A new workflow for patient specific image-based hemodynamics: parametric study of the carotid bifurcation

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ABSTRACT: Engineering applications involving biological fluids have highly transversal requirements in terms of domain definition from clinical images, complex flow conditions, rheological properties of fluids, structure motion and deformation, visualization and post-processing of the results. For these reasons, a properly tailored computer-aided–engineering workflow represents an elective environment where to perform realistic hemodynamics studies. Nowadays a large part of the technological requirements needed to tackle these problems in a computational environment are already available in open source and/or commercial codes. Nevertheless, success still strongly depends on technical knowledge and best practice. In other words, the design of the workflow must be translated into a stable and usable framework. Here we present a new workflow based on three fully validated software used to effectively fulfill the requirements related to hemodynamics: the **Vascular Modeling Toolkit (VMTK)** for the pre-processing step (i.e., from clinical images-to-anatomic models); the mesh morphing tool **RBF Morph** to impose changes to the vascular anatomy; **Ansys Fluent** as solver of the governing equations of fluid motion. As a first test case we focused our attention on the study of a realistic model of carotid bifurcation, where geometrical factors such as bifurcation angle and the bulb flare are deformed starting from image-based models. In perspective the herein proposed workflow could be a powerful tool supporting image-based surgical planning optimization in several arterial districts.

1 INTRODUCTION

1.1 *Background*

Engineering applications involving biological fluids have highly transversal requirements in terms of domain definition from clinical images, complex flow conditions, fluid rheological properties, structure motion and deformation, visualization and post-processing of the results.

In particular, in the last decade, it has been demonstrated that the coupling of medical imaging and computational fluid dynamics (CFD) allows to calculate highly resolved four-dimensional blood flow patterns in anatomically realistic models of the cardiovascular district, thus obtaining information, for example on quantities such as the distributions of the friction and pressure forces at the luminal surface, which are difficult to be measured in vivo [Boussel et al., 2009]. In detail, image-based CFD is becoming a powerful tool to quantify and classify local hemodynamic conditions,thus enabling the study of disease mechanisms [Friedman et al.,2010; Taylor and Steinman, 2010]. However, the increasing reliance on CFD for hemodynamic studies necessitates a close look at the various assumptions required by in silico modeling. For example, much effort has been spent to assess the sensitivity to assumptions regarding boundary conditions [Moyle et al., 2006; Wake et al.,2009; Morbiducci et al.,2010; Hoi et al.,2010; Spilker and Taylor,2010], blood rheology [Morbiducci et al., 2011], geometric uncertainties [Thomas etal.,2003], vascular compliance [Perktold and Rappitsch, 1995]. Moreover, great effort has been put in studying the links between disturbed flow, responsible for the onset and development of atherosclerosis and other vascular wall pathologies [Ku et al., 1983] and geometric features such as tortuosity of the vessel, bifurcation angle, flaring etc [Lee et al., 2008; Bijai et al., 2012].

In this scenario, linking fluid structures to wall deformations is a challenging task, due to the need to (1) have detailed knowledge of the highly complex mechanical behavior of the arteries or (2) impose realistic vessel wall deformation/motion, as extracted from clinical imaging, when only the hemodynamics is of interest.

In this work we present a new workflow based on three fully validated software used to effectively fulfill the requirements related to hemodynamics:

• the **Vascular Modeling Toolkit (VMTK)** for the pre-processing step. VMTK can take clinical images as an input and give anatomic models of cardiovascular districts as output;

• the mesh morphing tool **RBF Morph** to impose changes to the vascular anatomy;

• **Ansys Fluent** as finite volume-based solver of the governing equations of fluid motion.

As a first test case we focused our attention on the study of a subject-specific carotid bifurcation being this anatomical site of major interest in hemodynamics and its relation to atherosclerosis. The present study is focused on the impact that the shape of the carotid bulb and the bifurcation angle have on the resulting flow patterns, which are thought to be tightly related to the focal development of athermatous plaques at that site, or could be related to the output of remodeling surgical procedures. The effect of the shape is unrealistically magnified in order to emphasize the potency of the approach.

