ANALYSIS OF RED BLOOD CELL DEFORMATION FOR THE DEVELOPMENT OF HEMOLYIS SIMULATOR

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INTRODUCTION

A red blood cell (RBC) is elastic and deforms into various shapes by undergoing fluid forces while flowing. By exessive deformation, an RBC is damaged and haemolysis, the breaking open of RBC, can occur. In the present study, we develop an elastic RBC model that expresses its deformation behaviors in a high-shear flow. First, RBC behavior in steady and unsteady shear flows was simulated to corroborate the RBC model. Second, RBC in a stenosed flow was simulated to see if a conventional hemolysis index always reflects the degree of deformation in a realistic flow.

METHODS

An RBC has neither an internal cytoskeletal strucutre nor nucleus. Thus, the RBC was modeled as a closed membrane of spring-networks that has a mechanical nature of both lipid bilayer and spectrin [1]. In addition, area and volume constraints are imposed in order to assure incompressibility. Fluid forces exerted by external plasma and internal hemoglobin was estimated based on the momentum conservation and Newton's friction law. Given the fluid forces, the dynamic motion of an RBC in a flow field was calculated based on the minimum energy principe.

RESULTS AND DISCUSSION

1. RBC behavior in steady and unsteady shear flows

When the RBC was put in a steady shear flow, it elongated while its membrane rotated continuously. The deformation index L/W is plotted against the external fluid shear stress τ in Fig. 1(A). Here, L and W are the length of long and short axes of RBC. As seen, L/W increased linearly until τ=50 Pa and converged approximately ~5 Pa at τ=200 Pa.

The RBC in a cyclically reversing unsteady shear flow at the frequency of 3 Hz was also investigated. The RBC deformed in accordance with fluid shear. Figure 1(B) plots temporal variations of fluid shear stress τ and L/W. As seen, there was a phase difference between the fluid shear stress τ and L/W.

The results for steady and unsteady shear flows well agreed with experimental results [2,3], which demonstrates that the RBC model can express realistic behavior.

2. Relationship between RBC deformation and conventional hemolysis index *HI*

Figure 2 (A) shows the relationship between the maximum of the first principal strain over the membrane ε_{max} and the hemolysis index *HI* in a steady shear flow. *HI* is a conventionally used hemolysis index derived from an instantaneous fluid shear stress tensor [4]. As seen, there is a good correlation between these two factors in a steady flow.

The RBC behaviour in a stenosed artery with the Reynolds number of 800 was simulated. Figure 3 shows a trace of the RBC and its snapshots with contour plot of the first principal strain at (a), (b) and (c). At the proximal side of stenosis, RBC was biconcave and strain was almost uniform over the surface (Fig. 3(a)). However, as the RBC entered stenosis, it deformed into a complex shape (Fig. 3(b)), and locally high strain was found. When it left the stenosed region, the RBC recovered a biconcave shape (Fig. 3(c)). Figure 2 (B) plots ε_{max} against *HI* along the trace. As seen, there was no consistent tendency between ε_{max} and *HI* in the stenosed flow, contrary to the results in steady flow in Fig. 2(A).

The RBC flowing in the stenosed flow was exposed to different fluid mechanical environment as it moved. Although a viscous property of the membrane was not considered in this RBC model, viscous forces were generated through the interaction with surrounding fluid. As a result, the RBC behaves a visco-elastic material in which the shape was determined not only fluid force acting on it at that moment but also its deformation history. In support of it, no consistent tendency was found between ε_{max} and *HI* in the stenosed flow. These results address the necessity to reconsider defintion of a hemolysis index and the importance of the analysis of individual RBC deformation.

REFERENCES

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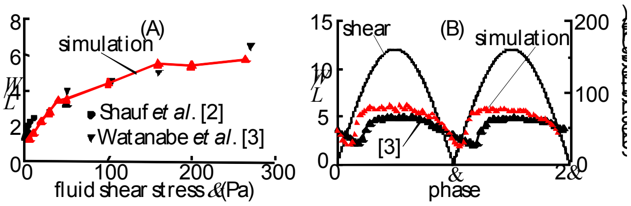

Figure 1: Relationship between fluid shear stress τ and L/W (A) in a steady shear flow and (B) in an unsteady shear flow.

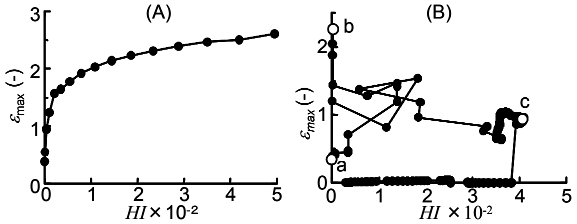

Figure 2: Relationship between ε_{max} and *HI* (A) in a steady shear flow and (B) in a stenosed flow.

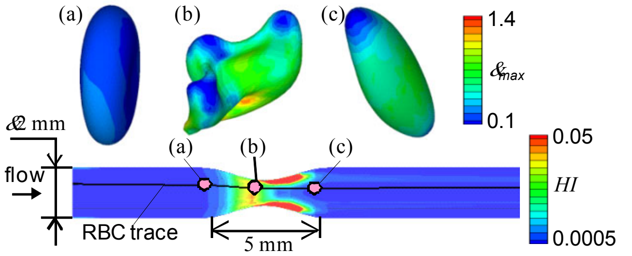

Figure 3: Snapshots of the RBC shape with a contour plot of the strain distribution along the flow trace