2nd International Conference on Mathematical and Computational Biomedical Engineering – CMBE2011
March 30 – April 1, 2011, Washington D.C., USA
P. Nithiarasu and R. Löhner (eds)

Hexahedral mesh generation for image-based computational fluid dynamic investigation of vascular districts

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SUMMARY

Mesh generation is a critical step in image-based computational fluid dynamic investigation of vascular districts. While structured hexahedral meshes are known to be superior to unstructured meshes for CFD/FEA simulations, their use has been very limited due to the complex and non-automated generation procedure. We propose a new meshing strategy to generate structured conformal hexahedral meshes inside a realistic vascular lumen by combining synthetic descriptors of vascular topology (centerlines and radii of the maximal inscribed spheres) available in *vmtk* with powerful geometrical tools implemented in *pyFormex,* both open source software packages. The final volume mesh closely matches the original surface and can be classified as optimal following usual cell-quality metrics, thus suitable for accurate CFD applications.

Key Words: *mesh, hexahedral, computational fluid dynamics (CFD), artery, pyFormex.*

1. INTRODUCTION

Accessing high temporal and spatial resolution flow data in vascular districts of a patient is becoming reality thanks to the image-based computational fluid dynamics. This approach requires a number of serial steps: medical imaging (CT, MRI, US) and flow measurements at the boundaries of the region of interest, vessel geometry segmentation, computational mesh generation, integration of the Navier-Stokes equations, and post-processing to extract the indices of interest. Among the others, the mesh generation is a critical issue, mainly because the geometry is not build in a bottom-up process (like in manufacturing industry), but appears all together in its complexity after the segmentation. Automatic meshing schemes are widely preferred in patient-specific CFD, typically using unstructured tetrahedral meshes with near-wall prismatic layer, while structured hexahedral meshes are rarely adopted. In a recent study we have compared the performance of unstructured and structured meshes in solving the flow equations with a commercial software (*Fluent, Ansys*) in a coronary artery district and, as expected, we found that unstructured meshes needed much higher resolution than structured meshes to reach mesh independency, with higher computational costs (computational time and memory). Interestingly, the wall shear stress (WSS, a differential quantity) did plateau with structured meshes but did not exhibit a clear converging trend with unstructured meshes [1]. Other sources support such a difference in performance, and attribute it to the high numerical diffusion errors associated with unstructured meshes [2]. As mainly differential quantities (e.g. TAWSS, OSI) are of interest in vascular domains, the CFD results need to have high accuracy. Thus, meshing the

volume domain with hexahedral cells would not only simplify the computational side but also improve the reliability of the calculated values.
In this paper, we present a novel structured hexahedral meshing methodology suitable for vascular districts, which has been implemented in pyFormex, a python-based open-source software under development at Ghent University dedicated to create and to handle large geometrical models [E1].

2. METHODS

A vascular surface (generally in a stereolithography format, STL) needs to be subdivided into simpler domains suitable for structured meshing. Thus, a different strategy is adopted for no/single bifurcating vessels (sweeping case, which represent a simplified case), and for generally branched vessels (mapping case).

2.1 Sweeping case - Single bifurcating vessels (e.g. carotid artery) can be oriented on a plane parallel to the bifurcation axis, which allows drawing some 2D lines around the vessels. Such lines can be used to guide a number of cutting planes which slice the vessel in semi-circular sections aligned longitudinally along the three branches. Then, a sweeping operation can be performed to generate a volume mesh [Figure 1-top].

