VIRTUAL STENTING OF CAROTID ARTERY STENOSIS

Catarina F. Castro(*), Carlos C. António, Luisa C. Sousa
INEGI and DEMec, Faculdade de Engenharia da Universidade do Porto, Porto, Portugal
(*)Email: ccastro@fe.up.pt

ABSTRACT
The present study quantifies the effect of stenting on the hemodynamics of a carotid stenosis under realistic conditions. The geometry and flow conditions are based on specific data to simulate the hemodynamics and to enhance the potential application of computational fluid dynamics prediction to clinical surgical planning. 3D models of stenotic artery were created before and after stent implantation, and realistic boundary conditions were imposed at the inlet and outlet of the computational vessels. The geometric configuration of vascular segments greatly affects the resulting flow patterns. ANSYS/Fluent software was used to perform the tetrahedral mesh generation and the blood flow simulation. The results show that stenting increased the blood flow rate compared to that for the stenosis artery model and that the hemodynamic values returned to near normal levels in the carotid artery fitted with a stent.

Keywords: Computational fluid dynamics, carotid artery stenosis, virtual stenting, artificial neural network.

INTRODUCTION
Stroke is one of the main causes of death in developed countries. Knowledge of the hemodynamic behavior at the carotid bifurcation is very important for accessing the atherosclerotic lesion, for developing diagnosis tools of the disease, for elaborating procedures that simulate and modify blood flow and finally to contribute towards the improvement of vascular surgery.

Design techniques have been developed for reconstruction of the real physiology of the carotid bifurcation. With proper boundary conditions, the reconstructed models can be used to perform computational simulations of the local hemodynamics. Based on published ultrasound data, an optimal artificial neural network (ANN) model was developed searching data dimensional reduction. ANN estimated pulsatile conditions were used as boundary conditions along different points of the carotid artery for fluid dynamic simulations (Castro et al, 2015). Combining these data it was possible to exploit hemodynamic simulation results of the carotid artery before and after performing virtual stenting. In this work, the use of computational tools for the surgical treatment of atherosclerosis of the carotid arteries is proposed. Further analysis intends to enhance the potential application of computational fluid dynamics prediction to clinical surgical planning.

There are two surgical treatment alternatives to heal carotids. One option is endarterectomy where vessels are opened to remove the atheromatous plaque substance. The other is stenting, a stent is a wire metal mesh tube placed into an artery or blood vessel to hold the structure open. The stent is collapsed to a small diameter and put over a balloon catheter. The stent is inserted by a catheter through a small cut in the femoral artery, mostly under local anesthesia.
To plan operation, precise determination of the stenosis morphology is required. Stent deployment following balloon angioplasty is used routinely to treat artery disease. These interventions cause damage and thus promote in-stent thrombosis and restenosis. Stents modify endothelial repair processes, in part, by altering fluid shear stress, a mechanical force that influences endothelial cells migration and proliferation (Van der Heiden et al, 2013). Little is known about the combined effect of shear stress and strain; however, it is likely that gene expression is regulated by an interaction between these mechanical factors.

METHODS
A more detailed understanding of the biomechanical processes that control endothelial healing would provide a platform for the development of novel therapeutic approaches to minimize damage and promote vascular repair in stented arteries. Building models of stent and artery with specific material properties requires a high effort including generation of the stent model, the simultaneous deformation of vessel and stent. Using the FEMAP software, a specific 3D model of the carotid wall and pulsatile conditions, hemodynamics simulations were able to suggest wall shear stress (WSS) distributions capturing abnormal flow conditions (Sousa et al. 2016).

