Hemodynamic Analysis of Virtual Stent Design for Atherosclerotic Carotid Artery

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Abstract

We propose a technique to reverse engineer a normal carotid bifurcation from an abnormal artery model based on B-Spline interpolation. This enables us to assess the blood flow pattern in a patient-specific artery for the stenosed and virtually stented conditions. This technique may be applied to understand the cardiovascular condition and to develop a stent to eliminate stenosis and flow resistance. Furthermore, we hypothesise that velocity, wall shear stress and pressure gradient are the key hemodynamics parameters for determining stent performance in terms of improved cardiovascular flow. We show that stenting are able to improve the diseased artery condition from the hemodynamics perspective.

1. Introduction

Stroke is one of the leading causes of mortility in developed countries, and is a major health concern. The cause of stroke is attributable to the complication of atherosclerotic disease that pertains to the carotid artery [1] and leading to Cardiovascular Disease (CVD). In 2006, CVD accounted for 34.3% of all deaths in the United States [2]. Stenting has now been well-established as the most feasible treatment for atherosclerotic lesions. It becomes an alternative to traditional endarterectomy due to its less invasiveness and high successful rate. Although carotid stenting has shown great promise, it is still generally accepted that the optimal approach to carotid artery stenosis lies in further developments in stent design, which are reflected by good knowledge of stent-artery interactions during stent placement. It has been reported that the placement of stents alters the hemodynamics and this coupled with wall movement may lead to the dispersion of late multiple emboli despite the fact that its exact mechanisms are not known [3]. The complex structures that are introduced into the blood flow may enhance biochemical thrombosis cascade [4, 5], as well as directly affect the local hemodynamics. Thus, understanding of the stent-vessel interaction before and after carotid stenting is of paramount importance to ensure the successful deployment of stents into the diseased vascular regions and reduce procedure-related complications such as restenosis or occlusion.

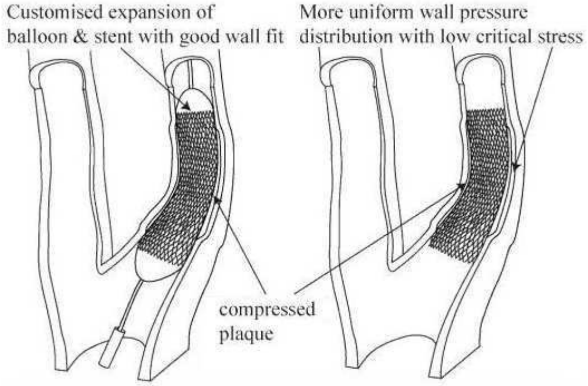


Figure 1. Restoration of stenosed artery by stenting.

For the surgical treatment of such diseased arteries, a stent can be deployed and expended uniformly to fit along the wall of the artery. In the case of asymmetric distribution of the plaque along the arterial axis, the stent was forced to bend against the artery wall and causing the sharp edge of the stent to cut through the artery wall (Figure 1). Over time, this may lead to platelets activation and thrombosis, which can result in stenosis of artery. Fragments of the formed thrombus may travel downstream of the carotid artery to block the blood flow in micro vessels, and thereby causing stroke.

This study has two objectives which are detailed as follows: 1) To verify the hypothesis for atherosclerotic disease progression, we present hemodynamics based on the reconstruction of normal and stenosed carotid bifurcation models. This is attributed to the understanding that without detailed comparison of WSS distributions at the location of the lesion, it is not feasible to correlate the role of WSS in atheroma deposition. 2) To model stents that accommodate the vessel based on reverse engineering of the stenosed artery, and determine the effect of hemodynamics for an atherosclerotic artery pre- and post- stent implantation to be used as a basis for a virtual stenting procedure platform.

2. Methods

2.1. Medical image reconstruction

The reconstruction of geometric models is based on the data obtained from Computed Tomography (CT) or Magnetic Resonance (MR) imaging of the neck including cerebral arteries [6]. Many studies have been performed in this area and some commercial software packages are available in the market as well. However, there are many problems in the geometries generated by these packages. The generation of models requires a series of post-processing approaches which is time-consuming before it can be directly imported into a CFD platform. Extensive work such as segmentation, surface reconstruction and smoothing as well as grid generation was performed to satisfy the simulation requirement.

