CAD Modeling for 3D Bio-printing of Human Coronary Artery

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***Abstract*—The purpose of this study is to develop Computer-Aided Design (CAD) tools to construct three dimensional (3D) bio-printing models of human coronary artery from medical images. Two methods are used to construct mimic models from Computed Tomography (CT) scans. A simple model is also constructed by simplifying the mimic model. Two local view method uses two orthogonal image to construct the model, while transverse image lofting method lofts a series of transverse image to construct the model. Both methods are effective. However, more mimic result can be acquired from transverse image lofting method.**

***Index Terms*—coronary artery, CAD modeling, bio-printing, image processing, rapid prototyping**

I. Introduction

Coronary Heart Disease (CHD) is caused by atherosclerosis of coronary artery [1]. In the past years, studies of the diameters of coronary artery have been made to evaluate the severity of CHD [1]-[3]. Then, some therapies have been developed to treat this disease, including Percutaneous Coronary Intervention (PCI) and Coronary Artery Bypass Grafting (CABG) [4]-[6]. In recent years, three-dimensional (3D) bio-printing technology has become so advanced that a new therapy of replacing arteriosclerotic coronary artery with artificial printed coronary artery becomes possible [7].

Before printing out coronary artery, construction of coronary artery model is essential. The development of medical facilities and software has advanced medical science so much that medical imaging such as Computed Tomography (CT) scans and Magnetic Resonance Imaging (MRI) of human organs are obtainable. Rapid prototyping technologies also provide fast visualization to assist clinical diagnosis [8]. However, a large gap exists between constructing solid models from those images because most of the medical images only depict the contour of human organs. As a result, modeling from medical image has become popular in recent years. Research such as modeling of spine vertebrae, liver and its vascular network from CT scans and MRI had be done [9], [10].

In 2014, Ferdinando et al. used two local view method to generate 3D mesh of branch blood vessel from X-ray angiography [11]. The advantage of this method is that only two section plane images are required to construct the model. However, the drawback is that the model will not be so mimic. For the study of CHD, the mimic model is required for analysis of the atherosclerotic coronary artery. Therefore, in this study, a method named transverse image lofting method is proposed to construct mimic model of coronary artery.

Both two local view method and transverse image lofting method aim to construct mimic models. These models benefit medical study of CHD. However, for practical use, the printed-out coronary artery has better be simple and smooth, or the fluid property may be affected. Thus, a method to construct simple coronary artery model is also proposed in this study.

II. Modeling Method

Before modeling, the medical images are processed and their directions are defined. Though the image source varies for different human organs and tissues, the section planes (image direction) are with same definition. There are three section planes in medical image system, which are frontal plane, sagittal plane, and transverse plane. Frontal plane and sagittal plane are vertical to ground and are orthogonal to each other, while transverse plane is horizontal to ground. In this study, for the two local view method, the frontal and sagittal plane images are used as source images, while for the transverse image lofting method, a series of transverse images are used as source images.

Two local view method and transverse image lofting method are used to construct mimic models, while a simple model can be generated by simplifying the mimic models. The branch part of human Left Coronary Artery (LCA) is chose for modeling. Instead of X-ray angiography, CT scans from a patient are used in this study because CT scans are captured by injecting developer in the blood and can get more detailed interior information of the blood vessel. The modeling process is detailed in the following sections. The Computer-Aided Design (CAD) software used is AutoCAD.

A. *Two Local View Method*

For the first step of two local view modeling method, the frontal section plan and sagittal section plan images are positioned in AutoCAD (Fig. 1a, b). Then, the left coronary artery is sliced by many imaginary horizontal lines and each line is marked by three points, two for the

Manuscript received October 19, 2016; revised March 18, 2017.
[1] Information from National Heart, Lung, and Blood Institute, http://www.nhlbi.nih.gov/health/health-topics/topics/cad

doi: 10.18178/joig.5.1.16-19

edges and one for the centerline. In the branch part, six points are marked on each imaginary line to describe the edges and centerline, three points for Left Circumflex Artery (LCX) and three points for left Anterior Descending Artery (LAD) (Fig. 1c, d).