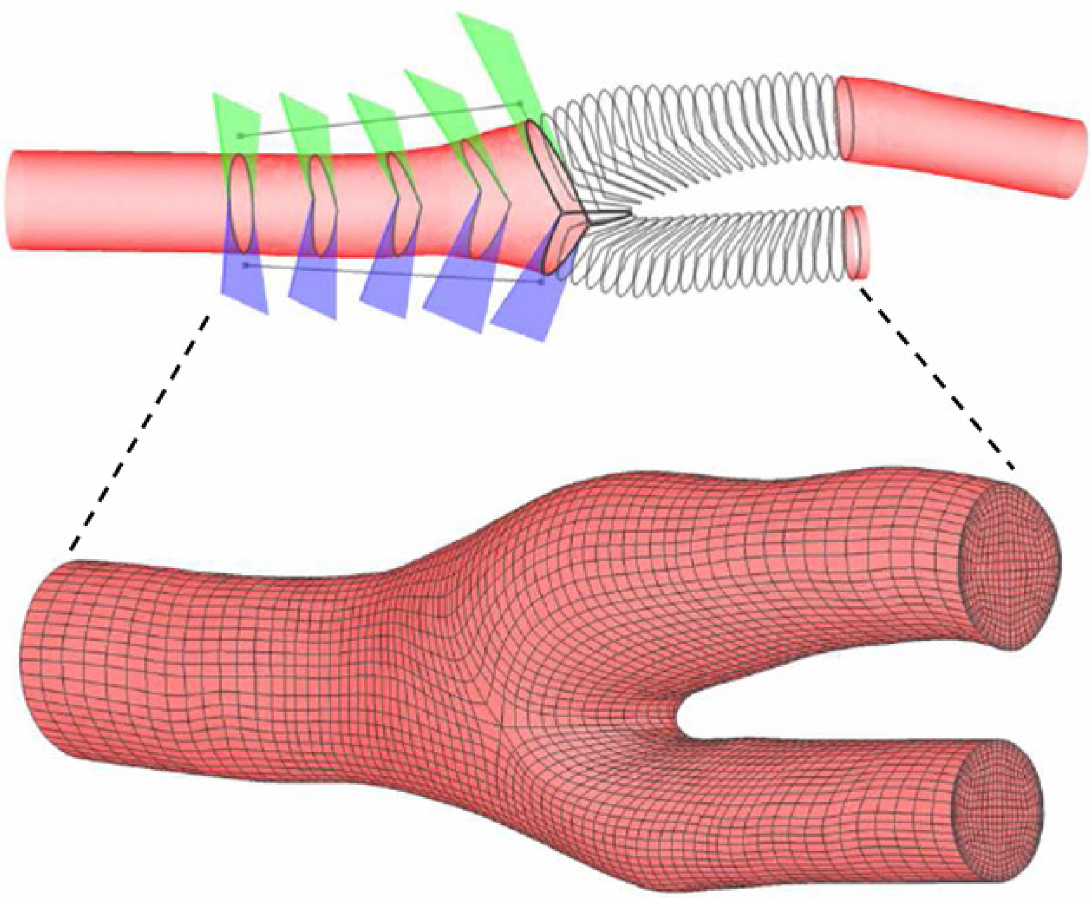

Figure 1: Meshing of a carotid artery by means of three sweeping operations. Top: subdivision of the bifurcation into three branches, which are then sliced into semi-circular sections. Bottom: conformal structured hexahedral mesh of the carotid lumen.

2.2 Mapping case - For more complex districts, such as mice and human aorta, synthetic descriptors of the vascular topology, like centerlines and radii of the maximal inscribed spheres, are needed. An open-source software package (i.e. the "vascular modelling toolkit, *vmtk*", E2) provides automated generation of these descriptors (Figure 2-left). Centerlines and radii can be imported in pyFormex in order to design a series of blocks around the vessel surface, including regions of branching (bif-, tri- or n-furcations, Figure 2-center). In each of these blocks, it is trivial to generate a structured hexahedral mesh and its resolution can be adapted parametrically. Projecting the mesh nodes of the lateral surface of these blocks on the vessel surface provides a one-to-one correspondence between block surface (source) and vessel surface (target). The source-to-target correspondence can be then used to map the volume mesh of each block inside the vessel lumen, by means of an isoparametric transformation. A human aorta is shown as example and the equiangle skew [1] and the scaled Jacobian at all cell nodes [3] are taken as metrics of mesh quality (optimal values are 0 for the equiangle skew and one for the scaled Jacobian).

