Lateral Migration of Capsules in Stokes Flow

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論 文 内 容 の 要 旨

Chapter 1　Introduction

It is well known that, in the microcirculation, red blood cells tend to migrate towards the center of the blood vessel, a process referred to as axial migration. On the contrary, other blood cells, such as white blood cells and platelets, have been observed to flow disproportionately near the blood vessel wall in a process called margination. As white blood cells interact with the vessel wall to promote immune system function and platelets interact with the wall to induce coagulation, the process of margination offers a number of benefits physiologically, but the mechanism of margination, as well as the origin in the difference in behavior between red blood cells and other blood cells, is still unclear.

This thesis examines the phenomenon of blood cell migration from a fluid dynamics perspective through the use of numerical simulation by investigating the lateral migration of a capsule. Blood flow is taken to be a Stokes flow, such that inertial causes of migration can be neglected. Thus, only the causes of lateral migration in a Stokes flow are considered: (1) lateral migration due to the presence of a wall; and (2) lateral migration due to the presence of a shear gradient.

Previous studies have taken several approaches in investigating the lateral migration of deformable particles. Analytical studies focused on the behavior of deformable drops near an infinite planar wall in the small deformation limit and found that the lift velocity was proportional to the extent of deformation of the drop. Numerical studies have clarified the lift velocity of various deformable particles at large deformation, but typical numerical methods are limited to bounded domains, so the separate effects of the wall and shear gradient have yet to be

clarified.

In this study, the lateral migration of a deformable capsule is investigated using a boundary integral method, which allows for the direct computation of infinite and semi-infinite domains. Capsule lateral migration is computed in three domains: near an infinite planar wall; in an unbounded parabolic flow; and in a parabolic flow bounded on one side by an infinite planar wall. The relative effects of the wall and shear gradient on capsule lateral migration are clarified by comparing the lift velocity in these three domains.

Chapter 2   Problem statement

In this chapter, an outline of the problem statement is given, and the governing equations are introduced. The capsule consists of a hyperelastic membrane that encloses an inner fluid with viscosity equal to that of the surrounding fluid. The membrane is taken to have negligible bending resistance, so the effect of bending moments is ignored. Two constitutive laws with contrasting material properties are considered: the strain-softening neo-Hookean law, which can be used to model materials such as a thin rubber membrane; and the strain-hardening Skalak law, which is often used to model biological membranes, particularly the red blood cell membrane. The fluid surrounding the capsule as well as the fluid inside the capsule are assumed to have a Reynolds number of Re << 1, and so are assumed to undergo Stokes flow. Thus, the velocity field of the membrane and surrounding fluid can be solved directly using the boundary integral equation.

Chapter 3   Numerical method

In this chapter, the specifics of the numerical method are described. The capsule membrane is treated as a continuous two-dimensional elastic material with a spherical resting shape. To solve the capsule properties numerically, the membrane is discretized into a unstructured triangular mesh with 5120 linear elements. The membrane tension is solved at each node on the capsule membrane using the surface strain energy function of the membrane constitutive law. Then, the viscous load on the capsule membrane is solved from the membrane tension using the finite element method.

Next, the velocity of the capsule membrane is solved from the viscous load by using the boundary integral equation. In cases where an infinite planar wall are considered, the effect of the wall is given by a special Green's function that takes the effect of the wall as an image of the capsule on the opposing side of the wall. The capsule volume is kept nearly constant through the use of Lagrange multipliers.

Chapter 4   Migration of spherical capsule near a wall

In this chapter, the results of simulations of the lateral migration of a capsule near an infinite planar wall are presented. The capsule velocity and deformation are shown for a large range of flow conditions, as well as for both the neo-Hookean and Skalak membrane constitutive laws. The lift velocity of the capsule, or the rate at which the capsule migrates away from the wall, agrees well with a previously-derived analytical solution that describes the lift velocity for a deformable particle placed far from an infinite planar wall. However, the capsule velocity is much lower than predicted by the analytical solution when the capsule is close to the wall.

