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Effects of an inhomogeneous magnetic field on flowing erythrocytes

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Abstract. Effects of an inhomogeneous magnetic field on narrow erythrocyte streams in a wide and transparent laminar buffer flow were studied. The stream line of erythrocytes containing paramagnetic hemoglobin showed distinct displacement toward the stronger magnetic field. The displacement increased in the order, oxygenated erythrocytes (no displacement), erythrocytes containing cyanomethemoglobin, deoxygenated erythrocytes, erythrocytes containing methemoglobin in the high spin state; more precisely the displacement was proportional to the square of the paramagnetic moment of hemoglobin contained in the erythrocytes. In addition, the displacement was proportional to the product of the magnetic flux density and its gradient, and approximately proportional to the hematocrit of the flowing-erythrocyte suspension, and was much larger than that calculated for a single erythrocyte. These phenomena could be successfully interpreted by the interaction of paramagnetic erythrocytes with the inhomogeneous magnetic field, the resistance force (Stokes Law) from the bulk water, and the hydrodynamic interaction between erythrocytes.

Key words: (Flowing) erythrocytes, magnetic field effect, paramagnetism

Introduction

In parallel with the increasing opportunities for employing strong magnetic fields, many reports concerning the effects of magnetic field on biological systems have appeared (Tenforde 1979; Adey 1981; Frankel 1984). Among possible basic mechanisms of magnetic field effects on biological systems, we consider here the effects on blood circulation. For example, a decrease of blood flow has been suggested theoretically (Vardanyan 1973; Chen and Saha 1984, 1985) and magneto-hydrodynamic effects (for example, Ferraro and Plumpton 1966), and orientation of flowing deoxygenated sickled erythrocytes (Brody et al. 1985) have been demonstrated. In addition, some basic interactions of erythrocytes with the magnetic field have been reported. The orientation (Murayama 1965) and rotation (Costa-Ribeiro et al. 1981) of sickled erythrocytes in a magnetic field have been observed. Melville et al. (1975) and Paul et al. (1978) reported a separation method for erythrocytes containing paramagnetic hemoglobin using a magnet and a column packed with iron wires, and Sharygin et al. (1983) observed migration of erythrocytes along the magnetic field gradient.

In view of these studies, we have investigated the effect of an inhomogeneous magnetic field on narrow erythrocyte streams in a laminar buffer flow using a rectangular glass cell. The electronic state of hemoglobin inside the erythrocyte was varied: oxygenated state [Fe(II), $S = 0$], deoxygenated state [Fe(II), $S = 2$], oxidized state (methemoglobin) with high spin configuration [Fe(III), $S = 5/2$], and oxidized state with low spin configuration (cyanomethemoglobin) [Fe(III), $S = 1/2$]. A distinct displacement, towards stronger magnetic field, of the narrow stream line of erythrocytes containing paramagnetic hemoglobin was observed in an inhomogeneous magnetic field. The displacement was dependent on the electronic state of hemoglobin contained in the flowing erythrocytes and the product of the strength and gradient of the magnetic flux density. These results are interpreted on the basis of the interaction of paramagnetic erythrocytes with the inhomogeneous magnetic field. Further, the displacement was dependent on the hematocrit of the flowing erythrocyte suspension. This hematocrit dependency is explained by hydrodynamic interactions between erythrocytes.

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Materials and methods

Erythrocytes

Freshly drawn venous blood from healthy donors was centrifuged (3000 rpm, 5 min) to remove plasma and buffy coat. After washing three times with an isotonic buffered saline solution (90 m*M* NaCl, 5 m*M* KCl, 5.6 m*M* glucose, 50 m*M* Na-phosphate, pH 7.4), the erythrocytes were suspended in the buffer and used as "erythrocytes with oxygenated hemoglobin". "Erythrocytes with deoxygenated hemoglobin" were obtained by treating the washed erythrocytes with $Na_2S_2O_4$ (25 m*M*). In the experiments with deoxygenated erythrocytes, solutions in the flow apparatus were deaerated by bubbling nitrogen gas. Hemoglobin in the erythrocytes was oxidized to methemoglobin with $NaNO_2$ (20 m*M*). The erythrocytes, then, were washed five times and suspended in an isotonic buffered saline of pH 5.7, to obtain "erythrocytes with high-spin methemoglobin". "Erythrocytes with methemoglobin in the low spin state" were obtained by treating the erythrocytes containing methemoglobin with KCN (10 equivalents of the total heme) to form cyano-methemoglobin, then washed three times with the isotonic buffer at pH 7.4.

