Three-Dimensional Blood Vessel Modeling Method Considering IVUS Catheter Insertion

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ABSTRACT

In this paper, we propose a new 3D (three-dimensional) blood vessel modeling method for FSI (fluid-structure interaction) analysis. Because of the nature of medical images, a 3D blood vessel model that includes intima and adventitia cannot be reconstructed using a single medical image. Many researchers have used IVUS (intravascular ultrasound) images to obtain detailed intima and adventitia information and X-ray angiogram images to calculate the position and orientation of IVUS images. By combining these types of medical images, 3D blood vessel model can be generated. However, when an IVUS image is taken, a catheter attached to a miniaturized ultrasound device is inserted into the blood vessel, so the shape of the blood vessel is deformed. The resulting 3D blood vessel model developed by combining the IVUS and X-ray angiogram images reflects the deformation of the blood vessel by the IVUS catheter. To solve this problem, we propose a novel method for 3D blood vessel modeling using undeformed intima and adventitia information obtained with an IVUS catheter.

Keywords

Blood vessel modeling, CT, IVUS, X-ray angiogram

1. INTRODUCTION

Recently, in the biomechanics field, many researchers have been studying methods for blood vessel modeling to better understand hemodynamics and vascular disorder mechanisms [Car74]. Prominent among the recent research on this subject has been the development of computerized FSI (fluid-structure interaction) analysis methods [You04, Qia10, Kni10]. For FSI analysis, a complete three-dimensional (3D) volume model that includes intima and adventitia is needed. However, it is difficult to reconstruct a 3D adventitial model from a single type of medical image.

The method most widely used to generate 3D blood vessel models employs computed tomography (CT) images. However, when a CT image is taken, a contrast medium is injected into the blood vessel to enable detection of its shape. The contrast medium only shows the shape of the intima, not the shape of the adventitia. For this reason, many studies have examined the use of IVUS images to obtain detailed intima and adventitia information [Qia99, Tse11].

Weichert reconstructed a 3D blood vessel model using IVUS image biplane angiogram images. From the IVUS images, contours of intima and adventitia extracted and using biplane angiogram, position and orientation of intima and adventitia were calculated [Wei03 , Wei04].

To obtain IVUS images, an IVUS catheter attached a miniaturized ultrasound probe is inserted into a blood vessel. The IVUS images, which show cross sections of blood vessel, are taken during pullback of the IVUS catheter. Therefore, IVUS images show intima and adventitia contours in more detail than CT images, but the overall shape of the vessel cannot be obtained from IVUS images [Wah99].

In previous research, we reconstructed a 3D blood vessel model including intima and adventitia information by registering CT and IVUS images [Son13]. A 3D intima model was acquired from CT images in the usual manner. From the intimal model, the centerline of the vessel, which mimics the catheter path, was approximated by a spline curve. Then, cross sections of the intima were obtained at the locations of the IVUS images. The contours of the intima obtained from the IVUS images were registered with the contours of the intima obtained from the CT images to calculate the transformation. The calculated transformations were applied to the contours of the adventitia from the IVUS images to obtain the contours of the cross sections of the intima and adventitia in the 3D space.

However, when the cross sections of the intima were obtained, the orientations in the normal plane did not coincide with the IVUS images, as shown in Figure 1 [Hof99].

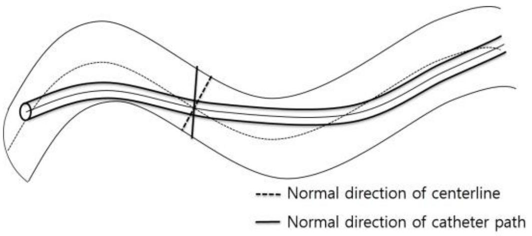

Figure 1. Comparison of the normal direction of the centerline and the IVUS catheter path [Hof99]

A blood vessel modeling method that uses CT, IVUS and X-ray angiogram images is proposed in this paper to solve this problem.

2. OVERVIEW

The object of this study was to reconstruct a 3D blood vessel model including undeformed intima and adventitia. In this study, we used three kinds of medical images, namely CT, IVUS, and X-ray angiogram.

