GEOMETRIC MODELING OF THE HUMAN AORTA FOR RAPID PROTOTYPING USING PATIENT DATA AND COMMERCIAL SOFTWARE PACKAGES

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INTRODUCTION

Accurate geometric modeling of the cardiovascular system is important when utilizing this information in clinical and research investigations. For example, Taylor *et al.* [1, 2] describe the development of a virtual environment in which surgeons can investigate alternative treatment plans based on an individual's vascular geometry derived from patient data. Various treatment scenarios can be tested by numerically simulating the flow in the resulting vascular geometry. Our particular motivation is to develop patient-specific physical models for in-vitro hemodynamic experimentation, and we have developed a procedure for manufacturing accurate rigid and compliant vascular models using rapid prototyping technologies [3, 4]. We have also developed a particle image velocimetry and tunable physiologically representative flow system capable of taking quick flow field measurements of anatomical models in a plug and play environment [5]. This system is useful for studying hemodynamics in large patient populations based on patient-specific flow characteristics rather than investigating the flow characteristics in a representative average anatomical model. However, the relevance of the experimental measurements depends in large part on the accuracy with which the vascular geometry can be first extracted and ultimately replicated.

Since our primary interest is in experimental hemodynamics and not software development, we developed a procedure using commercial software packages that meets our requirements for extracting vascular geometries from patient data (including both CT and MRI) and generating solid computer and physical models that accurately represent the anatomy of the individual. We recognize that 3-dimensional visualization packages provided by medical scanning companies are advancing at a rapid pace and ultimately will meet the needs of most researchers. However, these technologies are, at present, not readily accessible to the vast majority of researchers (and even most hospitals), and there are numerous existing datasets that could benefit from the procedure described here.

MATERIALS AND METHODS

Three software packages are utilized to generate the vascular structures from patient data: Mimics (Materialise, Ann Arbor, MI), a software package that creates solid models from medical imaging data; Rhinocerous®, a.k.a. Rhino, (Seattle, WA), a versatile CAD package with NURBS capabilities; and Geomagic® Studio (Research Triangle Park, NC), a software package with unique capabilities for manipulating 3-dimensional geometric datasets including point clouds, polygons, and surfaces. The procedure can be summarized as follows: Mimics imports the medical data, isolates the vascular structure, and creates a polygonal set of data (in either STL or IGES format), Rhino imports the polygonal dataset and creates the NURBS surfaces, and Geomagic® Studio imports the NURBS surfaces and creates a watertight geometry.

A procedure similar to that of Taylor *et al.* [1, 2] (thresholding the 2-D images, creating polylines, and then lofting the polylines together to create NURBS surfaces) can be implemented using the software packages above (although to create polylines in Mimics, an add-on to Mimics called MedCAD is required). However, complications arise when using polylines in regions, such as the aortic arch, where a single polyline (in the arch) must somehow loft into two polylines (the ascending and descending aortas). Geometric complications such as this one are due to the orientation of the imaging planes with respect to the cardiovascular system. As a result, a different approach has been developed.

Figure 1 provides an illustration of a healthy human aorta from a 40-year-old male including the ascending aorta, aortic arch, and descending aorta. These data were extracted from a set of Spiral CT images with 512 x 512 resolution, pixel size of 0.68-mm, 413 slices, and 1.5-mm interval. Mimics was utilized to generate the geometric solid (polygonal set of data saved in STL or IGES format) from the CT data utilizing a thresholding and region growing procedure. As shown in the figure, the vessel dimensions depend on when in the physiologic waveform the images were taken (the CT was not gated), and observation of the ascending aorta illustrates, as expected, that there is considerably more translation in the region closest (and attached) to

the heart. Our objective is to develop models that replicate the true anatomy as much as possible by removing differences in vessel size and location due to the physiologic waveform and movement during the scan.