Flow apparatus

Views around the flow cell from the two directions are shown in Fig. 1. The coordinate system is also shown in Fig. 1B: x-axis is parallel to the plane vector of the glass-cell; y-axis is along the flow direction; z-axis is along the vector which spans two poles of the magnet. The origin ($x = y = z = 0$; in units of mm) is taken at the top edge of the iron block. A narrow erythrocyte stream (diameter = 80–120 μm) was made in a relatively wide rectangular glass cell (4 × 150 × 0.4 mm microslide, Vitro Dynamics, NJ) by letting the erythrocyte suspension run into a laminar flow of the buffered saline from a narrow needle (at $x = 0$; $y = 0$; $z = 3$ mm) whose inner diameter was 0.2 mm. The erythrocyte suspension in the reservoir was stirred and continuously circulated in a loop to prevent sedimentation, and a small part of the suspension was fed into the flow cell through the needle by hydrostatic pressure. The flow velocity was about 150 mm/s initially, in order to establish a narrow erythrocyte stream line, and then abruptly decelerated (at $t = 0$) to 0.5 mm/s–30 mm/s by switching the flowing route to a narrow bypass at the outlet. The flow velocity after the deceleration was controlled by changing the hydrostatic pressure difference between the buffer reservoir and the waste-fluid reservoir (after the bypass). The flow

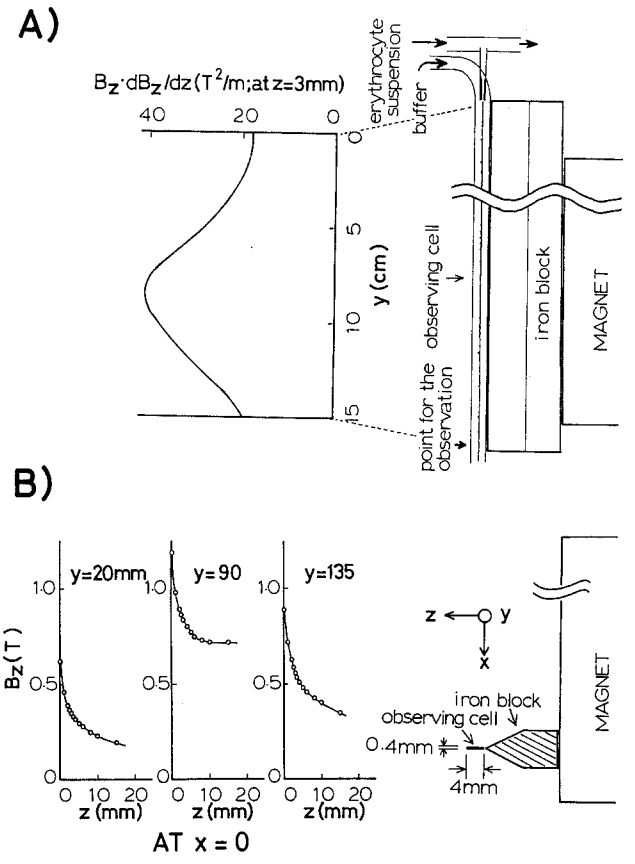

Fig. 1A and B. A schematic representation for the flow cell and the magnetic system projected to yz-plane (**A**) and xz-plane (**B**), and magnetic parameters as a function of spatial coordinates in the plane $x = 0$. The coordinate system is shown in the lower figure. A microslide was attached parallel to the edge of the iron block as the flow cell. The origin of the coordinate system is at the top edge of the iron block and the erythrocyte suspension is spouted at $(x, y, z) = (0, 0, 3)$ (in units of mm) into the flowing buffer solution. The fluid was allowed to flow downward vertically, and the erythrocyte stream line was observed at $y = 150$ (mm)

speed was measured with a microscope (slow speed < 2 mm/s) or directly (rapid flow > 2 mm/s).

The displacement of the erythrocyte stream was measured on photographs, which were taken (at $y = 150$ mm) under a microscope (SZ-TR-I, Olympus Optics, Tokyo). The position, where the density of erythrocyte was the largest, was determined on photographs with a TLC scanner (CS-910, Shimadzu Manufac., Kyoto) and was defined as the position of the erythrocyte stream line.

All the experiments were carried out at room temperature; 23 ± 2 °C.

