Analysis of Volumetric Residence Time of Blood Elements in Stenosed Coronary Artery

M. C. Kim* · C. S. Lee** · C. J. Kim*

1. INTRODUCTION

Blood flow in arteries has been understood to be closely related to atherosclerosis. Presence of recirculation zones, low and high wall shear stress(WSS) distributions, and oscillatory shear index(OSI) have been suggested to be major factors for causing development and progress of atherosclerosis.

Our study was motivated to understand how the residence time of blood particles in arteries influences atherosclerosis. A rigid stenosed coronary artery with 75% area reduction was employed to numerically simulate motion of particles (platelets) and delineate average residence time of the same in the artery. The pre-solved computational fluid dynamics (CFD) data was used to compute the so called volumetric residence time (VRT). [1] Our method was different from previous researches [2] in that viscous drag was considered in the differential equations describing the motion of particles. We presented a visualized VRT contour plot in the stenosed artery and particle motion tracks as well. Our results indicated lower values of VRT present in the recirculation zone in the post-stenotic area.

2. METHOD

2.1 Unsteady Particle Paths Modeling

Flow field of the axisymmetric stenosis model shown in Fig. 1 was obtained in the previous research and utilized in the current simulation.[3] Platelets modeled as spheres was seeded in section S 0.06m proximal to the stenosis throat. The particles were seeded uniformly along to the radial direction in the section S. Initial

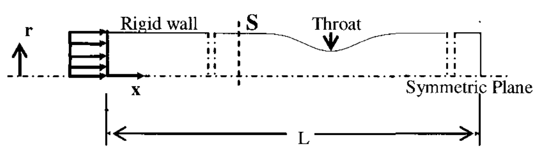

Fig. 1 Model for a straight stenotic blood vessel (axisymmetric) with area reduction of 75%.

* Department of Mechanical and Aerospace Engineering, Seoul National University
** Department of Mechanical and Control System Engineering, Handong University

position and velocity of the particles was imposed according to the Womersley solution.

In unsteady flows, local fluid velocity $\overrightarrow{u_f}$ is a function of space and time. The path of a particle at position $\overrightarrow{x_p}$ could be computed by solving particle motion equations (1). The equation considered particle inertia and drag force term. The drag force results from velocity difference between the particle and neighboring fluid.

$$\begin{cases} m_p \dfrac{d\overrightarrow{u_p}}{dt} = -f\left(\overrightarrow{u_p} - \overrightarrow{u_f}(\overrightarrow{x_p}, t)\right) \\ \dfrac{d\overrightarrow{x_p}}{dt} = u_p \end{cases} \tag{1}$$

In equation (1), subscript p means particle, and $f(=3\pi\mu d_p)$ is the Stokes friction coefficient. To solve the equations of the particle motion, Rosenbrock method, known to be reliable and offer simpler algorithm than the Runge-Kutta method for stringent parameters was implemented. [4] Fig. 2 shows the trajectory of a platelet across rectangular cells. Major task was to obtain carrier properties in the particle locations at time t and t+δt. Local fluid velocity in the particle location was obtained by interpolating the cell velocities obtained in the CFD study.

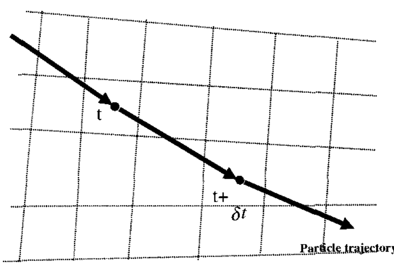

Fig. 2 Particle locations at times t and t+δt in 2D mesh

3. RESULTS

Fig. 3(a) ~ (h) shows history of the particle pathlines at the corresponding times marked ( ) in the flow waveforms shown in Fig. 4. At the peak of the cardiac systole (t=0.1s), recirculation are observed in the post-stenotic area. At the accelerating and decelerating phases of diastole, flow separation and reattachment are observed following particle movement in the downstream region.