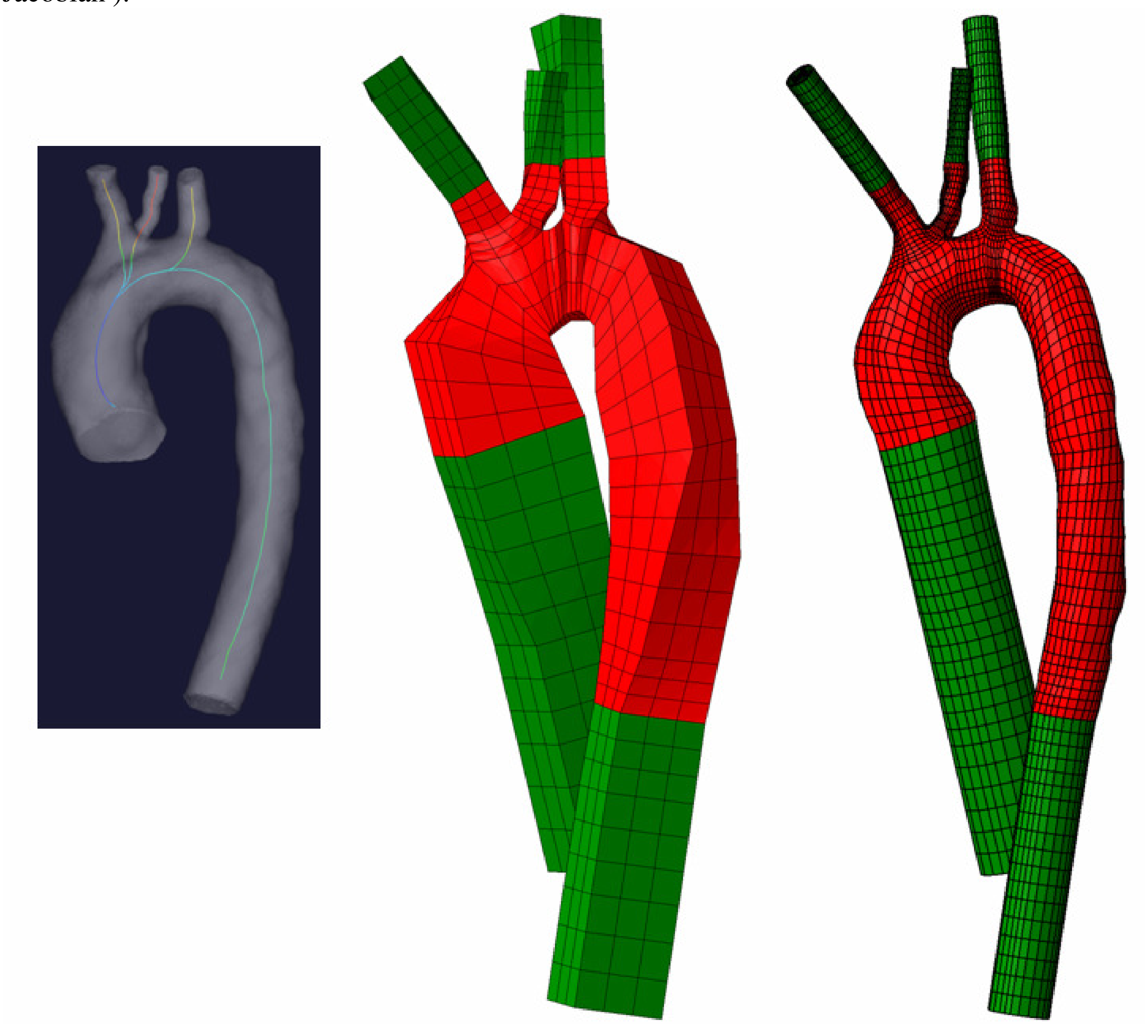

Figure 2: Meshing of a human aorta. Left: centerlines coloured by radius (vmtk). Center: series of blocks around the vessel surface (pyFormex). Right: lumen mesh, with real domain (red) separated from flow extensions (green). The equiangle skew is in average 0.21 and max 0.77; the scaled Jacobian is 0.90 on average, and the minimal value is 0.23.

3. RESULT AND DISCUSSION

3.1 Sweeping case - A carotid artery can be meshed using a Graphical User Interface in a matter of seconds [4, E3]. The mild stenosis present on the ICA does not produce distortion of the cells, as the cross-sections still resemble a nearly circumferential contour (Figure 1-bottom).

3.2 Mapping case -The cells of the aortic computational domain can be divided into two groups, in order to separate the real flow domain from the flow extensions (added with vmtk to apply correct boundary conditions), so that the post-processing can be performed only on the real domain (Figure 2-right). The elements are finer near the wall, to provide higher accuracy for near-wall quantities, and are globally aligned with the flow. Average equiangle skew is below 0.25, which is classified as optimal [E4] and the scaled Jacobian in all cells is positive (valid cells) and higher than 0.2 [3].

4. FUTURE WORK

Current development is aiming at conformal refinement of hexahedral meshes and generation of vessel wall around the lumen from image data (external wall surface) or, alternatively, from anatomical scaling data (variable wall thickness as percentage of lumen radius).

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