2 MATERIAL AND METHOD

2.1 *The VMTK toolkit*

The Vascular Modeling Toolkit is a collection of open-source libraries and tools for 3D reconstruction, geometric analysis, mesh generation and surface data analysis for image-based modeling of blood vessels (see Antiga et al. 2008). It has been designed to provide seamless integration with downstream CFD codes. For the present application, it has been used to segment the carotid bifurcations from clinical Magnetic Resonance (MR) images, to obtain and characterize the anatomy (centerlines, radius, bifurcation geometry, branch geometry, section areas, curvature, tortuosity), to generate a suitable triangulated, superficial mesh for CFD and export it directly to Fluent (.msh) format.

2.2 *The RBF Morph add-on*

RBF Morph (see Biancolini 2011) is a morpher code that combines a very accurate control of the geometrical parameters with an extremely fast mesh deformation, fully integrated in the CFD solving process. RBF Morph is the meeting point between state-of-the-art scientific research and top-level industrial needs.

For the present application it has been used to impose clinically relevant modifications on the carotid bifurcation geometry such as changes on relative internal/external angle between internal carotid artery (ICA) and external carotid artery (ECA), named ICA/ECA angle, deformation of the carotid bulb and presence of a stenosis at the ICA.

2.3 *Ansys Fluent solver*

The finite volume method was applied to solve the governing equations of the fluid motion. The general purpose CFD code Fluent ANSYS12 (ANSYS Inc., USA) was used on mesh-grids generated using the Gambit mesh generator software: the fluid domain was divided into about 1.40·000 tetrahedral cells. In order to solve the nonlinear system of matrix equations derived from the discretization of the flow equations on the computational grid, a second order upwinding method was used to obtain the solution at each time step of the time-dependent problem, respectively. The backward Euler implicit time integration scheme was implemented with a fixed time increment (time step equal to 2 ms). Fluid was modelled as homogeneous, isotropic and Newtonian (density equal to 1060 kg m^{-3}, dynamic viscositiy equal to 3.5 cP). As for the boundary conditions, a measured flow rate waveform was applied at the inlet section of the model in terms of flat velocity profile and a fixed 60/40 flow split repartition was imposed between ICA and ECA outlet sections (exhaustive details can be found in Morbiducci et al 2010).

2.4 *Changes to shape of the carotid bifurcation*

In order to perform a parametric study of the carotid bifurcation, in the present application, starting from the acquired carotid bifurcation, relevant modifications have been considered. Mesh morphing allows to continuously change the shape of the vessels, two specific shape modifications are herein explained in detail: the first one consists in the change on external angle (ECA angle), the second one consists in the deformation of the carotid bulb shape.

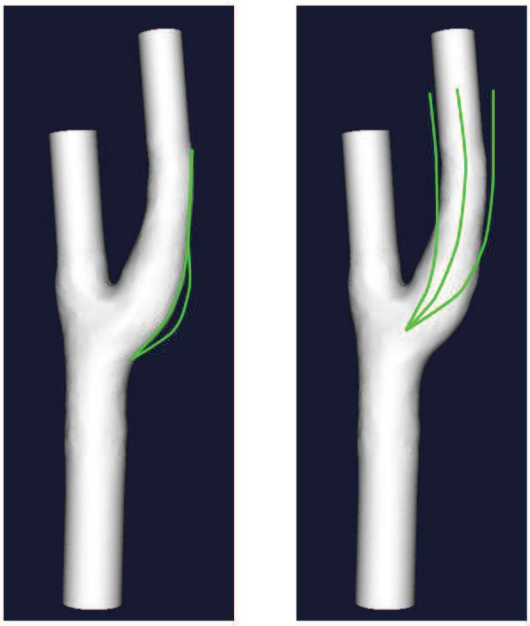

Figure 1. Addressed shape modifications: change of carotid bulb shape (left), changing of the ECA angle (right).

