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SMOOTH MESH GENERATION FOR NUMERICAL ANALYSIS OF BLOOD VESSEL FLUID FLOW

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ABSTRACT

A Matlab-based approach to image segmentation and mesh generation for creating high-quality hexagonal meshes is developed. The successful use of the procedure in patient-specific simulations of blood flow in a carotid artery is demonstrated.

INTRODUCTION

Image-based computational modeling of blood flow is a topic of significant importance and can provide valuable inside into the local hemodynamic conditions which can be correlated with the progression of certain cardiovascular deceases. In addition, image-based simulations can assist with the prediction of possible outcomes of certain surgical interventions in patient-specific cases, which is beyond the capabilities of in-vivo imaging alone. [1]. As a first step towards the patient-specific simulations, the suitable computational mesh must be generated from the patient vasculature images. Although several methods have been proposed in the literature for 3D image-based grid generation [1–3], most of them provide tetrahedral computational meshes suitable for finite-volume computations codes. In the current work, we are interested in using spectral-element computational solver for its high accuracy and good results previously obtained in simulating blood flow in a transitional regime [4], which requires hexagonal meshes. Creating high-quality hexagonal meshes is a challenging problem and is a topic of active research. In this paper, we will describe the methodology of generating smooth computational hexagonal meshes from the stack of MRI images and demonstrate its successful use in patient-specific blood flow simulations.

METHOD

Images

To develop the medical simulation-based diagnostic tools, a 3D mesh for numerical calculations must be constructed for patient-specific geometries. We have obtained a stack of MRI images of a healthy volunteer carotid artery from our collaborators at the Radiology group of Northwestern Medical School. The carotid artery is a good choice for developing mesh generation technology, since high-resolution medical images can be obtained. A set of forty transverse image slices of a patient's artery were taken. These images are the magnitude contrast images of blood flow in the carotid. They cover 80 mm of the length of the carotid, and each image slice has a thickness of 2mm, there is no distance between the slices. The images have a resolution of 512 x 512 pixels and have a pixel size of 0.3125mm x 0.3125mm.

Mesh Construction

To extract the blood vessel location from the images, the Canny edge detection method [5] was used to locate significant changes in contrast, and generate regions containing blood vessels. The reconstructed vessels were then segmented into left and right carotid and vertebral artery vessels. The carotid artery vessels were further segmented between the bifurcating branches. For each cross-sectional slice at each branch vessel, the center point of the vessel was identified and a polar spline was constructed through the points around the center. Using equally

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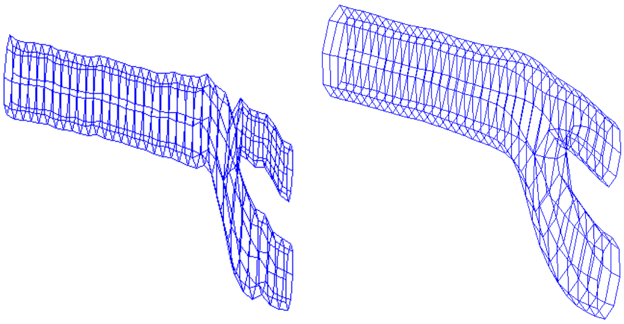

FIGURE 1. THE MESH ON THE LEFT IS THE ONE ORIGINAL MESH. THE MESH ON THE RIGHT IS THE SMOOTHED MESH.

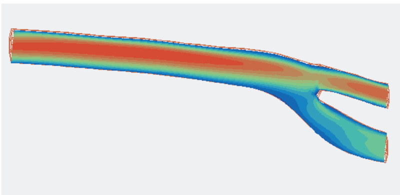

FIGURE 2. SNAPSHOT OF AXIAL VELOCITY FOR PATIENT-SPECIFIC CAROTID SIMULATIONS.

spaced angles, a specified number of points ranging from 8 to 32 was extracted from the spline depending on the current mesh template . The interior region was meshed according to a specified template. A simple circular joint was implemented at the bifurcation to connect the individual branch meshes, see Fig. 1.

Mesh Smoothing

The noise in the images and the relatively large distance between the image slices gave rise to edge irregularities in the mesh. These irregularities caused significant numerical problems, resulting in poor convergence and non-smooth solutions. To remedy this problem the mesh was smoothed using an averaging technique for the corresponding edge points. The points were incrementally moved to a weighted point between the original location of the point and midpoint of the line connecting the two points either above or below them. To allow for the smoothing of the end points, the mesh was artificially extended for smoothing by allowing three extra slices on bottom and on top. The smoothed mesh alongside the original mesh is shown in Fig. 1.

To analyze the effects of this method of smoothing a known problem was solved. A simple mesh, resembling pipe flow, was made noisy by adding a random amount of noise to the points in the slices. The mesh was then smoothed and the fluid flow was analyzed. While the noisy mesh produces unusable results, the smoothed mesh produced working results.

The created computational mesh was used for the hemodynamic simulations of a patient-specific carotid artery with the spectral element computational solver [6], and realistic blood flow patterns for pulsatile blood flow have been obtained, see Fig. 2, where the snapshot of axial velocity is shown.

CONCLUSION

We have developed efficient image segmentation and mesh generation technology for constructing high-quality smooth hexagonal meshes for spectral-element simulations of blood flow. The successful use of the created mesh in blood flow analysis was demonstrated by the spectral element simulations of a pulsatile blood flow. For further development of this technique, this process will need to be automated to produce patient mesh geometries quickly so that diagnoses can be made efficiently. In addition, in-vivo MRI measurements of patient blood flow velocity have been recently obtained by the Radiology group of Northwestern University, and comparison between the simulation results and in-vivo measurements is currently being performed.

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