Magnetic field

The inhomogeneous magnetic field was made using a magnet (E-3 EPR spectrometer, Varian Assoc. California) and an iron block with one side tapered

by about 53 deg as shown in Fig. 1, which also shows the magnetic flux density (B_z) as functions of z along three lines; ($x = 0$, $y = 20$), ($x = 0$, $y = 90$), and ($x = 0$, $y = 135$ mm), and its product with the gradient ($B_z \times dB_z/dz$; at $x = 0$, $z = 3$ mm) as a function of y. The magnetic flux density was measured with a gauss meter (GM-1200, Denshijiki Industry, Tokyo). The gradient of the magnetic field (z-component) at the position of the erythrocyte stream line ($x = 0$, $z = 3.0$ mm) was obtained as $\Delta B_z/\Delta z$ based on two B_z values at $z = 2.5$ mm and $z = 3.5$ mm. The "averaged" value of the product, $B_z \times dB_z/dz$, was calculated by the sectional integration method (increment for y-axis was 2.5 mm), i.e.:

$$(B_z \cdot dB_z/dz)_{\text{average}} = 1/n \sum_{i=1}^{n} (B_z \cdot \Delta B_z/\Delta z)_i \qquad (1)$$

from y_1; the coordinate of the observed erythrocytes at $t = 0$, to $y_2 (= 150$ mm); the coordinate for the observation. In Eq. (1), n represents the number of grid points for the integration. Magnetic field was varied by changing the current to the electromagnet.

Hematocrit measurement

The hematocrit of the flowing erythrocyte suspension was obtained as follows: (1) The erythrocyte suspension, which flowed out from the glass cell, was collected and the number of erythrocytes was counted with a Microcellcounter (CC-110, Toa Medical Electronics, Kobe). (2) The volume fraction of the erythrocyte suspension in the bulk buffer stream was calculated using the diameter of the erythrocyte stream line and the theoretical velocity distribution (for Newtonian flow in a rectangular cell of infinite width). (3) The product of the mean corpuscular volume and the number density of erythrocytes in the erythrocyte stream line gave the hematocrit. Hematocrits given thorough this manuscript were calculated using the diameter of the erythrocyte stream line at $t = 0$.

Results and discussion

Observed displacement of erythrocyte stream line

The effect of the inhomogeneous magnetic field on the stream of erythrocytes containing hemoglobins in various electronic state are shown in Fig. 2. The lower photographs show the displacements of narrow erythrocyte streams due to the applied magnetic field during 150 s after slowing down of the flow to the velocity of 0.7 mm/s[1]. Displacement of the stream line was the largest for erythrocytes containing high spin methemoglobin (labeled as MET in the figure) and decreased in the order, deoxygenated erythrocytes (DEOXY), and erythrocytes containing cyano-methemoglobin (CN-MET). While oxygenated erythrocytes (OXY) showed no displacement. The paramagnetic moment of hemoglobin (Pauling and Coryell 1936; Coryell et al. 1937; Iizuka and Kotani 1969; Nakano et al. 1972; Alpert and Banerjee 1975; Cerdonio et al. 1981) in these erythrocytes decreases in the same order. The observed displacements and the paramagnetic moments for hemoglobins in various electronic states are summarized in Table 1.

Figure 3A shows that the observed displacement is approximately proportional to the square of the magnetic moment of hemoglobin contained in the erythrocytes, and Fig. 3B shows the dependence of the displacement for erythrocytes containing high-spin methemoglobin on the averaged product of the z-component of magnetic flux density (B_z) and its gradient with the z-coordinate (dB_z/dz). It is clear that the displacements, in all cases shown in Fig. 2, are proportional to the averaged product of B_z and dB_z/dz. In addition the displacement was inversely proportional to the flow velocity.

Force from magnetic field

To interpret the displacement, we introduce the force which acts on erythrocytes in the inhomogeneous magnetic field.

$$F_{\text{mag}} = \chi V(\boldsymbol{H} \cdot \nabla) B + q(\boldsymbol{v} \times \boldsymbol{B} + \boldsymbol{E}) . \qquad (2)$$

The first term is obtained by differentiating the potential energy ($\varphi = V\chi \boldsymbol{HB}/2$) of a paramagnetic particle in the magnetic field, using $\nabla \times \boldsymbol{B}$ (and $\boldsymbol{H}) = 0$ e.g. (Kittel 1966). Here ∇ (nabla) is a differential operator. This term describes the magnetic interaction of erythrocytes (susceptibility: χ, volume: V) with the external magnetic field (magnetic flux density: $\boldsymbol{B}$, magnetic field intensity: $\boldsymbol{H}$). The second term is the interaction of the erythrocytes (charge: q) with the electric fields $\boldsymbol{v} \times \boldsymbol{B}$ (due to Lorentz's force) and $\boldsymbol{E}$ (due to Hall effect).