2.5 *Parameter setup for vascular morphing*

RBF Morph allows to set-up and store several shape modifiers. It's important to notice that only the information required for mesh updating (i.e. RBF coefficients) are stored and there is no need to save the morphed mesh. This approach makes the CFD model parametric; the desired set of amplifications for all the shape modifications can be applied at calculation stage just before the iterations.

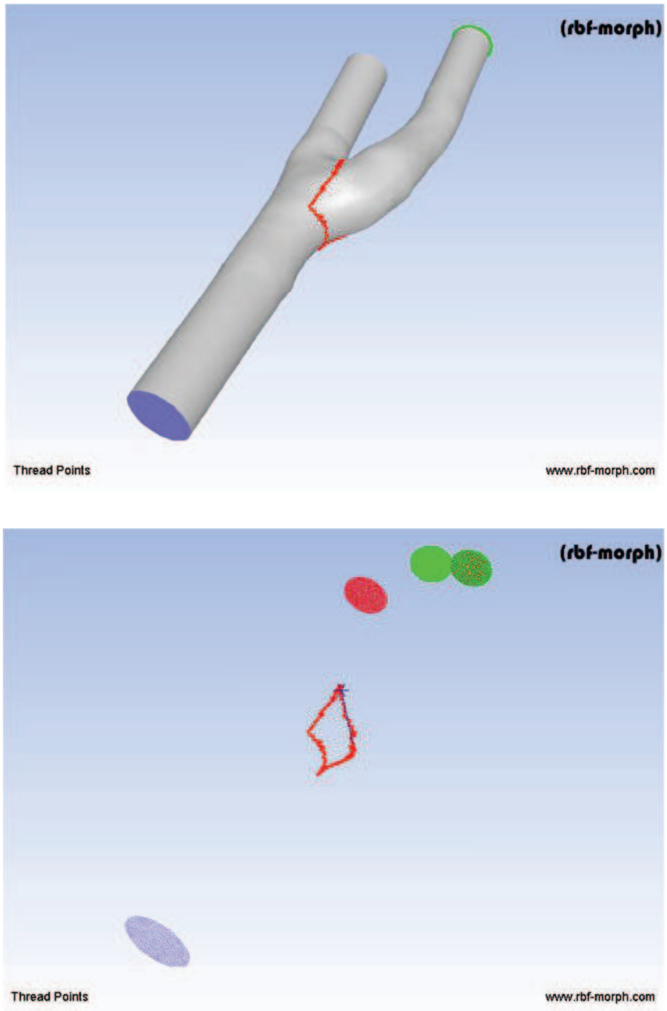

Figure 2. RBF Morph set-up for ECA angle variation. A zero movement is imposed to the red points at the branch root whilst a rotation around the branch is imposed to the points at the ECA surface (top). Rotation axis in blu and a preview of the ECA points in the rotated configuration (bottom).

The set-up of one of the two shape modifiers (ECA angle) is described in detail. A cylinder is used to limit the morphing action to the part of the model that has to be bended. Points at the branch root are extracted as surface points defining all the points on the wall and an auxiliary selection cylinder (with the outside option). The bending of the vessel is imposed applying a rigid rotation to all the points on the ECA outlet section. Extracted RBF points are represented in Figure 2 where the prescribed movement is highlighted. It is important to notice that even if a rigid rotation produces a non-linear deformation field, the software has the ability to deal with it and so even rotation are properly amplified with respect to the baseline value used for set-up.