A CT (X-ray computed tomography) image is generated by using an X-ray source that rotates around the object. Because a blood vessel constitutes a very small portion of a CT image, it is not possible to extract detailed information about the blood vessel. When a CT image is captured, however, a contrast medium is injected. With CT images, therefore, we can reconstruct a 3D intimal model and observe the overall undeformed shape of a blood vessel.

IVUS (intravascular ultrasound) is a medical imaging methodology that uses a catheter to which a miniaturized ultrasound probe is attached. By referring to an IVUS image, we can extract detail information about the cross section of a blood vessel. We cannot, however, determine its absolute position and orientation. In addition, the insertion of a catheter causes the blood vessel to be deformed.

To calculate the position and orientation of an IVUS image, we used X-ray angiogram images. Angiography is the medical imaging technique used to visualize blood vessels. If an X-ray angiogram image is captured before IVUS pullback, we can determine the catheter pullback path. In addition, by using two X-ray angiogram images that are taken at different angles, we can reconstruct the catheter pullback path in 3D space.

Using these medical images, our proposed method progressed the following process.

We reconstructed models of an undeformed intima, deformed intima, and adventitia. To reconstruct the undeformed intima model, we first isolated the intima from a CT image and then extracted the iso-surface of the intima voxel and converted it to a polygon model. To reconstruct the deformed intima and adventitia model, we combined an X-ray angiogram with IVUS images. To calculate the position and orientation of the IVUS images, we reconstructed a catheter path in 3D space by using two X-ray angiogram images. In addition, we extracted the contours of the intima and adventitia from the IVUS images by using a spline curve. By combining a 3D catheter path and the contours of the intima and adventitia, we reconstructed deformed intima and adventitia models (Chapter 3).

To register these two 3D blood vessel models, despite their being in different states, we calculated the centerlines of two intimal models by using a 3D Voronoi diagram. Along the centerlines, we obtained the cross sections of two blood vessel models at the same position. By registering the contours of the intima obtained from the deformed blood vessel model with those obtained from the CT model, we calculated the transformation between the two intima contours and applied the transformation to the cross sections of the adventitia (Chapter 4).

Finally, we generated a 3D blood vessel model including undeformed intima and adventitia.

Figure 2 shows the flow of data in our approach.

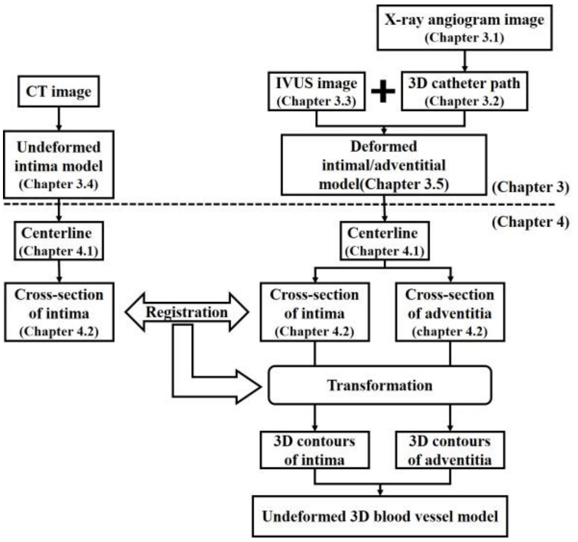

Figure 2. Overview of the 3D blood vessel model reconstruction process

In this study, to validate our proposed method, we made an artificial blood vessel model using a silicon tube and gelatin, as shown in Figure 3. Using this artificial model, we obtained CT, IVUS, and X-ray angiogram images.

