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Finite Element Modeling and simulation of arteries in the human arm to study the aortic pulse wave propagation

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Abstract

Finite modelling and simulation of the arterial network in the human arm has been presented in this paper with an objective to study the aortic pulse wave propagation. In the biomedical domain, it becomes extremely essential to understand the propagation of the aortic pulse along the arterial network, to get a better insight about the functioning of the cardiovascular system. This would assist in haemodynamic measurements, diagnosing disorders and visualizing the effect of medical treatment. The fluid structure interaction has been simulated using COMSOL Multiphysics 4.4 with an objective to obtain the pressure, velocity profile of the aortic pulse and wall shear stresses at the ascending aorta, carotid, brachial, interosseous, ulnar and radial artery. The arterial walls are considered flexible and pulsatile pressure pulse has been used as boundary condition. The validity of the finite element simulation has been supported by comparing the numerical results to the standard published results.

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Keywords: Finite Element Method; blood flow rate; velocity; pressure; human arm; wave propagation

1. Introduction

The bio-medical domain is a very challenging domain to understand since it deals with the factors that cause various ailments in the human body. The mechanics of blood flow have a considerable impact on health of individuals. The condition of the arterial wall may cause disturbances in the blood flow leading to clinical complications. Even though blood flow is usually laminar, periodically unsteady nature of flow may lead to

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turbulence in the narrower arteries at higher velocities. The concept of fluid dynamics can be readily applied in understanding of environment, influence of wall modifications, local pressures and velocities on flow patterns thereby providing better guidelines in diagnosis and finding faster and improved remedial measures. Computational analysis is very rare and has picked up pace only in the last decade. Besides, the pulsatile nature of blood flow which represents an actual cardiac waveform has been scarcely studied. In most cases, the artery is modelled as a simple cylindrical tube resulting in approximate solutions. A mathematical model for studying the interaction of blood flow with the arterial walls surrounded by cerebral spinal fluid was developed by Venuti [1]. Sankar and Lee [2] studied the effects of pulsatility, stenosis and non-Newtonian behaviour of blood, treating the blood as Herschel–Bulkley fluid. Siddiqui et al.[3], treated the blood as Casson's fluid and investigated the effects of non-Newtonian nature of pulsatile blood flow through a stenosed artery. In 2011, Razavi et al. [4], performed the simulation using Newtonian as well as non-Newtonian viscosity models. This work has been carried out for stenosed carotid artery with a pulsatile nature of blood flow. Nadeem et al. [5] in 2011, analyzed blood flow through a tapered artery with a stenosis. In 2013, Tian et al. [6] used a simplified model to simulate a pulsatile non-Newtonian blood flow past a stenosed 2D artery caused by atherosclerotic plaques of different severity. In 2012, Mortazavinia et al. [7] simulated the pulsatile blood flow to study renal artery stenosis and explored the its effect on the blood flow and vessel walls. The attempt was made to develop a realistic model of arteries from CT- scan images. Rabby et al. [8], in 2013 used finite volume method to perform numerical analysis of a pulsatile flow through a two-dimensional (2D) axisymmetric pipe with an idealized stenosis. Fojas and De Leon [9], in their paper presented in 2013, have demonstrated the use of computational software for hemodynamic analysis of two-dimensional model of the carotid artery and its bifurcation.

This paper aims at modelling the arterial network in the entire human arm and investigates variations in the aortic pulse wave parameters as it propagates from the ascending aorta towards the radial artery. In the biomedical domain, it becomes extremely essential to monitor these changes as they are indicators of proper functioning of the cardiovascular system. Disturbed blood flow and wall shear stress may lead to Atherosclerosis (Vascular Disorders). The numerical simulation of blood flow within the arteries not only helps in monitoring the significant parameters but also helps in obtaining the variations in these parameters at the aorta and the other nodes of the arterial network. Certain hemodynamic parameters such as cardiac output, stroke volume are measured either using invasive techniques or with techniques which are costlier and require a large setup. The results of this simulations can also be effectively utilized in devising mathematical relations between the aortic and radial parameters, thereby making bedside measurements of these parameters simpler.

2. Mathematical Model

The essential parameters which characterize the blood flow are velocity u and pressure p. These field parameters help in computing the stresses developed in the arterial wall subjected to the blood movement. This basically aids in monitoring the condition of the arterial wall. The blood flow being pulsatile in nature causes radial deformations in the arterial walls. Thus, in addition to the flow parameters, structural deformations also need to be considered, thereby leading to a fluid structure interaction problem. Arterial blood flow is a three dimensional flow, where the blood is considered to be incompressible Newtonian fluid. The Navier –Stokes equations thus can be applied [10]. Eq. 1 expresses the conservation of mass:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{1}$$

where u, v and w denote the velocities in x, y and z directions respectively. Eq. 2 expresses the conservation of momentum in x, y and z directions.