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Delaunay Tetrahedralization of the Heart Based on Integration of Open Source Codes

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Abstract. The Finite Element Method (FEM) is a way of numerical solution applied in different areas, as simulations used in studies to improve cardiac ablation procedures. For this purpose, the meshes should have the same size and histological features of the focused structures. Some methods and tools used to generate tetrahedral meshes are limited mainly by the use conditions. In this paper, the integration of Open Source Softwares is presented as an alternative to solid modeling and automatic mesh generation. To demonstrate its efficiency, the cardiac structures were considered as a first application context: atriums, ventricles, valves, arteries and pericardium. The proposed method is feasible to obtain refined meshes in an acceptable time and with the required quality for simulations using FEM.

1. Introduction

Studies using the Finite Element Method (FEM) may be used to improve cardiac ablation procedure, such as radiofrequency cardiac ablation, and reduce possible complications. The radiofrequency cardiac ablation is being used for over 10 years to treat tachycardia, atrial fibrillation and atrial flutter [1]. However, the esophageal injury is a common damage: the consequence for the patient is death due to the internal bleeding. The focus of the problem is monitoring the temperatures of the tissues and FEM simulations have contributed significantly to the improvement of this technique [2, 3, 4]. For such simulations, the finite element meshes should consider the anatomical and histological features of the target structures and its quality has to be acceptable. Some methods or tools used to generate meshes of biological structures are still limited by constructing non-detailed models or due to limitation in the use condition [2, 4, 5].

Therewith, strategies to integrate open source software as an alternative to solid modeling and automatic mesh generation are demonstrated in this paper. Some related ideas were previously presented in [6]. The novelty proposed here is the pericardium covering the internal layers, with detailed anatomical features. This was motivated by the importance that internal and external cardiac structures represent for studies of cardiac ablation. This approach brings many advantages for the community interested in FEM simulations and cardiac ablation, providing means to perform the entire pre-processing step (solid modeling and mesh generation) of complex geometrical problems.

2. Methodology

The choices of cardiac structures were motivated by the complex geometrical domain and by the clinical relevance that these structures represent for investigating esophageal injury. The model defined in our study was composed of three main parts: right internal portion (venous), left internal portion (arterial) and external portion (pericardium). Each internal portion has an atrium, a ventricle, an artery and valves. The dimensions of these structures are presented in Table 1 [7], which were defined in cardiac diastole. The pericardium was represented without thickness, because it is a very thin tissue which surrounds the heart. Also, an echocardiographic image was used as another reference during the construction process of the 3D model.

The Blender package was chosen as the solid modeler for this study. This package is a multiplatform integrated system of tools and contains resources to export and import objects in different formats using Python scripts. There are different methods for generating 3D meshes. We chose the Delaunay algorithm [8] for being one of the most popular and one of the most efficient algorithms [9], available in the TetGen package [8]. Both packages are under public licenses.

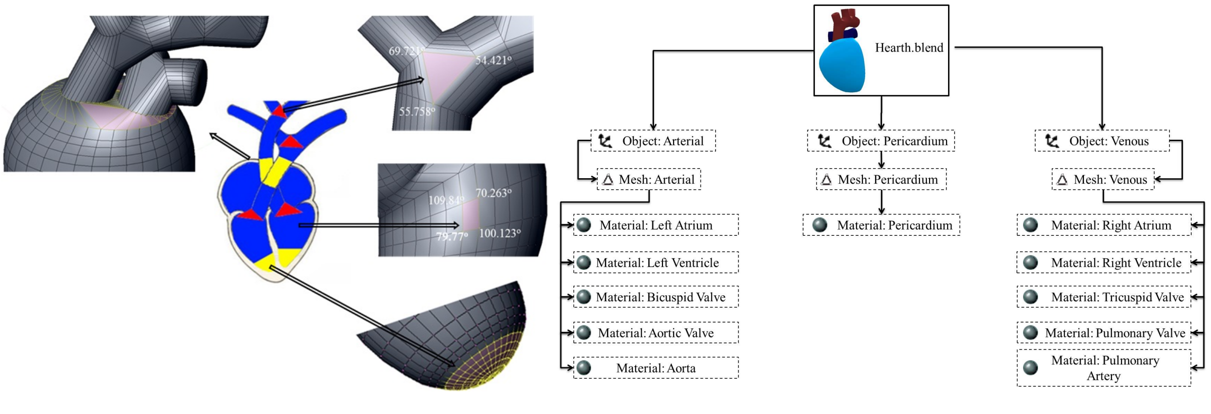
To ensure the integration of Blender with TetGen, two construction strategies must be respected: (1) definition of faces and (2) density control of vertices. The first strategy consists of choosing the appropriate type of face to discretize a solid. Regular or non-complex regions of the domain must be discretized with quadrilateral or rectangular faces (eg atriums and ventricles). Critical or complex regions must be discretized with triangular faces (eg bifurcations, regions of connections). The second strategy defines the number of nodes in a region. The increasing number of vertices allows a better representation of curved regions, smoothing the direction transition and respecting the features defined (eg arteries). Regions represented with triangular faces, quadrilateral or rectangular faces, and with increased density of vertices are shown in Figure 1(a). A domain discretized in Blender is stored in its native file format: *.blend.* This file is composed by datablocks (file structures which store data used to discretize a solid). It could be of object type, mesh type, scene type and other types. The final model is composed by 17 datablocks of object, mesh and material types (Figure 1(b)).