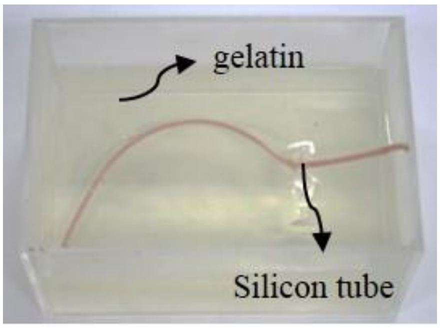

Figure 3. An artificial blood vessel model made using silicon tube and gelatin

3. INTIMAL AND ADVENTITIAL MODEL RECONSTRUCTION

3.1 A 3D catheter path reconstruction

As mentioned above, it is difficult to determine the position and orientation at which an IVUS image was obtained from the image itself. Therefore, biplane X-ray angiogram images were used to estimate the positions and orientations of IVUS images. The X-ray angiogram images were taken at two different angles before IVUS catheter pullback, as shown in Figure 4(a). First, the IVUS catheter paths were extracted from the X-ray angiogram images. Then, the IVUS catheter path was reconstructed in 3D space [Har03]. Figure 4(b) shows the reconstructed 3D IVUS catheter path.

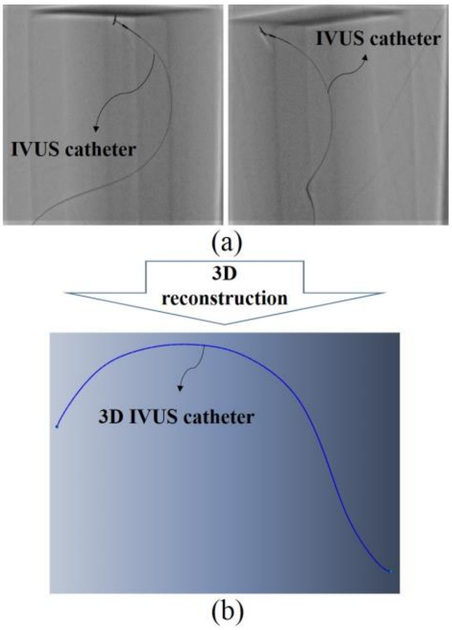

Figure 4. (a) X-ray angiogram images of the IVUS catheter (b) Reconstructed IVUS catheter path in 3D space

3.2 Calculation of position and orientation of IVUS images

The positions of IVUS images can be calculated using the reconstructed 3D IVUS catheter path because the pullback speed of the IVUS catheter is held constant while the IVUS images are being obtained. However, the orientation of an IVUS image cannot be known from this information. Andreas proposed the sequential triangulation method for use in calculating the orientation of IVUS images [Wah99]. The sequential triangulation method assumes that the catheter path is composed of an infinite number of joints and links, as shown in Figure 5. Using constant IVUS pullback speed, the location of IVUS images can be calculated and Using Frenet-Serret formulas, twist angle between IVUS images can be calculated. Using this method, the orientation of IVUS image can be calculated using information about the geometry of the joints [Wah99].

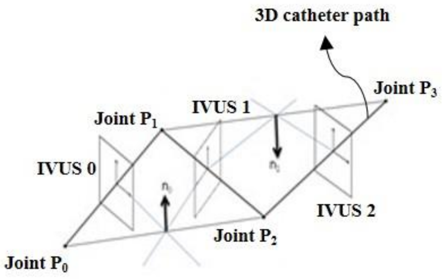

Figure 5. Calculating the orientation of IVUS images using the sequential triangulation method [Wah99]

3.3 Intima and adventitia segmentation from IVUS images

IVUS images are obtained by inserting an IVUS catheter into a blood vessel. Therefore, an IVUS image shows a cross section of a blood vessel, which is more accurate than the contour obtained from a CT image. In this study, a skilled operator worked manually to obtain the vessel contours, as shown in Figure 6. A closed spline curve was used, and 50 points were extracted from each spline curve.