After the points are marked on the image, two-dimension coordinate (X, Z) and (Y, Z) of the points can be obtained. The coordinates are then matched to define three-dimensional coordinate (X, Y, Z) of those points (Fig. 1e, f). The 3D point data is then imported to AutoCAD. Once the point data is imported, smooth cross section can be created by curve fitting those points (Fig. 1g).

Finally, a solid 3D model of left coronary artery can be built by connecting these cross sections. Three parts (LCA, LAD, LCX) of coronary artery were build up individually and finally combined together. To construct a solid model, making an offset of each cross section to create a new model. Then, subtract the original model from the offset model to get a hollow model (Fig. 1h).

B. Transverse Image Lofting Method

For transverse image lofting method, a STL model is first constructed by importing DICOM (Digital Imaging and Communications in Medicine) CT scan files to the medical imaging software ImageJ. A series of transverse plane images are imported into ImageJ and then a STL model is exported (Fig. 2a, b).

The STL model is a surface models. If imported to 3D printing program, the single surface model will be considered complete solid inside. However, the coronary artery is hollow and has a blood vessel wall of about 0.5 to 1 mm. To create a hollow model of coronary artery with wall thickness, a tool is developed to convert the shell STL model to 3D hollow solid model. This tool executes the following six steps:

1. Slice the STL model with STL-slice program to obtain the cross sections.
2. Curve fitting each cross section to get smoother boundary of the cross sections.
3. Offset the curve-fitted cross section to get larger cross sections with the same geometry for constructing the hollow model.
4. Loft the original (interior) cross sections and the offset (exterior) cross sections to get two solid model of coronary artery.
5. Connect the inner models and the outer models respectively and get the final inner model and outer model.
6. Use the offset model to subtract the original model to get a hollow solid model of coronary artery.