The exportation of the model was accomplished by a script written in Python. This script writes the information of all datablocks in a single *.poly* file, required as input by TetGen. The *.poly* file is composed by four lists: lists of nodes, faces, volume holes and region attributes (such as color markers). For a better visualization, a distinct color maker was assigned for each structure of the model, totalizing 11 markers.

The outputs of the mesh generation process are three files: *.node*, *.face* and *.ele* files,

Table 1. Morphometry applied in the hearth model (diastolic dimensions of an adult heart [7]).

Structure	Dimension (cm)	Longest Axis (cm)
Left Atrium	2.1 – 3.0	4.6
Right Atrium	1.9 – 4.4	5.3
Left Ventricle	3.1 – 3.8	4.3
Right Ventricle	2.1 – 3.7	4.2
Aorta, Pulmonary Artery and Bicuspid Valve	2.5	2.5
Tricuspid Valve	3.0	3.0
Aortic Valve	2.4	2.4
Pulmonary Valve	2.3	2.3
Interventricular Septum	0.8 – 1.2	4.0
Pericardium	—	10.6



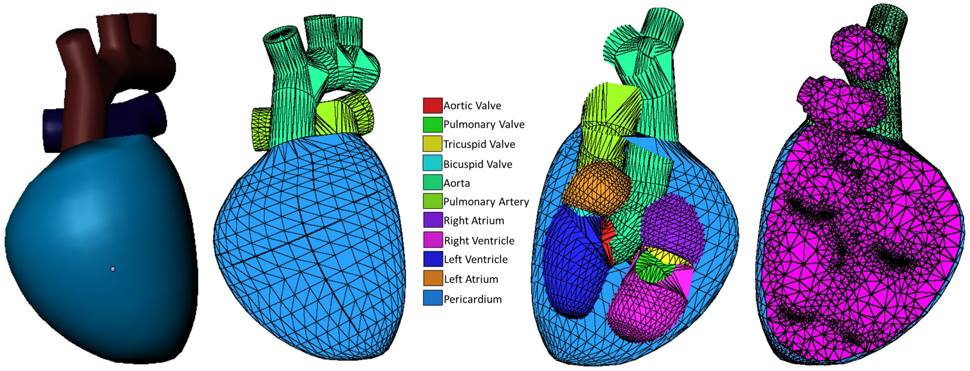
(a) (b)

Figure 1. Visualization of the location of different types of faces (a) and hierarchy of datablocks model (b).

containing information, about vertices, faces and tetrahedral elements of the resulting mesh, respectively.