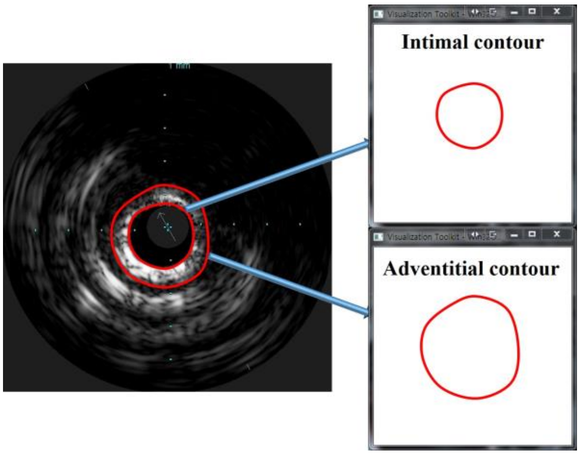

Figure 6. Contours of intima and adventitia from an IVUS image

3.4 Deformed intimal and adventitial model

By combining the positions and orientations of IVUS images and contours of the intima and adventitia, a series of cross sections constituting a deformed blood vessel model was obtained, as shown in Figure 7. By triangulation, a surface blood vessel model was generated, as shown in Figure 8.

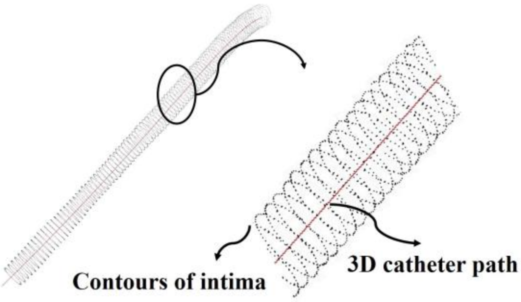

Figure 7. A series of contours making up the deformed intima model

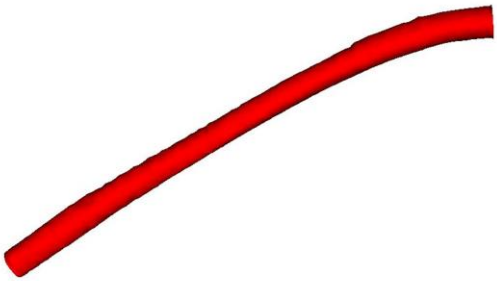

Figure 8. A surface model of a deformed intimal model

3.5 Undeformed intimal model

In CT angiography, a contrast medium appears in X-ray images of blood vessel and the collection of gray-scale images expresses the 3D shape of the vessel as a voxel [Yoo00]. To generate polygon data, an iso-surface is extracted from a CT image. In our study, to extracting the iso-surface of intima, the commercial medical image processing software 3D-Doctor was used. Figure 9 shows an undeformed intimal model generated using CT imagery.

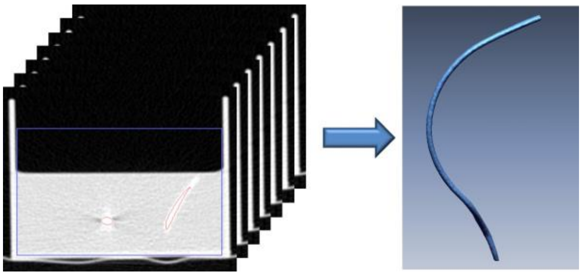

Figure 9. Undeformed intimal model generated from CT imagery

4. CROSS SECTION ACQUISITION

4.1 Calculation of the vessel centerline

Our approach to 3D blood vessel modeling involves registering cross sections from a model generated from combined IVUS and X-ray angiogram images with cross section from a CT model. The centerline of each intimal model is calculated to obtain the cross sections of models.

A set of reference points must be identified on the spline curve that describes the overall shape of the blood vessel model. We defined the center points as a series of centers of inscribed spheres of the intimal model. In this study, VMTK (the Vascular Modeling Toolkit) was used to calculate the center points of intimal models using a 3D Voronoi diagram [Ant03, Ant08, Ant03]. The internal Voronoi diagram is obtained using VMTK by computing the Delaunay tessellation of point set *P*, removing the tetrahedral whose center falls outside the object [Pic09]. Figure

10(b) shows the internal Voronoi diagram of the intimal model obtained from CT imagery.

Once the center points of 3D intimal models have been obtained, the parametric curve ***P***(*u*) can be calculated.