The decrease in the capsule lift velocity is shown to be related to the degree of asymmetrical deformation exhibited by the capsule. The capsule lift velocity is decomposed into terms representing the contributions of the capsule deformation and the wall to the total lift velocity. The lift velocity induced by the capsule deformation is found to be negative and also found to decrease at the same rate as the asymmetrical deformation of the capsule. When the wall term is decomposed into components that include the effects of the symmetrical and asymmetrical deformation, it is found that the asymmetrical deformation of the capsule acts to decrease the magnitude of the wall term, while the symmetrical deformation of the capsule acts to increase the wall component of the lift velocity.

Chapter 5   Migration of spherical capsule in parabolic flow

In this chapter, the lateral migration of a capsule in a flow with non-zero shear gradient, both in the presence and in the absence of a wall, is considered. When the capsule is placed in an unbounded parabolic flow, the lift velocity of the capsule is determined mostly by the magnitude of the shear gradient, with a small dependence on the nondimensional shear rate. In an unbounded parabolic flow, the extent of the symmetrical deformation of the capsule is mostly unaffected by the magnitude of the shear gradient, and the extent of the asymmetrical deformation is found to be proportional to the magnitude of the shear gradient as well as the lift velocity.

On the other hand, the lift velocity of a capsule in a near-wall parabolic flow is mostly determined by the presence of the wall, rather than the magnitude of the shear gradient. Using a scaling argument, the effect of the shear gradient is given in terms of the shear rate, the shear gradient, and the distance between the capsule and the nearest wall. When this equation is then applied to realistic systems, such as blood vessels or microchannels, it is determined that the contribution of the shear gradient to the total lift velocity is independent of the shear rate, and that the shear gradient plays a significant role in a large range of distances within large vessels and microchannels.

Chapter 6　Conclusion

In conclusion, this study clarified the role of a planar wall and shear gradient in the lateral migration of spherical capsules, which is necessary for a better understanding of migration that occurs in suspensions of deformable particles and cells, such as the blood. Combined with an investigation into the role of capsule-capsule interactions in inducing lateral migration, a more complete understanding of migration phenomena, such as axial migration and margination in the blood, may be achieved. Using these results as a starting point, other properties of capsules in biological systems, such as a non-spherical resting shape and non-unity viscosity ratio, and their effect on lateral migration, may also be clarified in the future.

論文審査結果の要旨

微小血管においては、赤血球は血管の中心付近を流動するが、白血球や血小板は血管壁近傍を流動している。このような細胞の移動現象のメカニズムを理解するためには、細胞の移動速度に対する血流のずり速度勾配、および血管壁の相対的効果を解明する必要がある。本論文は、これらの研究成果をまとめたものであり、全編6章からなる。

第1章は序論であり、本研究の背景、目的及び構成を述べている。

第2章では、問題設定および基礎方程式を説明している。細胞を膜と流体からなるカプセルとしてモデル化し、カプセルの膜の固体力学、カプセル内外の流体の流体力学、および本論文で重要となるパラメータについて述べている。

第3章では、無限平板を境界とするストークス流れ中のカプセルの移動現象を計算するための計算手法について説明している。膜の張力の計算方法、固体力学に対する有限要素法、流体力学に対する境界要素法、および無限平板を取り扱うためのグリーン関数について述べている。

第4章では、単純せん断流れにおける壁近傍のカプセルの移動現象を解析している。カプセルの上昇速度が解析解に比べて低いことを示し、これがカプセルの非対称な変形によるものであることを明らかにしている。これは細胞の移動現象を理解する基礎となる重要な成果である。

第5章では、カプセルの上昇速度に対する壁とずり速度勾配の相対的効果を明らかにするため、放物形速度分布におけるカプセルの移動現象を解析している。上昇速度に対するずり速度勾配の寄与は、ずり速度勾配および壁からの距離の二乗に比例することを示している。また、管路内を流動するカプセルに適用する場合には、ずり速度勾配の寄与を壁からの距離と管径の関数として記述できることを示している。これは実際の微小流路や血管中を流動する細胞の移動現象を予測するための重要な成果である。

第6章は結論である。

以上要するに本論文は、ストークス流れ中のカプセルの移動現象を詳細に数値解析し、カプセルの上昇速度に対する壁とずり速度勾配の相対的効果を明らかにしたものであり、医工学及び機械工学の発展に寄与するところが少なくない。

よって、本論文は博士（医工学）の学位論文として合格と認める。