Once the cardiovascular structure from the CT data is isolated and saved using Mimics, the file is imported into Rhino. In Rhino, different segments of the structure are defined based on geometry. Typically, the ascending aorta, aortic arch, and descending aorta are defined as different segments and additional segments within these regions are defined as required (such as individual arteries branching from the aorta). For example, as shown in Figure 1, the aortic arch is selected as one segment while the brachiocephlic, common carotid and the left subclavian arteries are additional segments. Once defined, the segments are sectioned with a series of planes to create contour lines (not all the planes used in this procedure are shown in Figure 1), and Rhino allows the definition of arrays of planes including polar (circular), horizontal, vertical, and others. In the arch, the polar planes enable the geometry of the arch to be extracted, while the horizontal planes assist in the extraction of the anatomy of the brachiocephlic, common carotid and left subclavian arteries and the vertical planes benefit the region where the arteries merge with the arch.

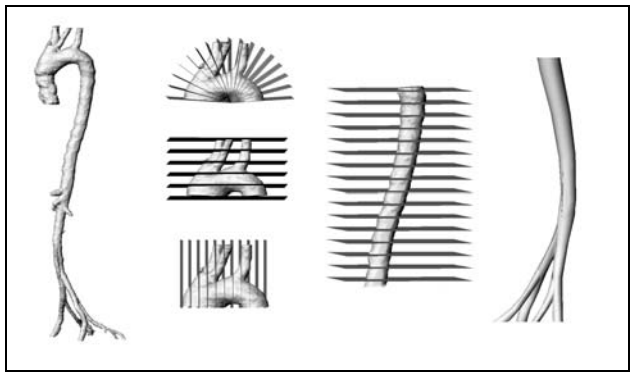

Figure 1. STL file of the complete abdominal aorta exported from Mimics (Left). Sectioning of segments in Rhino to create closed contour curves (Center). Joining NURBS surfaces using the intersecting curves (Right).

Using the contour lines defined by the planes, NURBS surfaces are created by lofting the closed contour lines together. The art in this process requires determining which contour lines to use in the generation of the surfaces so that physiologic waveform differences and vessel movements that occurred during the scan can be removed. Once the NURBS surfaces are created (and care is taken to ensure that all surfaces overlap), the intersecting curves of the surfaces are highlighted, the overlapping surfaces are trimmed to fit, and the surfaces are joined together. Invariably, the joined surfaces have some holes and thus are not watertight. The resulting STL or IGES file is imported into Geomagic® Studio where holes are filled and the final watertight geometric computer model is saved for use in our rapid prototyping process.

RESULTS

Figure 2 illustrates the results of the process described above on the CT data shown in Figure 1. The overall geometry of the aorta is retained while the vessel dimension variations and vessel movements during the scan have been removed. In the figure, a difference plot (in inches) illustrates the regions where differences exist between the final and original models.

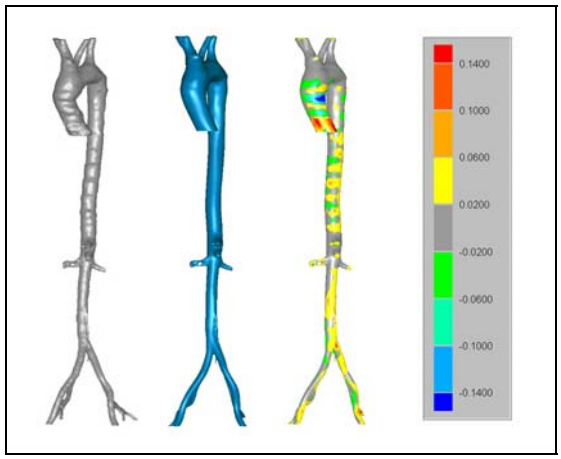

Figure 2. Extracted model from Mimics (Left), Modified model using manual technique (Center), Differences between models in inches (Right).

CONCLUSION

A manual extraction technique using commercially available software packages has been developed for the creation of geometric solid computer models of the human vascular system from patient data. This method represents a relatively low-cost solution for the generation of geometric computer models that accurately represent an individual's vascular geometry. Although we utilize these models in a process for manufacturing physical cardiovascular system models to be used in experimental hemodynamics research, the computer and physical models can be used for a variety of other clinical, research, product development, and educational applications.

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