morphometric data based on projected surface normals is described by Nordsletten et al. [8].

2 METHODOLOGY

The proposed system extracts morphometric data from volumetric data in several steps. The algorithm first segments the vessels within the volumetric image based on the image gradients. In order to get a more accurate representation of the vessel boundary, the points resulting from the segmentation step are moved along the gradient direction in such a way that they are located at the maximal gradient. This provides a more precise and smoother representation of the boundary compared to using the original voxel locations. Then, a vector field is computed in such a way that all vectors are pointing inwards to the center of the vessel. In the simplest case, the image gradients can be used at the boundary. Using a tri-linear interpolation, the vector field can be computed after a tetrahedrization of all the boundary points is determined. Finally, the points on the centerlines are computed using a topological analysis of the vector field within the cross sectional area of the vessels and connected based on the topology of the tetrahedrization. This then results in a precise representation of the centerlines of all vessels within the volumetric image. The algorithm was validated against manual, optical measurements proving its accuracy for a series of five porcine hearts. CT scans were performed at a resolution of 0.6mm. Vessel diameters were determined as the distances between center line and vessel boundary. The differences between optical measurements and computer-based measurements were statistically analyzed. The root mean square error was 0.l6mm and average deviation was 0.13mm.

Based on these accurate center lines, morphometric measurements can be extracted from the volumetric data. As described before, vessel radii are computed as the distance between the center lines and the vessel boundary. Additional measurements can be retrieved using the center lines as well to gain further knowledge of the data sets. Vascular volume can be determined as the volume described by the tetrahedra used during the computation of the center lines. Similarly, vascular wall area can be calculated as the surface area of these tetrahedra.

Bifurcation angles can be computed as well using the center lines. Bifurcation angles are of particular interest since the influence the flow properties significantly. In addition, certain configurations of bifurcations can lead to accumulation of plaque at the point of bifurcation. Due to the fact that the first segment of a center line representation merely represents the connection of the vessel branches but does not necessarily represent the bifurcation angle very well, more than the first segments are included in the computation of the bifurcation angle. The first center line segments usually only leads out of the main vessel formed by the parent and the larger child. Using this segment alone would result in erroneous bifurcation angles. Hence, the center line segments starting with the first one after the bifurcation until the length of the daughter segment reaches three times the radius of the parent vessel are considered. The vectors representing the center line segments identified in such a way are then averaged and weighed by the length of each vector to determine a representative for the orientation of the daughter vessels. These are used for computing the bifurcation angles as described before.

The visualization system makes use of the extracted knowledge of the data set to provide an interactive geometric reconstruction of the data set. The arteries are visualized as truncated cones based on the center line and radii information extracted from the volumetric data. Fig. 1 (left) shows an example of such a reconstruction based on the volumetric data shown in Fig. 1 (right). The user can then interactively explore the arterial structure. By picking specific segments, additional information can be shown that was previously extracted from the volumetric data. This knowledge includes the volume of the picked vessel segment, its surface are, length, etc. This information is shown in an overlay area on top of the vascular geometry. The system always ensures that the annotation is placed next to the selected vessel, even when the view is changed. Due to the use of transparency, the geometric configuration is always visible. Fig. 2 depicts an example of a picked vessel segment with additional information.

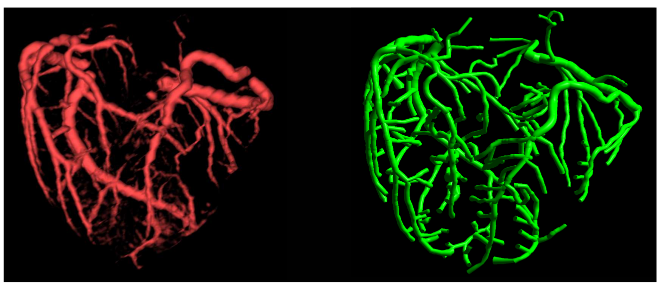

Fig. 1. Volume rendering (left) of a previously perfused porcine heart which was scanned using a standard hospital CT scanner and geometric reconstruction of the same porcine vasculature based on extracted morphometric data, such as vessel lengths and vessel radii.

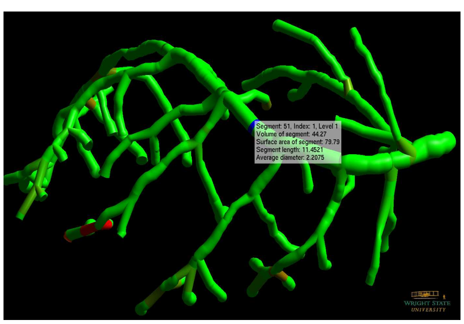

Fig. 2. Additional information of a specific vessel segment can be shown in an overlay area by picking the segment.

In order to put the bifurcation angles into context, the numeric data can be shown on top of the vascular geometry next to the bifurcation itself. In interesting aspect to researchers of bifurcation angles is that they tend to be planar. Planarity can be measured as the angle between the parent vessel and the plane described by the daughter segments. The planarity is then described by the scalar product between the direction of the parent vessel and the normal vector of the plane. Instead of just showing a statistical summary of the planarity, color coding based on this knowledge can then be used to visualize the planarity of the bifurcations putting it into context. By choosing colors proportional to the planarity of the bifurcation, those bifurcations stand out that do not appear to be planar as shown in Fig. 3. Putting the planarity into context in such a way can be of great help when investigating bifurcations that do not adhere to the common assumption of planarity of bifurcations.

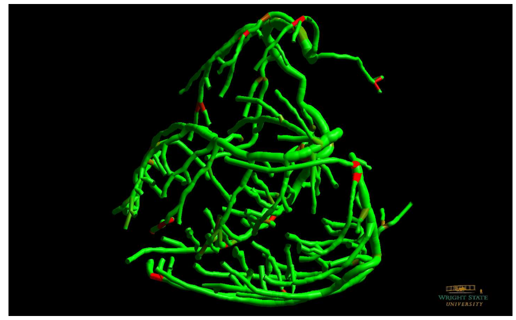

Fig. 3. Color coding of the vessel bifurcations proportional to the planarity enhances those bifurcations that are not planar which is commonly assumed as unusual among cardiovascular researchers; red indicates non-planar bifurcations.

3 Conclusion and Future Work

In this paper, a system is described that is capable of extracting morphometric measurements from volumetric data. Morphometric measurements such as vessel length, vessel diameter, vessel volume, and bifurcation angles, are extracted from CT scanned porcine hearts and then incorporated into a geometric reconstruction of the vasculature. Morphometric data can then be explored interactively by overlaying the quantitative measurements on top of the geometry, thereby putting it into context. Hence, this analysis and visualization tool is capable of providing detailed insight into the vascular structure represented by the volumetric data which is of great importance for studying the functional properties of the vasculature.

Acknowledgements

The author would like to thank Ghassan Kassab and Jenny Choy-Zorrilla for providing the porcine heart data sets. I would also like to thank the Wright State University and the Ohio Board of Regents for supporting this research.

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