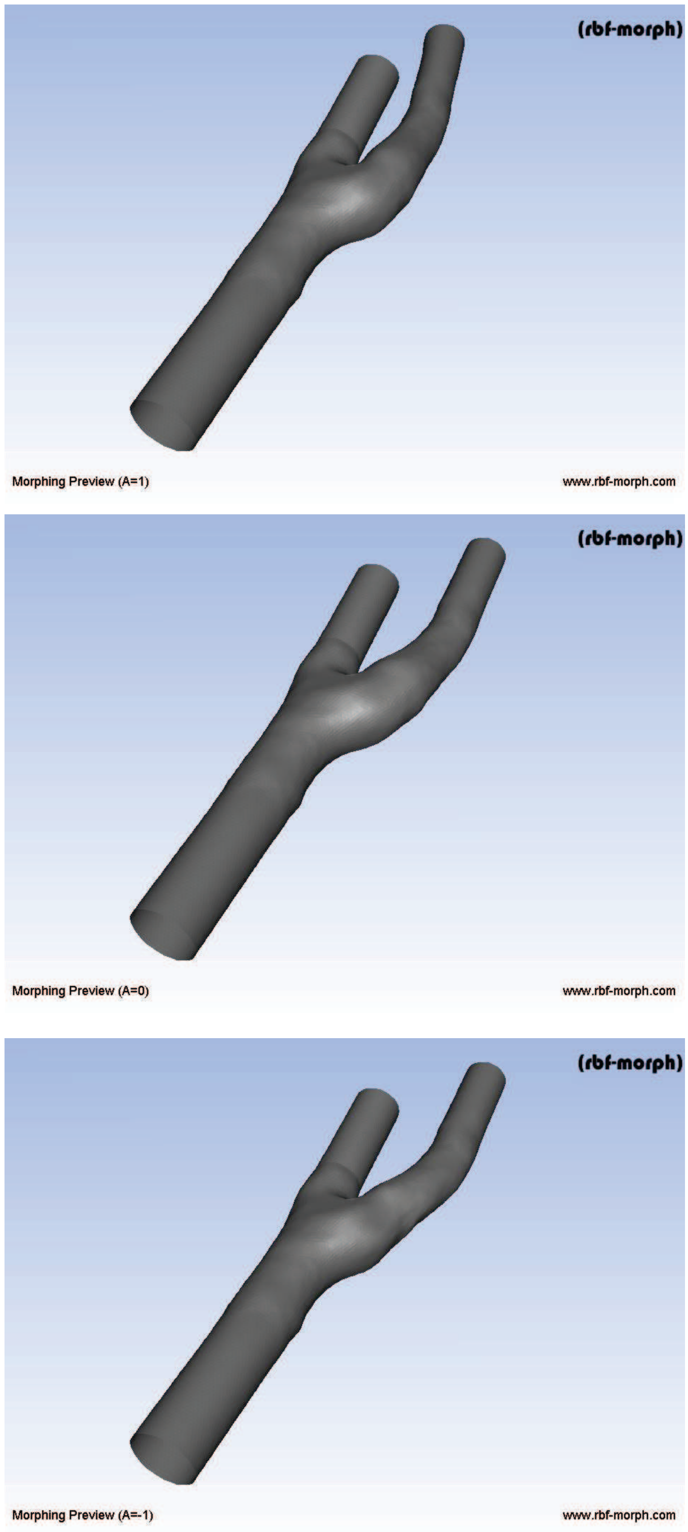

Figure 3. The effect of shape modification (ECA angle) is previewed at 3 values of the amplification (-1,0,1).

The effect of shape modifier is clearly represented in Figure 3 where various amplifications are explored (all previewed configuration were also checked for the quality of resulting volume mesh). Whilst a preview is advisable at set-up stage the best practice is to morph the model just before the CFD calculation; the morphing module works in Fluent parallel.

The second shape modifier is defined limiting the action of the morpher with a sphere surrounding the carotid bulb. A second sphere is used to select vessel points (with outside option); this allows to define points at the boundary of the bulb area that are fixed.

