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Numerical Study on the Dynamics and Oxygen Uptake of Healthy and Malaria-Infected Red Blood Cells

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Abstract. Red blood cells (RBCs) are very important due to their role of oxygen transport from lungs. As the malaria parasite grows in the malaria-infected red blood cells (IRBCs), the properties of the cells change. In the present work, the oxygen uptake by RBCs and IRBCs at the pulmonary capillaries is simulated using a numerical technique based on the two-dimensional immersed interface method. The results for the oxygen uptake by a stationary single RBC have fair agreements with the previously reported results. The numerical results show that the malaria infection could significantly cause deterioration on the oxygen uptake by red blood cells. The results also suggest that the oxygen uptake by individual stationary RBC/IRBC would not be significantly affected by the neighboring cells provided the separation distance is about the dimension of the cell. Furthermore, it appears that the oxygen uptake by both RBCs and IRBCs is dominated by mass diffusion over the convection although the Peclet number is of the order of unity.

AMS subject classifications: 76Z05, 76M20, 76D05, 76R99, 65M06, 74F10, 92C10
Key words: Red blood cell, malaria, oxygen, biomechanics, numerical simulation.

1 Introduction

The human red blood cells (RBCs) play a very important role since they help to carry gases such as oxygen and carbon dioxide between alveolus and tissues. The biconcave

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RBC has an average diameter of 6-8μm and the life time is about 100-120days. The irregular deformation of RBCs and the change in mechanical properties may be responsible and associated with various diseases. As such, the study of the mechanical properties of RBCs and their deformation under different flow conditions has important implications on health.

The RBC shape is asymmetric when it flows along blood vessels. Secomb and Skalak [1] showed that the asymmetric motion of RBC results in the tank-treading motion of the RBC. The shape of the deformed cell may depend on many factors such as vessel diameter, cell velocity, cell membrane stiffness etc. [2]. Pozrikidis [3, 4] studied the RBC deformation and motion in shear and channel flows using the boundary integral method. Some other researchers have considered RBC aggregation too. Liu and Liu [5] numerically modeled RBC aggregation through a potential function, while Zhang et al. [6] studied the RBC aggregation under different shear rates. Varity of mathematical models have been developed to simulate RBCs [7].

Another class of research work on RBCs concerns the gas transfer by RBCs. Understanding gas transfer by RBCs is important to diagnose various pulmonary diseases and the design of effective drugs and treatments. In addition, the aforementioned knowledge is important to design efficient oxygenators and artificial lungs. As such, several researchers have been studying this problem for more than three decades. Hellums [8] studied the resistance to oxygen transport in the capillaries by modeling the capillary and RBCs simply as a circular tube and cylindrical slugs, respectively. Groebe and Thews [9] also modeled the RBCs as cylindrical particles and showed that the motion of RBCs could enhance oxygen release and make oxygen flux more uniform along the capillary. W ang and Popel [10] investigated the effect of the shape of RBC on oxygen transport and showed that the deformation of initial biconcave RBCs to "parachute" shape decreases spatially averaged oxygen flux.

One of the most infectious diseases affecting the circulatory system is the malaria. Each year about 1 million people die due to malaria. When healthy RBCs are infected by the malaria parasite, Plasmodium falciparum, the mechanical properties of cells are changed [12–14]. When the parasite matures in the malaria-infected red blood cells (IRBCs), the cells' membrane becomes stiffer and the deformability of the cells decrease significantly and hence exhibits difficulty in passing through capillaries [15]. Malaria infection produces knobs on the surface of the cells' membrane and these cause the membrane to become more adhesive. As such, IRBCs adhere to RBCs and endothelium cells which results in increasing flow resistant as reported in Kondo et al. [16]. Imai et al. [17] investigated the interaction between RBCs and IRBCs using a three-dimensional model and showed that IRBCs could marginalize during their interactions with a longer duration of contact with endothelium cells. Secomb et al. [18] used a theoretical model to examine the effect of glycocalyx on haematocrit and blood flow resistance. Also, Fedosov et al. [19] simulated the adhesive dynamics of IRBCs and revealed that IRBCs are flipped due to increased stiffness and the solid parasites inside the cells.

As mentioned earlier, when the malaria parasite matures inside an IRBC, the cel-