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Analysis of the effects of different pulsatile inlet profiles on the hemodynamical properties of blood flow in patient specific carotid artery with stenosis

Senol Piskin*, M. Serdar Celebi

Istanbul Technical University, Informatics Institute, Computational Science and Engineering, Ayazaga Kampusu, Maslak 34469, Istanbul, Turkey

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ABSTRACT

In this study the biomechanical characteristics of a realistic carotid artery [3] are studied numerically using different inlet velocity profiles. Several experimental data measured [32] at the common carotid artery are used as inlet boundary conditions. Computation domain is generated using computed tomography (CT) data of a real patient. Three dimensional (3D) transient NS equations are solved, in this actual domain, using the proposed boundary conditions. Effects of different input conditions on the results of simulation are discussed. Main parameters such as velocity profiles, wall shear stress (WSS) and pressure distributions are investigated at the critical parts of the carotid artery such as bifurcation and sinusoidal enlargement regions. Results show that the input boundary conditions and slope/curvature discontinuities in the realistic geometry have strong relationship with the velocity, pressure and WSS distributions as expected. The most important conclusion obtained from our model is the existence of negative relation between velocity at several inner points of the internal carotid artery and velocity at the inlet of the common carotid artery.

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1. Introduction

Cardiovascular mechanics is of great importance, since it is known that very serious diseases are related to heart and/or artery malfunctions. Majority of people in many countries die because of diseases connected with cardiovascular system [21]. Atherosclerosis is one of the most common of these diseases. It is defined as hardening of the arteries [1] and thickening of the intimal layer of the artery is known as a beginning step of atherosclerosis [35]. Atherosclerosis causes stenosis which is the narrowing of the arteries. Many other diseases such as aneurysm, stroke or heart attack develop as a result of stenosis and atherosclerosis. Formation of atherosclerosis depends significantly on the blood. So, it is essential to know how blood behaves in arteries. There are a large number of researches leading to understand the effect of blood flow mechanics in human arteries. The presence of atherosclerotic plaques is closely related to the vessel geometry as shown by Nerem et al. [30], Friedman et al. [14] and Caro [8,7]. Localizations are especially clustered at bifurcation regions as told by Zarins et al. [46] and Motomiya et al. [28] and curvatures and multiple bends as told by Asakura and Karino [4], Sabbah et al. [37] and Wada and Karino [44,12]. The relation between plaque thickness and presence of low or oscillating shear stress is shown by Zarins et al. [46], Ku et al. [22], Sawchuk et al. [38], Davies et al. [10], Thubrikar and Robicsek [42], Deplano and Siouffi [11], Malek et al. [25], Botnar et al. [7] and Zhang et al. [47]. The disruption of blood flow may cause low velocity and low WSS. Therefore, the regions with flow separation, recirculation, reattachment and secondary flow zones are susceptible to atherosclerosis [29,24,15,31].

This is still an active research area and there are recent studies reported in the literature focusing on blood flow simulation in large arteries. Most of them use either artificial models [35,12,32,33] or real geometries of carotid artery [47,45,24,5,34] or artificially modelled [19,23] or real geometries of aorta [6,2,3,13,27,26]. It is specifically important to investigate the mechanical properties such as velocity, pressure and wall shear stress (WSS) of blood flow in real artery geometries with diseases. Changes of these values with respect to time may give us valuable information.

In this paper, the blood flow in a real carotid artery geometry is simulated using experimental inflow data at main carotid

* Corresponding author. Tel.: +90 533 356 3595, +90 212 285 71 94x123.
E-mail addresses: senol.piskin@itu.edu.tr, senol@be.itu.edu.tr, senolpiskin@gmail.com (S. Piskin), mscelebi@itu.edu.tr (M. Serdar Celebi).

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artery. Geometry is obtained by using the scanned data (CT) of a real patient with atherosclerosis (and also stenosis) disease. Eight critical regions are selected for monitoring the time history of velocity, pressure and WSS values. These regions are critical because of stenosis disease, bending or bifurcation at the geometry. Five different inflow data are used as inlet to analyze the magnitude and pulsative effect of ECCOMAS conference [48].

The paper is organized as follows; Section 2 describes the modeling steps of the simulation including the three dimensional (3D) geometry reconstruction, inlet data preparation and governing equations of the model. Section 3 presents the results and discusses the outcomes. Finally, Section 4 gives a brief conclusion.