Because the observing glass cell is fixed, the difference between the forces on the buffer solution and on the flowing erythrocytes, determine the displacement of the erythrocyte stream line. In addition, as mentioned above, we could not observe any displacement of the stream line of oxygenated eryth-

1 The erythrocytes travel about 105 mm during this period. Strictly speaking, the stream line may be displaced a little even at time zero because the magnetic field is already applied before the deceleration. This displacement, however, was less than 5% of that observed during 150 s at the flow velocity of 0.7 mm/s, thus it was neglected

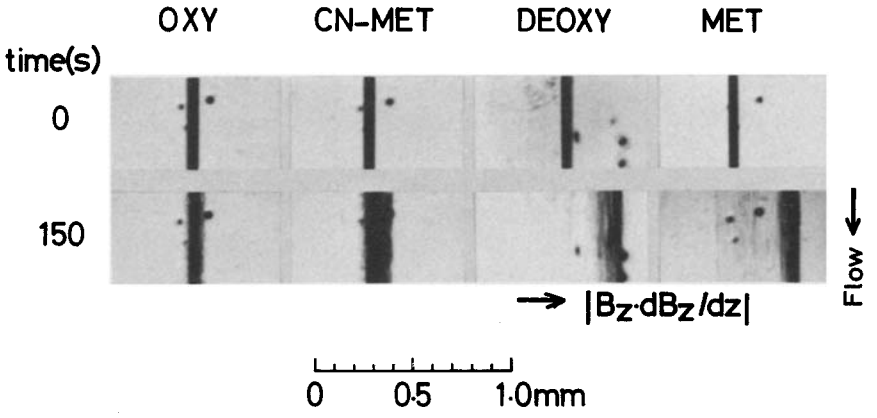

Fig. 2. Effect of an inhomogeneous magnetic field on the narrow streams of erythrocytes containing hemoglobin of various electronic states in a relatively wide buffer stream. The upper photographs are those before slowing down of the flow, and the displacements were measured based on this. The lower photographs are those taken after the 150 s flow at 0.7 mm/s, thus the observed erythrocytes traveled about 105 mm. The "averaged" product of the magnetic flux density and its gradient was 29 T^2/m. A few static spots in each photographs come from dirt outside the glass cell. The hematocrit value at $t = 0$ is 6.0% for all cases

Table 1. Observed and calculated displacement toward stronger magnetic field of the erythrocyte stream line in the inhomogeneous magnetic field

	Oxy-Hb	CN-metHb	Deoxy-Hb	MetHb
Magnetic Moment (Bohr magneton)	0	2.2	5.3	5.8
Observed[a] [μm]	0	57	300	390
Calculated for single erythrocyte[b] [μm]	0	2.5	14.5	17.7
Calculated for a volume of erythrocyte suspension[c] [μm]	0	42	245	300

[a] The velocity of the flow was 0.7 mm/s and the displacement was measured after 150 s flow, i.e. the erythrocytes travelled 105 mm during this period. The diameter of the erythrocyte stream line was about 80 μm. Displacements are given in units of μm. The temperature was 293 K

[b] Hemoglobin density of erythrocyte: 1.32×10^{25}/m^3; volume of erythrocyte: 9.0×10^{-17} m^3; hydrodynamic radius of erythrocyte: 3.0 μm; viscosity of the medium: 1.0×10^{-3} N · S/m^2; the averaged value of $B_z \times dB_z/dz$ was 29 T^2/m

[c] Hematocrit of the flowing erythrocyte suspension was 6%. The diameter of the erythrocyte stream line was about 80 μm

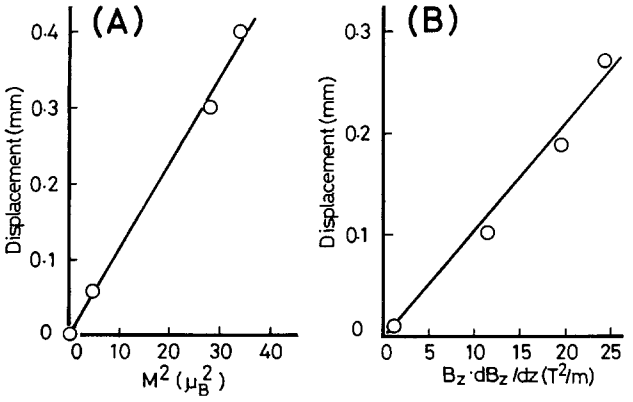

Fig. 3 A and B. Displacement of the erythrocyte stream line as a function of the square of the magnetic moment of hemoglobin contained in the erythrocytes **A**, and displacement of the narrow stream line of erythrocytes containing high-spin met-hemoglobin as a function of the "averaged" $B_z \times dB_z/dz$ (**B**), during the flow (150 s) at a velocity of 0.7 mm/s. In case of (**A**), the averaged product of the magnetic flux density and its gradient was 29 T^2/m. The hematocrit at $t = 0$ was 6.0% for all cases