The scans demonstrate the obliquity of the stenosed arteries and our next procedure is to prepare the virtual stents design based on the proposed B-Spline interpolation technique.

2.2. Patient-specific model

The modelling of a mechanical geometry in a Computer Aided Design (CAD) platform is based on the parameters of free-form or sculptured surfaces. Reverse engineering is applied to reconstruct the models of a healthy carotid bifurcation based on an abnormal one. In particular, B-Spline surface modelling is applied to extrapolate the data clouds obtained from the abnormal carotid bifurcation to predict the geometry of a normal vessel (Figure 2).

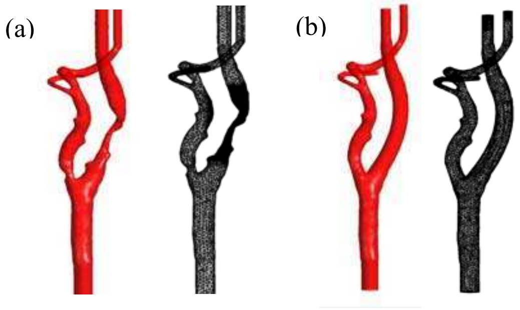


Figure 2. Generation of meshes of stenosed and normal carotid bifurcation models.

To achieve B-spline patches, the shortest distance algorithm, which has been used by Eric and Hoppe [7] in surface re-construction, is applied to find the control points in the surface generation process. This is performed by minimizing the distance function

$$E_{dist}(S) = \sum_{i=1}^{N} d^2(P_i, S), \tag{1}$$

where E_{dist} is the distance function, d is the distance, P_i is the point, N is the total number of data points, and S is the surface patch.

2.3. Design of virtual stent

After restoration of the ideal channel for the diseased artery, the curvature, dimensions and location of the stent can be predicted via superimposing the stenosed and normal arteries, and deleting the surface of overlap to leave only the unblocked segment as the stent of best fit into the stenosed region (Figure 3). Based on this procedure, the placement of a virtual stent at the diseased location can be simulated.

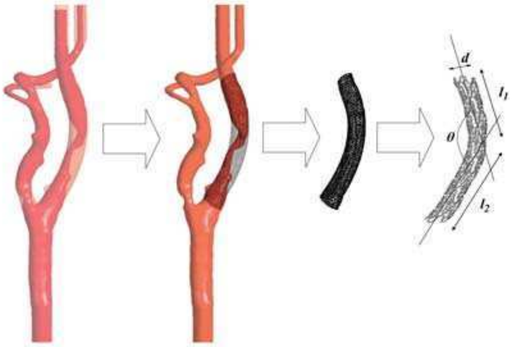


Figure 3. Reconstructed virtual stent based on reverse engineering in a diseased carotid artery.

In summary, the virtual stent design solution includes the following steps:

1. Construct initial triangle meshes of the stenosed artery;
2. Re-parameterise the triangle mesh over a quadrilateral domain;
3. Generate B-spline patches of the vessel in order to predict a normal arterial condition;
4. Superimpose the diseased and normal arteries and deleting the surface of overlap to obtain the lengths of the affected artery (l_1, l_2), which conforms to two parts of the unaffected arterial curvature. The angle (θ) formed by the two lengths is determined;
5. The cross-sectional shape areas at the upstream and downstream of the unaffected arterial region are extracted. The circumferences of these shapes ($C_{1,2}$) are used to determine the diameters (D_1, D_2) of the stent based on $C_{1,2} = \pi D_{1,2}$. Note that d is set to be the larger of the two diameters;
6. Computationally design the curved stent based on (l_1, l_2, d and θ).

To test the effectiveness of the proposed stenting solution, the next step is to perform computational fluid dynamics analysis of the flow in the atherosclerotic artery for its abnormal condition versus it’s stented state.