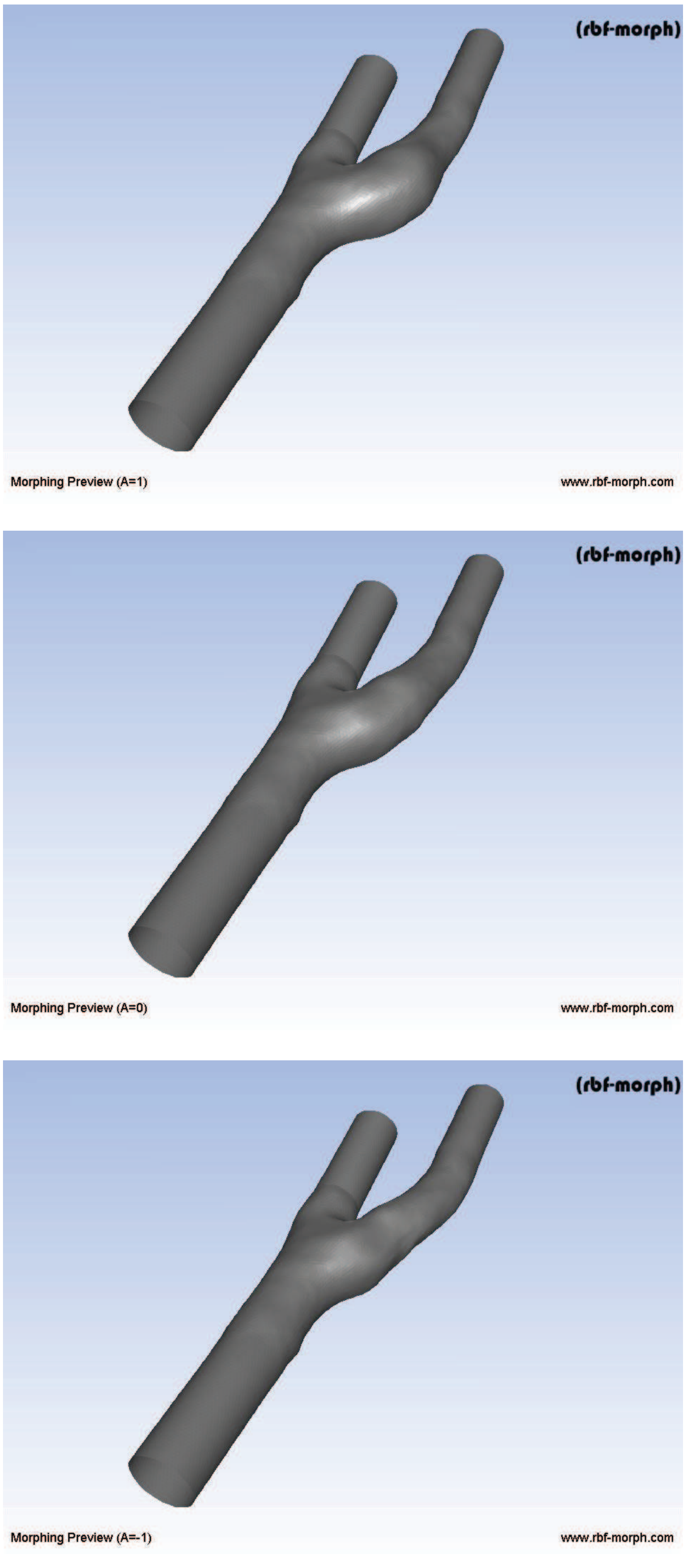

Figure 4. The effect of shape modification (bulb shape) is previewed at 3 values of the amplification (-1,0,1).

The bulb shape is then controlled adding individual points on the bulb surface, each one with a movement normal to the surface defined so that the combined action gently deform the bulb surface in a meaningful fashion. The action of the shape modifier is represented in Figure 4.

