A PARTICLE METHOD COMPUTER SIMULATION OF BLOOD FLOW

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Summary A particle method computer simulation of blood flow is proposed to directly evaluate mechanical interactions between red blood cells (RBCs) and plasma. A moving particle semi-implicit method was used for flow analysis of blood plasma. An elastic membrane model was used for RBC deformation. Two-dimensional simulation of blood flow revealed that an RBC moved into downstream direction due to pressure drop of plasma flow and deformed itself in a parachute shape, corresponding to experimental observations.

INTRODUCTION

The blood flow at microscopic level plays an important role in pathological events in the vascular system such as thrombosis and hemolysis. Recent studies show that the particle method is useful in evaluating the mechanical behavior of blood cells under blood flow [1]. Since this method needs only computing nodes and is free from meshes, it is advantageous in directly tracking the blood cell motion by a particle in the Lagrangian coordinates, and in tracking the interface between solid blood cell and liquid blood flow. In this study, a computer simulation method using particle method for blood flow is proposed to directly evaluate mechanical interactions of red blood cells (RBCs) and plasma.

METHODS

Blood Plasma Flow
Navier-Stokes equations were solved for blood plasma flow using a particle method in which continuum body was discretized by moving particles. In this study, moving particle semi-implicit (MPS) method [2] was used as a particle method, where the particle number density was kept to be its reference value in order to express the incompressibility condition. Spatial differentiation such as gradient and Laplacian of physical quantity was expressed by the sum of the interaction between two particles with weighing function of the particle distance.

RBC Deformation
A two-dimensional circular model of RBC membrane was constructed from $N = 60$ line elements, as shown in Fig. 1(a). Elastic energy of the membrane was considered for changes in the length of the element and the angle between the neighbor elements [3]. Based on minimum energy principle, the nodal displacements of the whole membrane were solved using the following equation:

$$m\ddot{\mathbf{r}}_i + \gamma\dot{\mathbf{r}}_i = -\partial W/\partial \mathbf{r}_i , \quad W = E + \Gamma , \qquad (1)$$

where i denotes node, $\mathbf{r}_i$ position vector, m mass, γ coefficient of viscosity, E total elastic energy of the membrane, and Γ penalty function of constant area constraint. As a result, shape change of a swollen RBC was obtained by decreasing the area by 70%, as shown in Fig. 1(b). The membrane changed its shape from the initial circular to the final biconcave as observed in the actual RBC. In the following sections, the final state of the RBC in this simulation was used for coupled analysis of the RBC deformation and plasma flow.

Particle Model of Blood Flow
A two-dimensional particle model was constructed for the blood flow between parallel rigid plates placed as vessel walls, as shown in Fig. 2. The model consisted of fluid particles for the blood plasma, elastic particles for the RBC membrane, and rigid particles for the vessel wall. The physical property of the plasma was assumed to be the same as that of water. The total number of the particles was 4737, and the mean distance between two particles was $0.5\,\mu$m. The size of the model was $75\,\mu$m in the flow (axial) direction and $12\,\mu$m between the walls. The RBC was placed
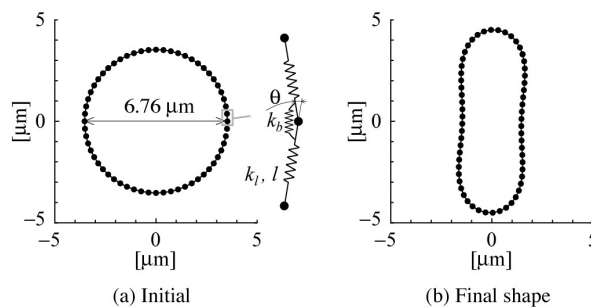

(a) Initial   (b) Final shape

Fig. 1 Two-dimensional simulation of shape change of a swollen red blood cell using elastic membrane model based on minimum energy principle
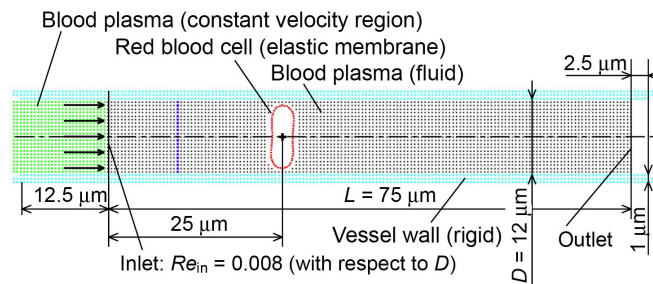
Fig. 2 A particle model of blood flow between parallel plates

between the walls and $25\ \mu$m away from the inlet. As a boundary condition, constant and uniform velocity in the axial direction was applied to the virtual fluid particles placed at the inlet, as shown in Fig. 2. Reynolds number to the distance between the plates D was 0.008. Zero pressure was applied at the outlet, and non-slip condition at the inner vessel wall. In the computer simulation, at first, the RBC was fixed and the plasma flow was solved by MPS method. The coupled analysis of the plasma flow and RBC membrane motion and deformation was carried after the plasma flow became steady. In solving the membrane deformation, fluid force was added to the right side of the Eq. (1).

RESULTS

A simulation result revealed change in RBC shape and position in flowing plasma, as shown in Fig. 3. At the initial state, the plasma flow with the fixed RBC was steady as shown in Fig. 3(a). Poiseuille flow of the blood plasma was obtained in the upstream side of the RBC. The plasma flowed between the fixed RBC and the vessel wall, as indicated by the arrows in Fig. 3(a), with decreasing its pressure. The fluid force due to pressure was higher at the upstream side than the downstream. The RBC was subjected to the pressure force near the wall, leading to compression of the RBC in the direction perpendicular to the vessel walls. These forces drove the RBC to move toward the downstream side, and caused deformation of the RBC in parachute-like shape, as shown in Figs. 3(b) and (c).
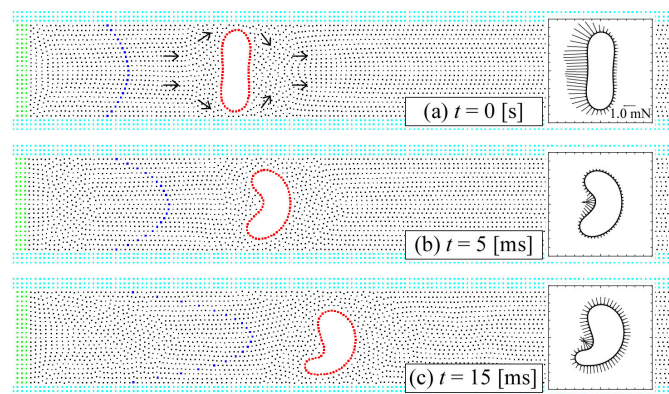

Fig. 3 Motion and deformation of RBC due to fluid pressure under blood plasma flow

DISCUSSION AND CONCLUSIONS

A particle method computer simulation was proposed for the microscopic blood flow by combining a MPS method for blood plasma flow and an elastic membrane model of an RBC. A two-dimensional simulation revealed temporal changes in the RBC movement in the downstream direction due to pressure drop of plasma flow. The RBC was deformed in a parachute shape during the movement, corresponding to experimental observations. The results indicate that the proposed method will give us an insight into the mechanism of the blood flow at from microscopic level of the blood cells and plasma and up to resultant rheological properties.

References

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