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Structured meshing of large vascular networks for computational fluid dynamics.

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Keywords structured meshing, cerebral vascular network, centerline

1. Introduction

Computational fluid dynamics (CFD) simulation provides valuable information on the relationship between vessel geometry and blood flow. However, numerical simulation requires to extract accurate models of arteries from low resolution medical images, which remains a challenging task.

When it comes to large arterial networks, simplified models based on centerline with radius information are often used. The only publicly available databases of whole cerebral vasculature [3], rely on this representation. In this context, being able to generate a smooth and structured volume mesh suitable for CFD directly from centerlines would open the way to numerical simulation in more complex vascular trees.

In the literature, existing methods to produce structured meshes require the preliminary extraction of a clean surface mesh from the data by segmentation [2], [1]. In this work, we propose a fully automatic method for computing a structured mesh from centerline information only. Our algorithm overcomes the limitations inherent to existing centerline datasets, such as noise or sparse information.

2. Methods

The input data required is a set of points with 3D coordinates x, y, z , radius r and connectivity information.

2.1 Spline approximation

In order to deal with noisy data points, the different branches of the arterial network are first approximated using 4D splines (x, y, z, r). Least-square fitting method is used to optimize the position of the control points. The number of control points, the knot vector and the initial parametrization are chosen to minimize the number of parameters while reducing the distance between the fitted and the original data under a given error bound. The error bound is selected in accordance with the spatial precision of the input data.

At the bifurcations, the splines corresponding to daughter branches share a common starting point and are C^1 continuous with the main branch. This results in a light and anatomically meaningful parametric modelisation of the network, as illustrated in Figure 1 (a).

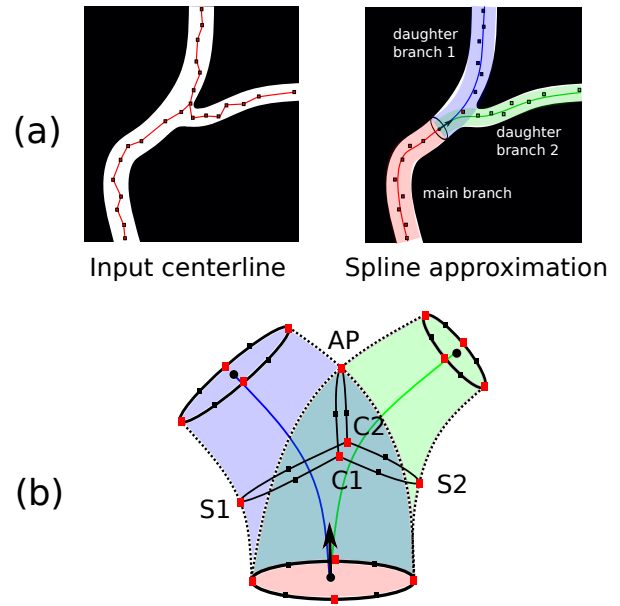


Figure 1: Illustration of the 4D spline approximation of centerlines (a) and the proposed bifurcation model (b). In (b), three half sections are defined by the key points AP, S1, S2, C1 and C2. AP is the apex of the bifurcation. S1 and S2 are located at the opposite of AP according to their respective centerlines. The center of the bifurcation is defined by averaging points AP, S1, S2 and is projected to the surface to give C1 and C2.

2.2 Bifurcation model

Due to the low resolution of the centerlines, the information around the bifurcations might be partial. However, the shape of the bifurcations impacts the blood flow and an anatomically accurate modeling is crucial for CFD studies. Zakaria et al. [4] proposed a surface model of bifurcation which was validated in regard to both the geometry and the CFD simulation, using a physical model of human cerebral artery.

The bifurcation model proposed in this work considers the shape features of the bifurcation of Zakaria et al. but was adapted to allow volumic structured meshing of the bifurcation and to integrate the spline representation of the network described in the previous section. For this, we use a branch junction scheme based on three half cross sections, each shared by two branches. The computation of the junction half

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sections relies on the determination of a number of key points, as described in Figure 1 (b). The junction sections are finally connected to the upstream and downstream vessel cross sections to form the faces of the mesh.

2.3 Mesh generation

The full network is divided into bifurcations and connecting segments. The bifurcations are meshed as described in section 2.2. The surface mesh for the tubular segments between bifurcations is then generated by sweeping evenly circular cross sections along the spline centerline. A parallel transport frame is employed to prevent twisting. In order to handle cases of segments joining two bifurcations, a smooth rotation is applied along the centerline to match the target cross section, following the method described by [2]. Once the surface mesh is produced, hexahedral cells can easily be computed using a structured O-grid template for each cross section.

3. Results and discussion

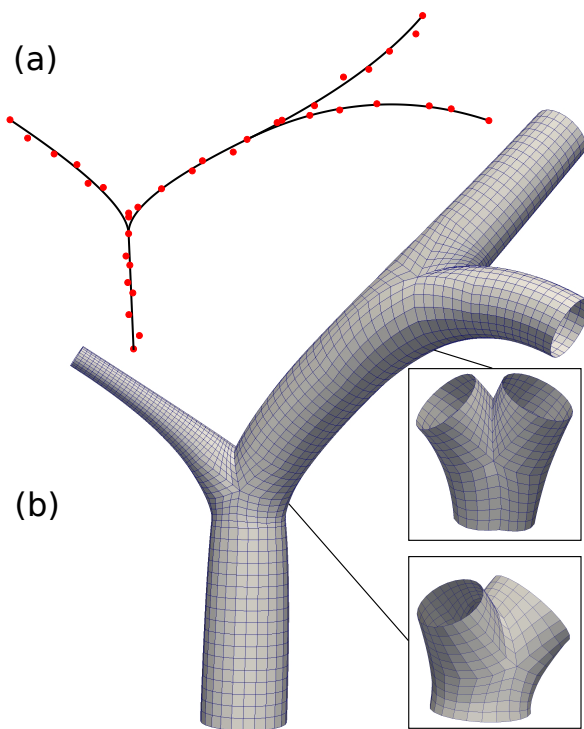


Figure 2: Structured mesh (b) generated by our method from a noisy centerline (a). The input data (red dots) was generated in order to illustrate different types of bifurcations, with vessel radiuses between 0.6mm and 2mm. A gaussian noise ($\mu = 0\text{mm}$, $\sigma = 0.3\text{mm}$) was applied to the centerline points.

As illustrated in Figure 2, the proposed method enables to generate a structured mesh with flow-oriented hexahedral cells. The error from the input data is controlled, and the bifurcations reproduce the anatomical

features of the human arterial bifurcations. Although only a small arterial network was represented here for space reasons, our algorithm is also able to deal with important radius difference of the daughter branches, small connecting segments and cycles.

In order to carry out a quantitative validation of the results as future work, we plan to gather a variety of patient specific arterial surface meshes, extract and deteriorate their centerlines, and compare the mesh obtained by our method to the original mesh.

4. Conclusion

In this work, we proposed a method to obtain a structured mesh of vascular network from noisy centerlines, based on a 4D spline representation of the data. Our method is fully automatic and can be applied to available data like [3]. Thus, it could notably enable to produce a database of structured meshes of large whole cerebral networks, to be used for computational fluid dynamics, stent deployment or fluid-solid interaction simulations. We acknowledge some limitation to our work, notably that the hypothesis of tubular shape was made for the arteries. Moreover, the method needs to be generalized to trifurcations, which are rare but may be present in the human arterial system.

5. Acknowledgements

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