3 RESULTS

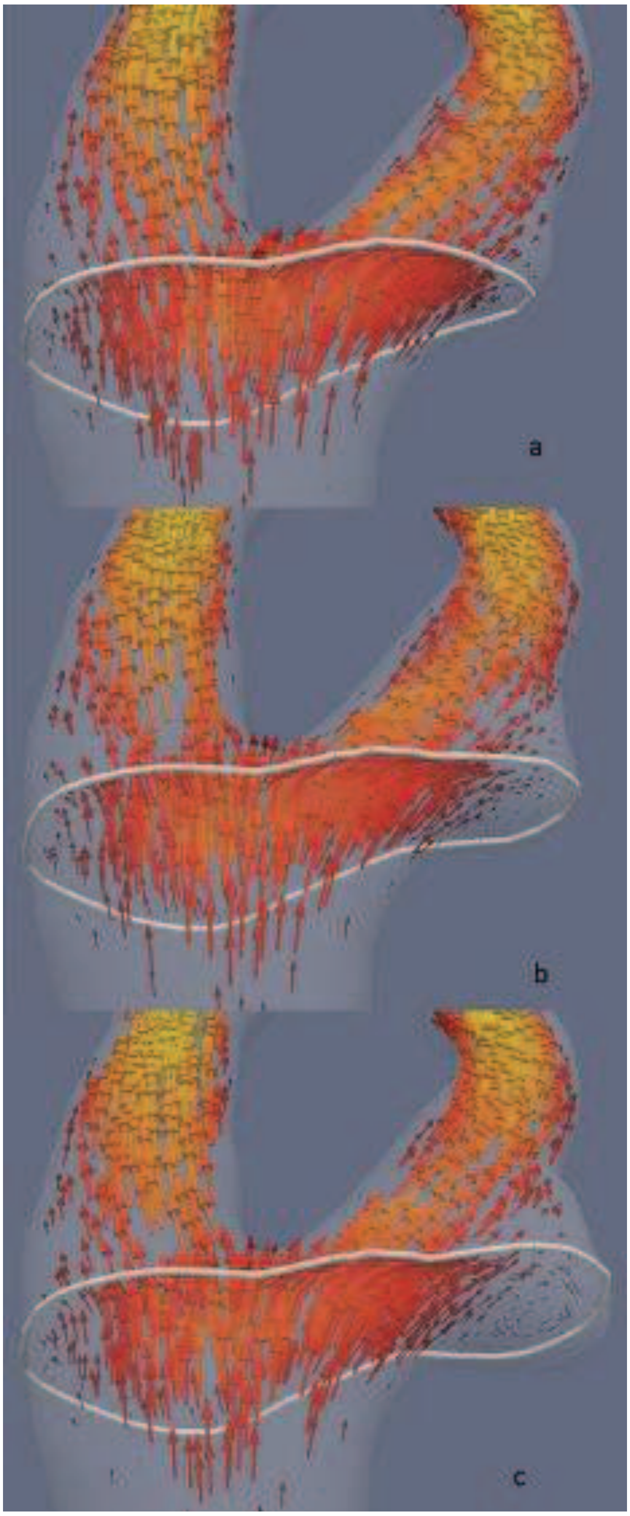

Figure 5. Effect of the increasing bulb dimension. The bulb dimension is increased from panel (a) to (c) and accordingly the velocity flow patterns show relevant changes highlighted by the vectors distribution.

The new parametric model of the carotid bifurcation allows to investigate several new shapes. The two shape modifiers can be combined; other shape modifications (for instance vessel bending in other planes) can be easily added and combined as well.

The case of bulb shape is here presented to demonstrate how the parametric model can be exploited. Three different amplifications have been considered (see Figure 5). The bulb shape has a relevant effect on the shape of the flow field. Qualitative and quantitative hemodynamics parameters could be extracted via user-defined functions (UDF) to understand how they are related to the shape parameters, as in [Morbiducci et al., 2010; Morbiducci et al., 2011].

4 DISCUSSION AND FUTURE WORKS

Here we show that thanks to the proposed new workflow, a comprehensive fluid dynamics study of a patient-specific carotid bifurcation with several relevant anatomical modifications can be performed successfully. The workflow takes clinical images as input and it is capable to generate and visualize flow fields in reshaped vascular districts. The power, the usability and the full level of integration demonstrated by the three computational bricks, together with the possibility of exploiting their features in High Performance Computing environments make this new workflow very attractive for future applications on a wide range of clinically relevant hemodynamics problems. The parametric nature of the model allows an easy integration of the workflow with additional computational tools (modeFRONTIER, Ansys DesignXplorer) for shape optimization problems, with particular reference to virtual testing of surgical connections, virtual surgical training/planning and medical devices design.

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