3. Results and Discussions

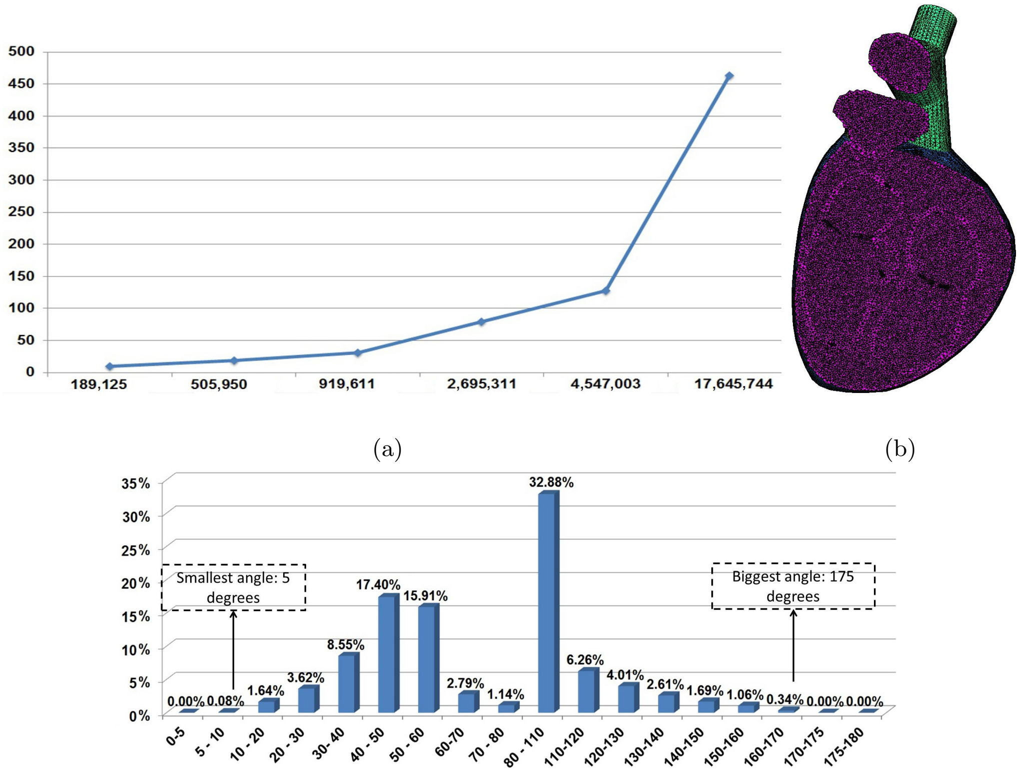
FEM simulations require highly refined meshes of simple or complex domains, and its generation in an acceptable time. The methodology proposed in this paper performs the requirements. The complex geometry of the cardiac structures allowed testing the feasibility of the combined use of anatomical features, free and open source packages and the application of the defined strategies (Figure 2). The *.poly* file stores data of 4,363 vertices, 8,718 faces and 11 color markers. This file is shown in Figure 2(b). A first mesh was generated in 9.235 seconds with 189,125 tetrahedral elements and is shown if Figure 2(c).



(a) (b) (c)

Figure 2. Resulting model: (a) *.blend* file with assigned boudary markers, (b) *.poly* file with assigned color markers and (c) .ele file with tetrahedral mesh.

Meshes were generated through successive refinements of the initial mesh (Figure 2(c)): this strategy allowed estimating the processing time growth due to the number of tetrahedral elements (Figure 3(a)). The most refined mesh was generated in 7.72 minutes with 17,645,744 elements. The quality of the mesh is an important aspect in proposals designed to generate meshes through FEM simulations. Adopting the criterion of measurement of dihedral angles, the results are relevants. This can be verified in a histogram constructed with the total of dihedral angles present in ranges of angles, as well as identification of the smallest and largest values involved. A highly refined mesh is shown in Figure 3(b) and the corresponding histogram is presetend in Figure 3(c). In this histogram, the tetrahedral elements were constructed with dihedral angles whose values are between 5 and 170 degrees, with 32.88 percent belonging between 80 and 110 degrees, which are close to values set on a regular tetrahedron [10].



(a) (b)

(c)

Figure 3. Processing time (seconds) (y axis) versus number of elements (x axis) is shown in (a), refined mesh with 4,547,003 elements is shown in (b) and total of dihedral angles (y axis) inside prescribed angle intervals in degrees (x axis) is shown in (c).

4. Conclusions

The proposal presented in this paper considers strategies for solids construction and automatic mesh generation through integration of open source packages. We have proved the efficiency of this integration. Highly refined and detailed meshes (atriums, ventricles, valves, arteries and pericardium) were generated in acceptable times and with the required quality for simulations using FEM: the values of dihedral angles are compatible with the specialized literature. Thus, our proposal provides a significant contribution to mesh generation for studies using FEM which can be applied in different areas, such as studies to improve cardiac ablation procedures.

5. Acknowledgments

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