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A FSI Simulation of Thromboembolism in Carotid Artery Bifurcation: Roles of Bifurcation Dividing Angle on Arterial Hemodynamics

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ABSTRACT

Although embolism is important as a major cause of brain infarction, little information is available about the hemodynamic factors governing the path large emboli tend to follow. In this research, we simulated embolus movement in three carotid artery bifurcations, each of them having different dividing angles. Y-shaped geometries were investigated. The governing equations for blood flow are the Navier-Stokes formulations. In this paper, the phenomenon was modeled under laminar and Newtonian flow conditions. The measured stress-strain curve obtained from Ultrasound elasticity imaging of thrombus was set to the Sussman-Bathe material model for embolus material properties. Shear stresses in the inner wall of the internal carotid artery (ICA) were measured. High magnitude of wall shear stress (WSS) in the areas in which embolus and artery are in contact with each other was observed. Stress in the embolus was also calculated and areas prone to rapture were identified.

KEYWORDS

Thromboembolism, Carotid Artery Bifurcation, Finite Element Method, Fluid-Structure Interaction

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1- INTRODUCTION

Arterial embolism is responsible for the death of many people around the world [1]. It is generally known that arterial embolism is a chief mechanism of stroke. A method which detects the trajectory of emboli in carotid arteries would be of great value in understanding stroke mechanisms.

It is not easy to experimentally study a blood clot's movement in arterial geometries. Movement of embolus through a stenosed artery and the effect of hemodynamic factors on embolus have been studied [2]. Also an in-vivo experimental model was studied to test the effect of hemodynamic parameters in the distribution of embolic particles [3].

The aim of this research is to present a model for an embolus passing through human carotid artery bifurcation using computational fluid dynamics (CFD) techniques. Two major geometries are usually considered for carotid artery bifurcations: Y-shaped geometries and tuning-fork shaped geometries. In the presented research, the Y-shaped geometries were investigated (Fig. 1). Three carotid artery bifurcation geometries which have different dividing angles were considered.

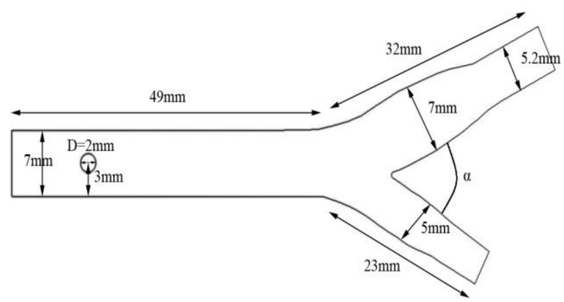

Figure 1: Outline of studied carotid artery bifurcation geometries. Entry length was considered long enough for flow to become fully developed. Three different dividing angles are α = 32, 52, 72 degrees

2- METHODS

The governing equations for blood flow are continuity and Navier-Stokes equations. Flow was assumed to be laminar, viscous, incompressible, and Newtonian. The blood clot is modeled as a homogenous, isotropic solid with an initial circular geometry.

The kinematic coupling conditions, which represent the no-slip conditions at the interface, are:

$$d_i^f = d_i^s \tag{1a}$$

$$\frac{\partial d_i^f}{\partial t} = \frac{\partial d_i^s}{\partial t} \tag{1b}$$

The kinetic coupling condition, which represents the equilibrium of forces, is:

$$n_j \tau_{ij}^f = n_j \tau_{ij}^s \tag{2}$$

n is the unit vector normal to the interface. The measured stress-strain curve obtained from Ultrasound elasticity imaging of thrombus was set to the Sussman-Bathe material model [4] for solids with a large strain formulation. The coupled fluid and structure model was solved by the finite element package ADINA (ver 8.5.1, ADINA R&D, Inc., Cambridge, MA). Fluid and solid domains were both discretized using 2-D elements. To analyze large structure interfacial movement, an arbitrary Lagrangian-Eulerian (ALE) formulation was used.