2. Modelling

2.1. Geometric reconstruction

Scanned patient data are bunch of sliced raw images of the body. It consists of skin, bones, soft tissues and liquids. The target region, which is the artery in this case, should be extracted from this huge data. Artery regions are relieved by first restraining the Hounsfield unit between the values of artery. Hounsfield unit is an arbitrary scale for describing the attenuation of radiation or radiodensity of materials. Radiodensity is the intensity of the transmitted radiation during CT scan. Hounsfield unit scale is 0 for water, while having a range of 100–300 for vascular contrast, and 20–40 for blood [39]. This scale is used in our study, used to identify the blood and artery tissues. Then, the artery cross-section (i.e. region) at each sliced image is selected (Fig. 1). So, the edges (contours) of each region are detected and fitted with b-spline curves. The sequence of contours are lofted to obtain the 3D surface of the carotid artery (Fig. 2). As a result of this image reconstruction process, the boundary and surface of the artery are obtained in STL format. At the final shape, the surface meshes are expanded with volume meshes using tetrahedral elements. Further improvements on the final mesh are done by some techniques to generate a volume mesh with a better quality of skewness. After these enhancements, the artery geometry contains 25 K surface and 125 K volume elements [3] and ready for simulation.

Volume mesh was generated using ANSYS TGrid 3D mesh generator software which uses Delaunay tetrahedral initialization scheme with advancing front- or skewness based tetrahedral refinement algorithm.

It can be observed from Fig. 2 that at the first level, common carotid artery bifurcates into internal and external carotid arteries. At the second level, external carotid artery bifurcates into two narrower arteries. Internal carotid artery has the sinus region and stenosis disease as shown in zoomed region 1 (Fig. 4).

Critical regions of the geometry are selected for analysis and marked with points. Points 1 and 2 indicate two bifurcation regions as shown in Fig. 3, and represent the first and second level bifurcation regions respectively. Points 3 and 5 are selected at sinus region of internal carotid artery since this region is known to be vulnerable to atherosclerosis disease because of low wall shear stress (Fig. 4). Point 3 is selected on the non-divider wall while point 5 is on the divider wall.

The geometry data belong to a patient with disease as can be understood from stenosis which is indicated by points 4 and 6 (Fig. 4). Points 7 and 8 show the bending geometric regions where slopes and curvatures of artery wall are high (Fig. 5). Point 7 also refers to the region with highest WSS values.

2.2. Governing equations and boundary conditions

Three dimensional continuity and Navier–Stokes (NS) equations are used as the governing equations of blood flow (2). Energy equation is not included in the governing equations since the effect of temperature change is assumed relatively small. Blood is modelled as a Newtonian fluid and the density is taken as constant throughout the domain and time. Viscosity (μ) and density (ρ) are taken as 6×10^{-3} kg/m s and 1060 kg/m^3,

Fig. 2. Actual carotid artery geometry extracted from CT data.

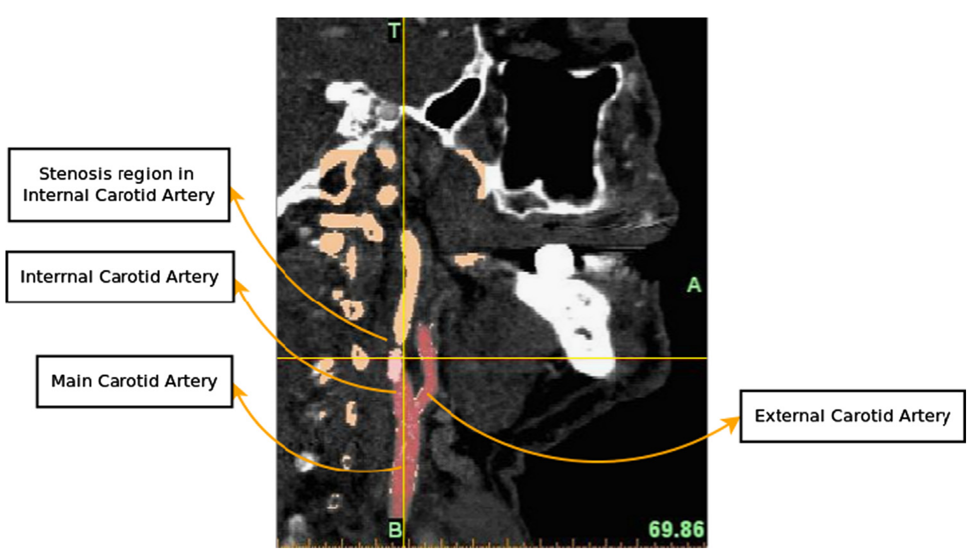

Fig. 1. A sample slice of scanned CT data with relieved carotid artery (sagittal plane).

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