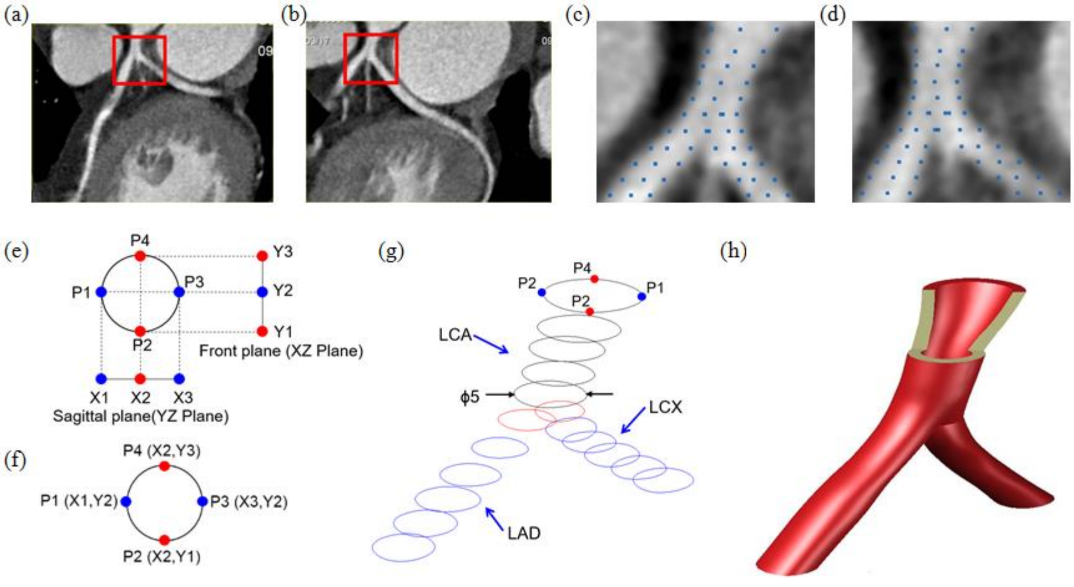

Figure 1. CT scans of human left coronary artery and modeling process of two local view method. (a) Frontal plane image. (b) Sagittal plane image. (c)(d) Series of points are marked on the edges and centerline on the frontal plane image and sagittal plane image. (c) is partial magnified images of (a). (d) is partial magnified images of (b). (e) Cross section coordinate is generated by match the 2D coordinates of points on frontal plane and sagittal plane. (f) Generated cross section with (X, Y) coordinate. (g) Generated cross sections of left coronary artery. Cross sections in color of black, red, and blue represent main LCA before the branch, branch part, and two branch blood vessel (LAD and LCX), respectively. (h) Hollow left coronary artery model is generated by lofting the cross sections.

The STL file is basically composed of lots of triangle surfaces. The STL-slicing program uses plane to intersect with those triangle surfaces to get the cross section profile (Fig. 2c). To create a mimic model which reserves not only the path geometry but the shape of the original STL model, the original cross sections of the STL model are required. However, the boundary of those cross sections sliced from the STL model are connected by polylines, which are not smooth enough. As a result, curve fitting is required to obtain smoother boundary of the cross sections. To fit the boundary with smooth curve, the centroids of the cross sections are first found. Then, from each centroid, eight radical lines are plotted every 45 degrees to intersect with the boundary of each cross section. A spline is then used to connect the intersect points to curve fit the cross section (Fig. 2d). This step is to ensure that all the curve-fitted cross sections have same number of vertexes at same angle in 3D space. In

AutoCAD, this condition is important to be ensured for lofting those cross sections later.

In order to create hollow blood vessel, boundaries of the cross sections are offset for creating outer model (Fig. 2e). Once all the cross sections are plotted, each part of the coronary artery can be lofted. In this paper, the coronary artery is divided into two parts for lofting (Fig. 2f). Inner and outer parts of coronary artery are lofted and connected separately (Fig. 2g). Finally, the outer model is used to subtract the inner model to get final hollow model of coronary artery (Fig. 2h).