Before virtual stenting can be performed, ultrasound acquired data has to be pre-processed by segmenting the carotids. Three-dimensional (3D) models of the lumen and wall boundaries were reconstructed from B-mode longitudinal images completed by B-mode cross-sectional images registered at the end of diastolic phase to control physiologic variations of vessel diameter along cardiac cycle. Based on the hypoechochogenic characteristics of the lumen, B-mode images were segmented to automatically produce the lumen and bifurcation boundaries of the carotid artery. Using this software each input image was initially processed with the application of an anisotropic diffusion filter for speckle noise removal, and morphologic operators for selection of relevant ultrasound data. Segmented transverse contours were realigned and oriented in 3D space. The information obtained was then used to define initial artery wall contours of lumen and bifurcation. Fig. 1 (left) shows the specific 3D surface reconstruction for defining the reconstructed bifurcation shape and Fig. 1 (right) presents the volume tetrahedral mesh. After this geometrical construction, the initial mesh contour will be iteratively radially deformed by using external and internal forces simulating stent expansion maintaining the conformity of stent and artery wall.

The common carotid artery (CCA) bifurcation and the proximal external (ECA) and internal (ICA) carotid arteries are prone sites to atherosclerosis associated diseases. Inlet and outlet flow conditions were available from Doppler images of the select bifurcation. Pulsatile Womersley velocity profiles were derived from the registered velocity envelope. Flow discrepancies due to small branches or uncertainties in measurements were corrected using
the instantaneous blood flow velocity ratio (ICA/ECA) and maintaining the CCA flow. It is, however, possible that the distensible arteries produce instantaneous flow mismatches at the bifurcation. Calculated velocity field near peak systolic phase is shown in Fig. 2.

![Velocity waveform used for hemodynamic pulsatile simulation (left) and calculated velocities [cm/s] near peak systole (right).](image)

**RESULTS**

A noninvasive approach for simultaneously quantifying flow and WSS fields at CCA bifurcation is considered. The simulation includes an explicit model of the vessel wall. It is reconstructed from ultrasound data and deformed.

Fluid structure interaction is a complex two-way coupling system: the fluidic pressure exercised by blood flow causes structural deformation in the wall, while the wall deformation changes the hemodynamic characteristics of blood flow. Low stiffness of artery compared to that of fluid requires a strong coupling system between the artery and blood, causing numerical difficulties: managing careful densities of artery and blood to avoid numerical instabilities, nonlinear displacements in the artery solving the fluid on a moving domain and taking care of fake reflection phenomena from the structural boundary. Considering a fluid structure interaction analysis enables a reliable 3D blood-artery-plaque simulation that mimics a realistic deformable vessel.

In this study the blood is considered a Newtonian fluid with 1060 kg/m$^3$ for density and 0.0035Ns/m$^2$ for the dynamic viscosity. The arterial wall is considered to be isotropic and elastic with Young’s modulus 1.06 MPa, Poisson’s ratio 0.45 and density of blood vessel wall of 1120 kg/m$^3$.

Blood flow simulation was performed in an Intel Core I3 computer of 2.4GHz processor and 4GB of RAM. In addition, it was made for three cardiac cycles and results for flow velocities and WSS values correspond to the last cycle. Fig. 3 illustrates the relevance of numerical simulation models applied to virtual stenting. Blood flow behavior is shown to be sensitive to surgery and to have a strong influence on local quantities of interest that would potentially affect luminal obstruction. A detailed understanding of flow would aid in the evaluation of therapeutic options available to a given patient namely, serving as the input to generate 3D geometry models of pre- and post- interventional carotid artery.
CONCLUSIONS

In this paper, we present a fast and practical method for patient-specific virtual stenting of carotid stenosis ignoring the fluid surface interaction which requires low computational effort and few user interactions. Pre-interventional simulation of stent expansion is useful to analyze the conformity of stent and vessel wall and there are a few publications dealing with stent/wall interactions (Egger et al. 2008). Future work plans to analyze patient-specific stent surgeries including the simulation of an elastic artery wall.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the funding by FCT, Portugal, of the Research Unit of LAETA-INEGI, Faculdade de Engenharia da Universidade do Porto.

REFERENCES