2.4. Details of numerical simulation

After the meshing procedure, the computational models were then imported into the widely adopted CFD package – ANSYS CFX 12. In general, flow governing equations based on mass, momentum and energy conservation are discretized using finite volume method and solved numerically via iterative procedures. In the present study, the transient, three dimensional, isothermal, turbulent flow nature was assumed. External force has been ignored and the arterial wall is assumed to be non-elastic and impermeable since the simulation of Newtonian fluid flows in such rigid stenosed carotid bifurcation has been applied previously [3].

The blood flow at the orifice of the common carotid artery (CCA) is assumed to be driven by the pulsatile blood velocity waveform [8]. At both inlet and outlet of the branches, zero normal velocity gradients were assumed. For boundary conditions, the velocity pulsatile waveform is imposed at the upstream end of the CCA (Figure 4). The time period of one cardiac cycle was 1 s. In addition, the blood was considered as Newtonian fluid with a constant density of 1060 kg/m^3 and constant dynamic viscosity of 0.0035 Pa s. A fully implicit scheme with a fixed time computational time step (0.01 s) was set for the transient simulations. For each time step, satisfactory convergence criteria with 1x10^{-4} root mean square residual for all variables should be achieved.

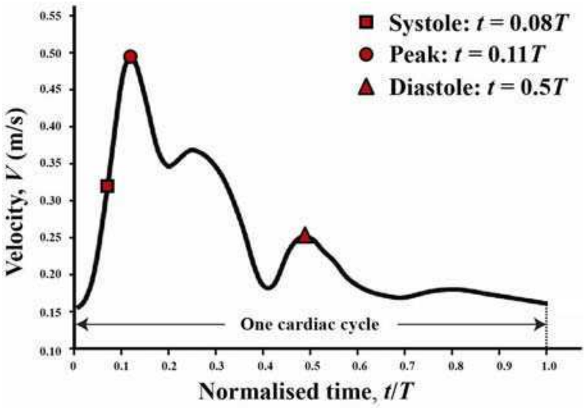


Figure 4. Velocity waveform for the common carotid artery (CCA) over one cardiac cycle.

3. Results

3.1 Analysis of velocity

The time-dependent streamline of the blood flow through the healthy and stenosed carotid bifurcations are plotted only for the peak time point of cardiac cycle. Based on the stenosed model, high velocity blood flow occurred at the stenosis due to the occlusion caused by the plaque. From Figure 5, it can be also noticed that reversed and re-circulated flow were found immediately downstream of the stenosis on the inter walls of the internal carotid artery (ICA) and external carotid artery (ECA). At the peak of the cardiac cycle, the maximum blood flow velocity was 1.70 m/s. It is shown that such a high velocity flow induced high WSS on the circumference of the blood vessel (Figure 6).

3.2. Analysis of wall shear stress

The stenosed artery experiences irregular distribution of WSS. For example, higher WSS at the stenosed region of the ICA is due to the higher velocity. The spatial distribution of the time-dependent WSS at the peak of the normal and stenosed models are given in Figure 5. In general, high WSS forces were highly concentrated at the stenosis and its vicinity region. Resulted from the high velocity caused by the vessel occlusion, the maximum WSS occurred at the narrowest wall. Such high shear stress value may lead to platelets activation and potentially generating thrombus formation.

On the contrary, after virtual stenting, flow pattern becomes regular and laminar since there is no stenotic section in the artery which interferes with blood flow. The maximum velocity in the patented vessel is 0.62 m/s. Low WSS (of magnitudes of less than 8 Pa) is noticed in the normal carotid artery with simulated stent in place, and this contrasts apparently to the high WSS with its maximum value at approximately 155 Pa that is observed in the stenotic carotid artery (Figure 6).

3.3. Analysis of pressure gradient

The pressure gradient correlates to the resistance of flow in the channel of interest. The factors determining this resistance are functionally the dimension of the channel vessel, and in the case of stenting, it will be the effective orifice area of the vessel and excludes the stent strut areas. We analyse the pressure gradient instead of pressure because of the effect of change on the flow resistance caused by the stenosis, and its reduction after stenting. The maximum pressure gradient in the region of interest for the stenosed artery is 3.69×10^6 kg m^{-2} s^{-2}, and that of the stented artery drops to 346 kg m^{-2} s^{-2} (Figure 6).

