A225 オリフィス管内流れにおける血栓形成のCFDによる予測

Prediction of thrombus formation on pipe orifice flow by CFD analysis

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1. Introduction
Recently artificial organs, especially rotary blood pumps, have been developed in the worldwide, but in this development, hemolysis (red blood cell damage by shear stress) and thrombus occur in the pumps. To suppress the hemolysis and avoid the thrombus is very important and serious problem in developing the rotary blood pumps[1]. In case of developing the artificial heart valve and stent, there are also same problems.

As for thrombus formation, it is very important to predict it for designing the medical fluids with blood flows. Compared with hemolysis, the mechanism of thrombus formation is much complicated because it includes biochemical factors. In spite of this complicity, it is preferable for mechanical designer to design simply using the some thresholds of physical factors. The main physical factors of thrombus formation are shear stress (shear rate), wall properties for blood’s adhesion and transport process of aggregation factor in the flow. There are many fundamental investigations related to the thrombus formation by microscopic and chemical binding approach, but there are still now no apparent improvements for actual devices based on the fundamental investigations. In this paper, the models to predict the thrombus formation using simple estimation in the orifice flow are proposed.

In this study, several types of orifice-pipe flows by using two turbulence models are computed. Using CFD with partially patched modified k-c model (Lauder-Kato partially patched model: LK-Zonal) [2], the flow fields in the orifice flow are computed. As these predicted flows agree well with experimental data, the prediction methods of thrombus formation using transport equation of concentration for activated platelet and threshold of shear stress and wall effect are investigated.

2. Computational Models and Fundamental Equations
In this investigation, objective configurations for predicting thrombus formation are the several types of orifice-pipe flow shown in Fig.1 and other configurations. Using the flow data in the CFD computation in case of Re=10000 (Turbulent flow), the concentration of platelet is transported for following scalar transport equation:

\[
\frac{\partial c}{\partial t} + (\mathbf{u} \cdot \nabla) c + \frac{1}{r} \frac{\partial}{\partial r} (r \mathbf{v} c) = \lambda \left( \frac{\partial^2 c}{\partial x^2} + \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial c}{\partial r} \right) \right)
\]

\(c\): Concentration
\(\mathbf{u}\): Velocity of x-axis
\(\mathbf{v}\): Velocity of r-axis
\(\lambda\): Diffusion coefficient of concentration

where c is concentration of platelet, \(\lambda\) is coefficient factor of protein or platelet (\(\lambda = 1.0 \times 10^5 \sim 1.0 \times 10^7\)).

After putting the initial distribution of platelet before the contraction part, the platelet is transported using eq.(1). As for the boundary conditions for transport equation of concentration, they are axisymmetric condition for center line and for gradient free for the normal direction of the wall. And the given velocity profile for inlet, they are two types of pulsatile patterns as follows [3]:

\[
\frac{U}{U_{in}} = 1 + \alpha \sin 2\pi ft
\] (2)

\[
\frac{U}{U_{in}} = \left( (0.251 + 0.29(\cos \Phi + 0.97 \cos 2\Phi) + 0.47 \cos 3\Phi + 0.14 \cos 4\Phi) \times \alpha \right) \times (1/0.251)
\] (3)

\(\Phi = 2\pi ft - \sqrt{2\pi f}

Fig.1 Configurations of orifice and thrombus circuits to observe thrombus

where $U_\infty$ is mean inlet velocity, $\alpha$ means amplitude of waves and $f=1$(Hz). The patterns of the waves are (1)sine wave and (2)vasculature wave.

3. Results and Discussions

Figure 2 shows effect of and $\alpha$ on the concentration contour in case of configuration AB and vasculature wave at time 6.0. From Fig.2, it is found that the high concentration region is located in front of the contraction and near the re-attachment point of the flow even if $\alpha$ changes from 0 to 0.7. As for $\alpha$, the larger $\alpha$ becomes, the more widely the concentration profile pattern changed.

Figure 3 also shows the concentration contour in case of all configurations, vasculature wave and $\alpha=0.7$ at time 6.0. From Fig.3, it is found that the high concentration region is also located in front of the contraction and near the re-attachment point as same as the configuration AB.

Considering the mechanism of thrombus formation, it is important to include the factors like shear rate and adhesion force (effective length to adhere the wall such as potential core). In this investigation, the supposition is that the thrombus occurs when the shear stress is exposed under the threshold level and the length from the wall is under the threshold length. In other words, the new estimated concentration is defined as follows:

$$c_{est}(x,r) = c(x,r) \cdot F(S(x,r),l)$$

$$F(S,l) = \begin{cases} 1 & (S \leq S_{th} \text{ and } l \leq l_{th}) \\ 0 & (S > S_{th} \text{ or } l > l_{th}) \end{cases}$$

where $S$ and $l$ means shear rate and effective length respectively, and suffix th means threshold level. Using the result of concentration distribution and the above supposition, the concentration of platelet of every configuration, which is likely changing the thrombus, is obtained shown in Fig. 3. In this case, the threshold of shear rate is $S_{th}=100$ (1/s), which corresponds to 80% possibility of thrombus in general. As the effective length increases, the adhesion force becomes weaker in this figure. As the high possibility region of thrombus formation is considered to be the same area of high concentration region, the possibility is high at the front of the contraction part and after the re-attachment point from this figure.

In the conference presentation, integrated estimation quantity is also shown and discussed because final purpose of the prediction thrombus is for all flow regions in the device.

More detail optimization should be done with changing the parameter, and the threshold should be determined by the experiment of the visualization of thrombus formation in our group. But the trend of this result is similar to the actual thrombus formation in our previous experiments.

Conclusions

The methods to predict the thrombus formation using FDM was proposed, and the threshold of shear stress and the length from the wall for thrombus was determined or the function was determined comparing with previous experimental results. Further investigation of the activated model of platelet is required for precious prediction of thrombus formation by shear rate

References