3- RESULTS AND DISCUSSION

A. Stress distribution in embolus and artery divider wall

Stress analysis showed that there is a high increase of stress magnitude in the clot during contact with the internal carotid artery divider wall. Figure 2 shows the areas which are enduring high magnitudes of stress and are thus more prone to rapture. Positions (a) and (b) display positions in which the embolus is moving toward the divider wall but has not reached it yet. Positions (c) and (d) display the contact with embolus and internal carotid artery inner wall. High magnitudes of strain and stress occur at this point. After the separation, the embolus continues its path along the internal carotid artery. Results show that an increase in the bifurcation angle leads to an increase in maximum shear stress in the embolus. This occurs due to a larger bifurcation angle causing larger contact time between the embolus and artery dividing wall and therefore resulting in larger stress magnitudes.

Additionally, when in contact with embolus, high magnitude of stress occurs in the artery divider wall which can lead to deterioration of the endothelial surface consisting of cell swelling and deformation.

B. Fluid flow and recirculation zones

Hemodynamics of blood when the embolus reaches the apex of bifurcation was investigated and recirculation areas were observed (fig. 3). The flow recirculation region develops when embolus enters the internal carotid artery (ICA). A sudden drop in wall shear stress magnitude is a result of this flow. The recirculation region occupied a smaller area during the few moments afterwards. This is of clinical importance because cell residence time and plaque growth is related to the recirculation region.

4- CONCLUSIONS

In this paper, a better understanding for complicated movement of a blood clot released in an arterial bifurcation using fluid-structure interaction (FSI) techniques is provided. For future works, three dimensional patient-specific models can be used to simulate more realistic situations.

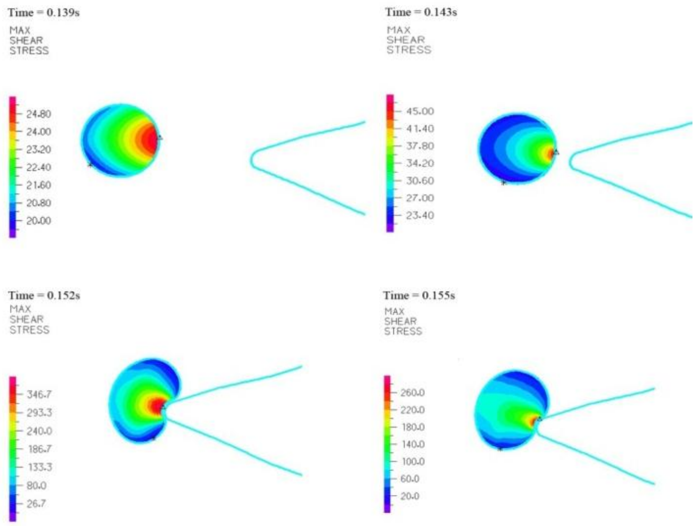

Figure 2. Stress distribution in embolus at six time step. The curved line indicates the divider wall. High values of shear stress are present when embolus is in contact with the divider wall

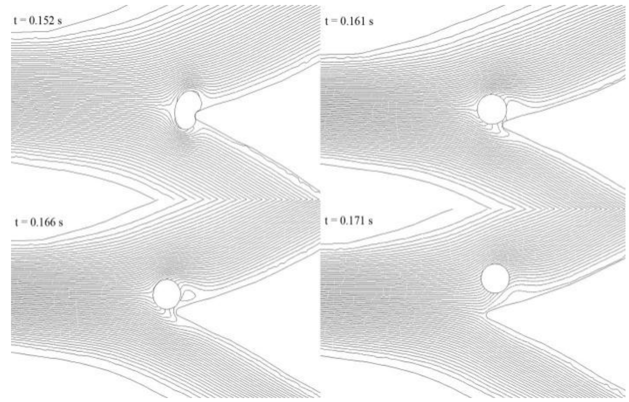

Figure 3. Streamlines show that recirculation occurs when embolus is in its route to enter internal carotid artery (t=0.166s).

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