Meshing Arterial Networks From Manually Extracted Centerlines

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ABSTRACT

In large vascular networks with small vessels, the low resolution of medical images causes the segmentation algorithms to fail. Simplified models based on the vessel centerline are convenient to represent complex networks, but are associated with a loss of information. In this work, we propose a pipeline which overcomes the limitations of manually extracted centerlines (low sampling, noise) to reconstruct an anatomically accurate surface or volume mesh suitable for numerical simulation.

1. Introduction

Many severe pathologies, such as stroke, affects the vascular tree. The geometry and topology of the arteries of a patient carry key information to predict the evolution of the condition or the treatment outcome. However, if medical imaging gives an insight on the shape of the major vessels, the accurate segmentation of large networks including small vessels remains challenging. In some cases, the manual extraction of the vessels by an expert is required. The use of simplified models based on centerline and radius information only enables to alleviate this time-consuming task, but it results in an important loss of geometric information due to low-sampling and noise.

Here, we propose a method which integrate anatomical a-priori to reconstruct the geometry of an arterial network from manually extracted centerlines. The skeleton is approximated by splines with smoothness constraint to get a C1-continuous model robust to the noise in the input data. The bifurcations are reconstructed according to a physiologically validated model [1]. Finally, a surface and volume mesh is generated from the spline network. The resulting mesh fulfills all the requirements for numerical simulation : it is structured, with hexahedral flow-oriented cells and adjustable boundary layer and cell density.

2. Method

The input data is a centerline network represented by a set of points with 3D coordinates (x, y, z), radius r and connectivity information.

2.1 Spline reconstruction

In order to obtain a continuous centerline from the given data points, the branches of the arterial network are approximated using penalized splines with 4-coordinates control points (x, y, z, r). The coordinates of the control points are optimized by the least-square method with the cost function below:

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$$f(P_0, ..., Pn-1) = \sum_{k=0}^{m} |D_k - C(t_k)|^2 + \lambda \sum_{j=2}^{n} (P_j - 2P_{j-1} + P_{j-2})^2 \quad (1)$$

where $P_{0,...,n-1}$ are the spline control points, $D_{0,...,k}$ are the input data points, C is the evaluation function of the spline and t_k is the chord length parametrization.

In this function, the first term of the sum controls the closeness of the fitted spline to the data points and the second term the smoothness of the spline. Those two criteria are balanced by the λ parameter. The value of this parameter is chosen so that it maximizes the smoothness while keeping the maximum distance from the data points to a value chosen according to the level of noise in the data. A different λ value can be used for the radius and for the spatial coordinates.

A first approximation is performed in order to estimate the position and the tangent of the bifurcation points. Then, each connecting vessel undergoes a second approximation, with additional constraints of fixed end and tangent at the bifurcation points, to keep the G^1-continuity, as illustrated in figure 1.

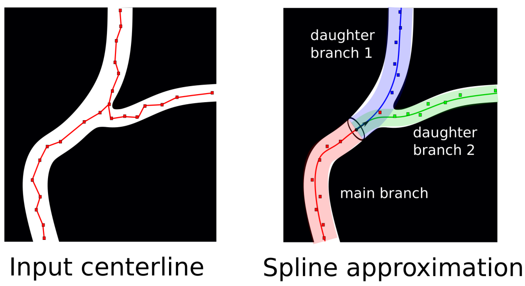

Fig. 1 The spline approximation pipeline. The black dot on the right is the estimated bifurcation point.

This results in a light and anatomically meaningful parametric modelisation of the network, where the bifurcations are modelled as the merging of two tubes, as proposed by [1].

2.2 Structured Meshing

In this part, we aim at generating a structured volume mesh from the spline model of the previous section. For this, the network is divided in two parts : the bifurcations, which have particular topology, and the connecting segments. Our meshing technic relies on connecting successive cross sections oriented tangentially to the vessel centerline, as illustrated in figure 2.

The surface mesh for the connecting segments between bifurcations is produced by sweeping evenly spaced 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]. For bifurcations, we use a branch junction scheme based on three half sections, each shared by two branches. The computation of the junction half sections relies on the determination of a number of key points. The junction sections are finally connected to the upstream and downstream vessel cross sections to form the faces of the mesh, as shown in figure 2.

To produce the volume mesh, each cross section of the tree is filled with a O-grid pattern to form hexahedral cells.

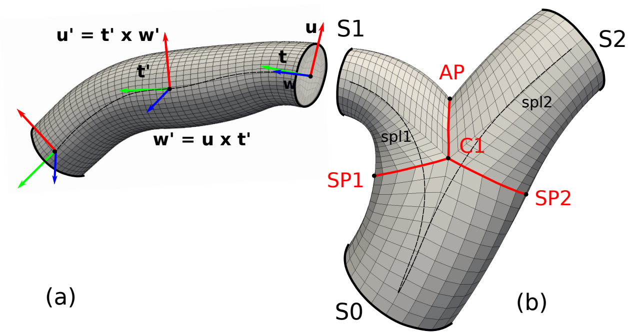

Fig. 2 Illustration of the meshing procedure for the connecting segments (a) and the bifurcations (b). In (b), three half sections are defined by the key points AP, SP1, SP2, C1 and C2. AP is the apex of the bifurcation. SP1 and SP2 are located at the opposite of AP according to their respective centerlines. The center of the bifurcation is defined by averaging points AP, SP1, SP2 and is projected to the surface to give C1 and C2.

3. Results and Discussion

As illustrated in Figure 3, the proposed method enables to generate a structured mesh with flow-oriented hexahedral cells. The error from the input data is controlled, and the anatomical features of human vessels and bifurcations are preserved. The thickness and the number of layers inside the volume mesh can be specified by the user, as well as the number of cross sections along the vessels.

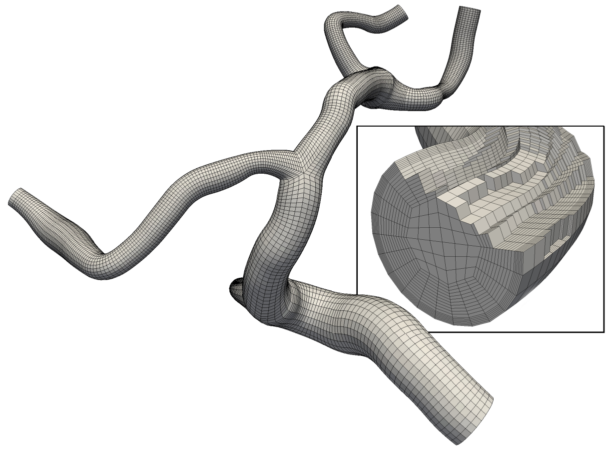

Fig. 3 Structured volume mesh generated with the porposed method.

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. Concluding Remarks

In this work, we proposed a method to automatically mesh an arterial network for numerical simulation from manually extracted centerlines, based on a reconstruction of the data using splines. It can alleviate the vessel extraction task and thus opens the way to the meshing of large vascular networks with vessels of small diameter. We plan to use this method to mesh the database of cerebral arterial networks braVa [3]. Such data could be used to study cerebral pathologies such as stroke, by running computational fluid dynamics simulation, stent deployment or fluid-solid interaction simulations in whole brain arterial networks. We acknowledge some limitations to our work, notably that the hypothesis of tubular shape was made for the arteries. Moreover, the method needs to be generalized to trifucations, which are rare but may be present in the human arterial system.

Acknowledgments

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