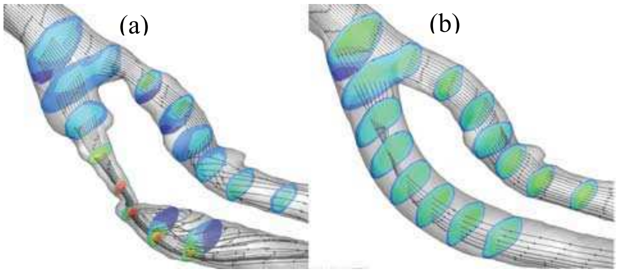
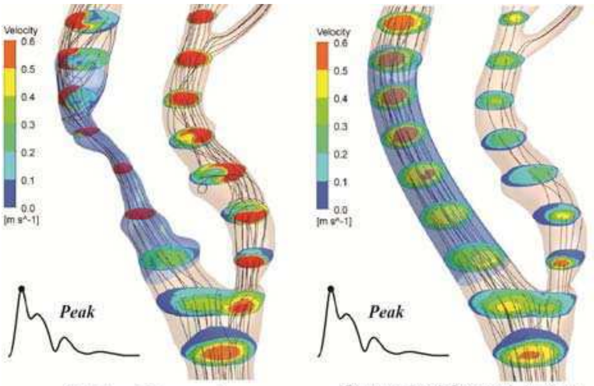
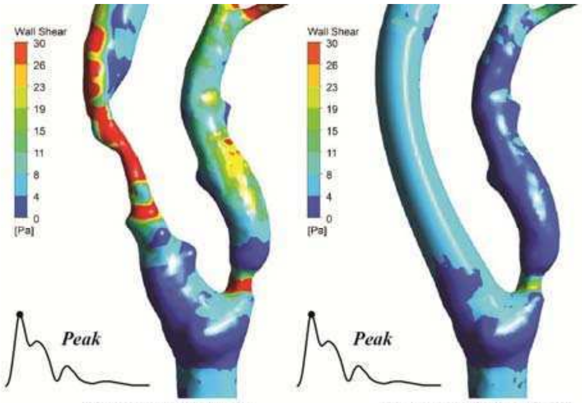


Figure 5. Presence of vortices in the region downstream of stenosis (a) versus laminar flow after stenting (b).



Original Stenosed Artery Customised Stented Artery



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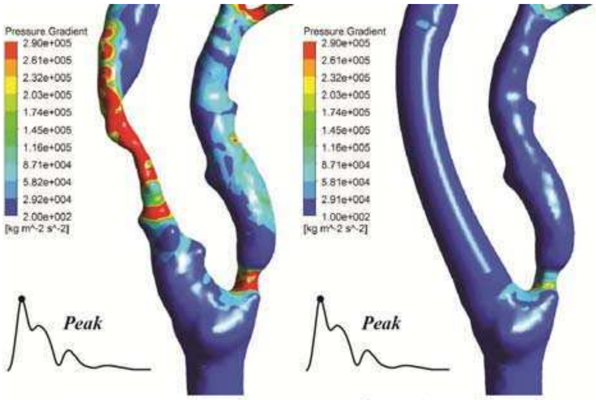

Original Stenosed Artery Customised Stented Artery

Figure 6. Comparison of the blood flow field in the stenosed and the virtually stented carotid bifurcation using streamline, velocity, WSS and pressure gradient.

5. Conclusion

In our paper, we have proposed virtual stenting and hypothesise that stents can improve treatment from the hemodynamics perspective. The wall shear stress (WSS) distribution is investigated for stenosed artery prior to stenting and is demonstrated to be highly non-uniform. For a stented artery, due to the lower curvature and asymmetry of the carotid sinus and flow divider (at bifurcation point), distribution of the WSS is more uniform. High WSS values was located at the bifurcation point and extended to inner walls of the ICA and ECA. It is resulted from the blood flow have tendency to flow along the inner walls conforming the curvature of the implanted stent in the carotid bifurcation. As a result, low WSS values were constantly formed at the roots and along the outer walls of sinus bulbs. Notably, locations of low WSS values are in accordance with the plaque locations of the stenosed model. Therefore, the simulation results presented in this study may affirm that the stenting has improved the hemodynamics of the artery.

Acknowledgements

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