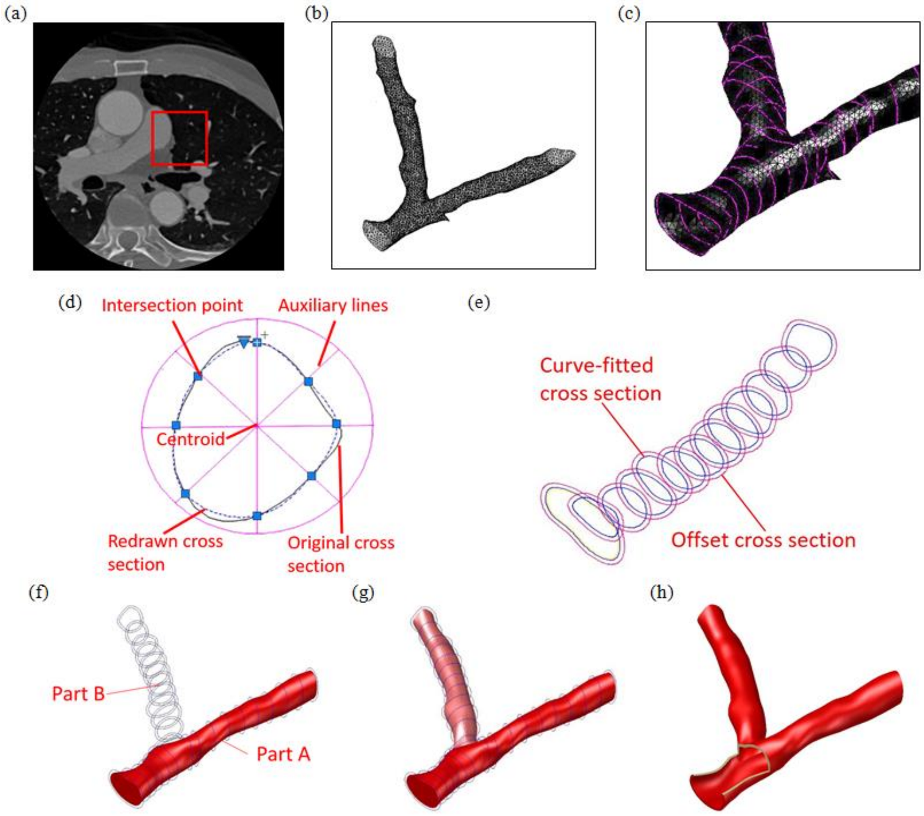

Figure 2. Modeling process of transverse image lofting method. (a) A transverse plane CT scan image. A cross section of coronary artery is in the marked area. Since the image is on transverse plane, the cross section is small and thus not very clear. (b) Exported coronary artery STL model. (c) Coronary artery STL model is sliced. The purple curves are the sliced cross sections. (d) Centroid of the cross section is found. Then, eight auxiliary lines are plotted and intersect with boundary of the cross section. A new cross section is defined with those points. (e) Smoothed cross sections and offset cross sections. The blue curve represents the cross section after curve fitting. The red curve represents the offset cross sections. (f) Coronary artery is divided into two parts for lofting because the geometry is complicated. (g) Inner model of coronary artery is connected. (h) Outer model is used to subtract inner model to get hollow solid model of coronary artery.

C. *Constructing Simple Coronary Artery Model*

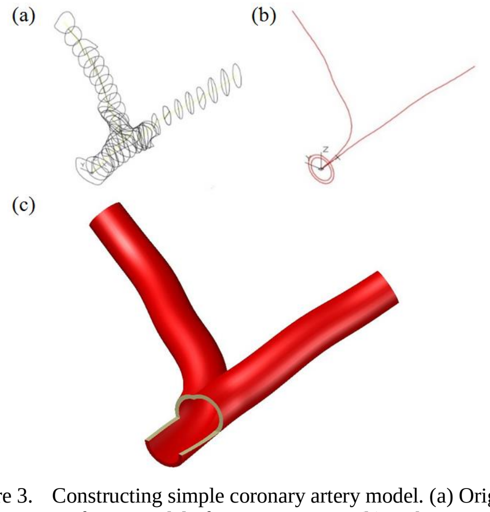

Figure 3. Constructing simple coronary artery model. (a) Original cross sections of STL model of coronary artery. (b) Path generated by connecting centroids of each cross section. (c) Hollow simple model created by sweeping the circle cross section over the path.

The simple coronary artery model can be acquired by simplifying the mimic model. This model remains the path of the original STL model (Fig. 3a, b), while the sweep cross sections can be customized. Furthermore, the diameter of the sweep cross sections can be adjusted and scaled to fit the size of patients' coronary artery. In this study, the cross sections are customized to simple circle. The diameters of LCA, LAD and LCX are assumed to be 5 mm, 4 mm, and 4 mm, respectively. The decreasing scale is 0.8, which means that LAD and LCX have narrower diameter than LCA. The constructed simple model is shown in Fig. 3c. The surface of the simple model is more smooth compared with that of mimic models.

III. CONCLUSION

In this study, we construct human coronary artery model by two methods, which are two local view method and transverse image lofting method. The CT scan images are used as source because they are captured basing on the developer applied to the coronary artery, which result in detailed interior geometry of coronary artery. The model constructed by transverse image lofting method is more mimic than that constructed by two local view method. For medical research, our mimic model would benefit researchers with the geometry and fluid properties of patients' coronary artery. For practical use, a simple model is constructed and can be printed out with bio compatible materials to replace the atherosclerotic coronary artery of patients. This study uses rapid prototyping technologies to shorten the gap of constructing 3D printable model from medical images.

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