Fig. 5 shows contours of VRT in 75% area-reduced stenosed coronary artery. VRT was calculated at each cell from 75 time steps during the pulse. The calculated VRT was normalized with the total number of seeded particles and volume of the corresponding cell. Fig. 5 clearly indicated low values of VRT in the post-stenotic regions obviously.

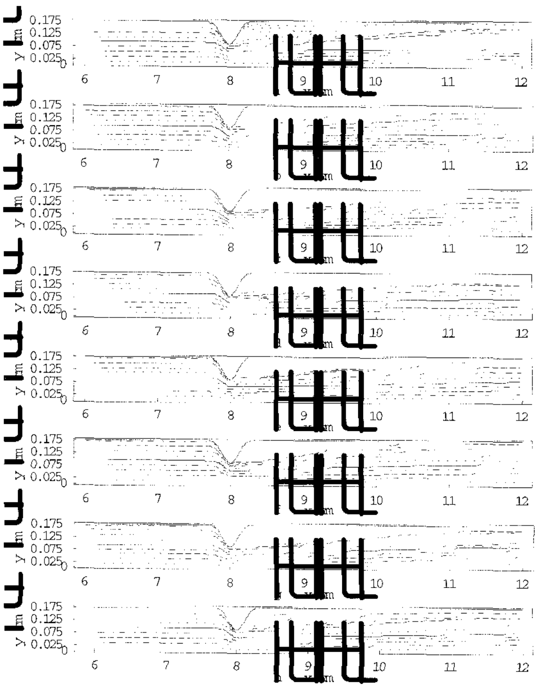

Fig. 3 Variation of particles' pathline in the stenosed coronary artery during one pulse period

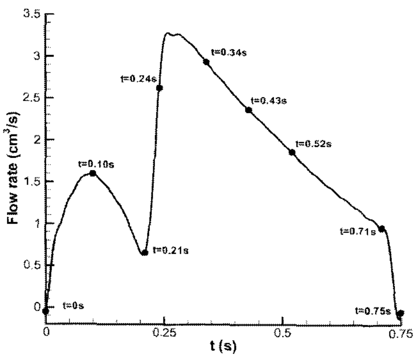

Fig. 4 Physiological flow waveform in the coronary artery

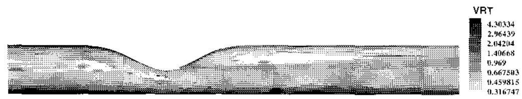

Fig. 5 Distribution of Volumetric Residence Time contours in 75% area-reduced stenosed coronary

4. CONCLUSION

Platelet particles concentrated on the core of the blood vessel. Low VRT values were present in the post-stenotic region. Length of contours of low VRT in the post-stenotic region was similar to the length of recirculation zone.

In case of red blood cell, it would cause deficiencies in supplies of nutrition and oxygen in the wall of coronary artery, which may accelerate atherosclerosis. Therefore, VRT can be an index relating to atherosclerosis.

Acknowledgment

This study was performed by the supports of Korean Ministry of health and welfare, 02-PJ3-PG3-31403-0004.

REFERENCES

(1) Mads J. Kunov, et. al., 1996, "Particle Volumetric Residence Time Calculations in Arterial Geometries," ASME Journal of Biomechanical Engineering, pp. 158~164.
(2) Mauro Tambasco, et. al., 2002, "On Assessing the Quality of Particle Tracking Through Computational Fluid Dynamic Models", ASME Journal of Biomechanical Engineering, pp. 166~175.
(3) Min-Cheol Kim, et. al., 2002, "Comparison of Wall Shear Stress Distribution between Stenosed Coronary, Abdominal, Femoral Arteries," The Fifth JSME-KSME Fluids Conference, submitted.
(4) William H. Press, et. al., "Numerical Recipes in C", Cambridge University Press.