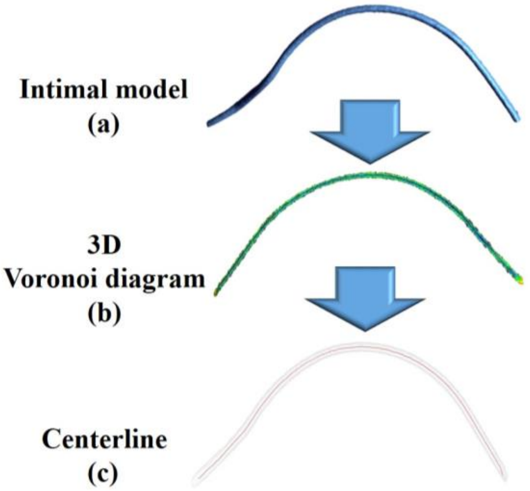

Figure 10. (a) Undeformed intimal model from CT imagery (b) Internal 3D Voronoi diagram of the intimal model (c) centerline of the intimal model

Figure 10(c) shows the centerline of the intimal model calculated from CT imagery.

4.2 Acquisition of intima and adventitia cross sections from models

Using the computed centerlines, the cross sections of intima models can be obtained. Before obtaining the cross sections, the origin of the cutting plane has to be determined because the cross section of each intima model has to be at the same position. The centerlines are interpolated spline curves divided into segments of equal lengths with the same number of points. In this manner, the origin of the cutting plane is determined, and the normal vector of the plane is defined as the tangential vector at the origin, as shown in Figure 11. Using this plane, the cross sections of intimal models at the same position are obtained.

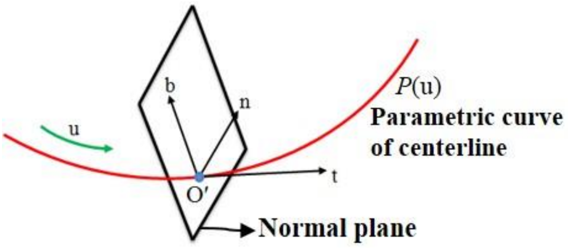

Figure 11. A perpendicular plane of an intimal model

5. CONCLUSIONS

In this paper, we proposed a novel method for 3D blood vessel modeling that overcomes the problem of intima and adventitia deformation caused by IVUS catheter insertion. To Validate our proposed modeling method, we generated a 3D undeformed intima model and a 3D deformed model, including the intima and adventitia.

An undeformed intima model was reconstructed using CT images, and by combining this model with IVUS and X-ray angiogram images, deformed intimal and adventitial models were reconstructed. Because the position and orientation of an IVUS image cannot be determined from the image itself, we reconstructed a 3D IVUS catheter path by using two X-ray angiogram images. By applying the sequential triangulation method, the positions and orientations of the IVUS images were calculated. To register the cross sections of the intimal models, the centerlines of the intima models were calculated by using a 3D Voronoi diagram. This centerline was used to obtain the cross sections of two intima models at approximately the same position.

In our previous research, we proposed a blood vessel modeling method using CT and IVUS images. In that study, however, we did not consider the blood vessel shape deformation caused by catheter insertion. In addition, when we combined the CT and IVUS images, we did not consider the fact that the centerline of the intima model does not coincide with the catheter path. To overcome these problems, in this study, we reconstructed an intima model by using only a CT model in the undeformed state and intima/adventitia models that combine X-ray angiogram and IVUS images of the deformed state. Furthermore, for registering these two models, we obtained cross sections using the centerlines of each intima model.

Future work will include an examination of the method used to register two cross sections of a reconstructed blood vessel model and a complete reconstruction of a 3D blood vessel model including undeformed intima and adventitia. Furthermore, in this study, we did not validate the proposed method, because it is difficult to assess the accuracy of the reconstructed 3D blood vessel model. To evaluate its accuracy, therefore, we will project the resulting blood vessel model onto X-ray angiogram images that show the outlines of a blood vessel. By comparing the outlines of the blood vessel with the projected blood vessel model, we expect to be able to calculate the accuracy of the 3D blood vessel model.

6. ACKNOWLEDGMENTS

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