rocytes, and the displacement for the other cases were solely dependent on the paramagnetism of the flowing erythrocytes. Therefore we can neglect the second term of Eq. (2) in the analysis of the data, and χ in Eq. (2) can be replaced with χ_p, the paramagnetic susceptibility of the erythrocyte, which is given by the Curie-Langevin formula,

$$\chi_p = (g \cdot \mu_B)^2 S(S+1) \mu_w N/3kT. \quad (3)$$

Here, g and S are the g-factor and the spin quantum number, respectively, for the paramagnetic centre of the molecule. μ_B represents the Bohr magneton, and μ_w represents the magnetic permeability of the solvent (thus $\mu_w H = B$). N is the number of the paramagnetic centre in unit volume (1 m^3). The force which causes the displacement of the erythrocyte stream line can be simplified as follows using the magnetic moment (M; $M^2 = (g \cdot \mu_B)^2 S(S+1)$) of the paramagnetic centre:

$$F_{\text{mag}} = M^2 N(\boldsymbol{B} \cdot \nabla) \boldsymbol{B}/3kT. \quad (4)$$

The external force (F_{mag}), which acts on a particle, may be equilibrated with the friction force (F_f) in a short time. F_f is given by Stokes law,

$$F_f = 6\pi\eta R u\,, \tag{5}$$

where u is the velocity of displacement (z-direction towards the stronger magnetic field), R is the hydrodynamic radius of the moving particle in a fluid of viscosity η.

The displacement (L) due to the force F_{mag} can be calculated by integrating the displacement velocity with respect to time.

$$L = \int_0^T u\,\mathrm{d}t = \int_{Y_1}^{Y_2} F_{mag}/6\pi\eta R v \cdot \mathrm{d}y\,, \tag{6}$$

where Y_1 and Y_2 are the y-coordinates of the particular erythrocytes at $t = 0$ and at $t = T$ when the observation is made, respectively, and v is the flow velocity (y-direction), thus $\mathrm{d}t = \mathrm{d}y/v$.

Equations (2)–(6) qualitatively explain the observation that the displacement is proportional to $B_z \mathrm{d}B_z/\mathrm{d}z$, M^2 (Figs. 2 and 3), and $1/v$. Thus, we reach the conclusion that the displacement of the erythrocyte stream line is due to the magnetic interaction of paramagnetic hemoglobin with the inhomogeneous magnetic field.

Calculation of displacement

By decomposing the right hand side of Eq. (4), it is shown that only the $B_z \cdot \mathrm{d}B_z/\mathrm{d}z$ term contributes to the displacement in our experimental setup. Thus, from Eq. (6) we finally obtain the following equation for the displacement (L).

$$L = V\chi_p/(6\pi\eta\mu_w R v) \cdot \int_{Y_1}^{Y_2} B_z(\mathrm{d}B_z/\mathrm{d}z)\,\mathrm{d}y\,. \tag{7}$$

The integration in Eq. (7) was made by numerical calculation with the assumption that the erythrocytes flow along the y-axis at $z = 3$ mm. (Although the z-coordinate of the erythrocyte stream changes slightly and the $B_z \times \mathrm{d}B_z/\mathrm{d}z$ value is increased by the displacement, we neglect it because a displacement of 0.4 mm in the z-direction at the observing point does not lead to an increase of the integrated value of $B_z \times \mathrm{d}B_z/\mathrm{d}z$ by more than 10%.) The calculated displacements are shown in Table 1 together with the observed values.

Hematocrit dependence of displacement

Table 2 gives the dependence of the displacement on the hematocrit of the flowing erythrocyte suspension. The displacement was approximately proportional to the hemotocrit. In addition, the calculated displacements for a single erythrocyte are much smaller than the observed values appearing in Tables 1 and 2. These facts suggest that hydrodynamic interactions among erythrocytes may intensify the displacement of the erythrocyte stream line, in such a way that a group of erythrocytes are pulled as a whole by the external force. If we assume 'a volume', erythrocytes within which are attracted as a whole by the interaction with the magnetic field, a large displacement of the erythrocyte stream line may be explained. In this case V and χ in Eq. (2) represent the volume and the susceptibility, respectively, of 'the volume'. As a first approximation for 'the volume' we consider a sphere whose diameter is equal to that of the erythrocyte stream line. Adopting 40 μm for R, 6% for the hematocrit, and 0.06× [paramagnetic susceptibility of single erythrocyte] for χ_p, we obtained the values in the last row of Table 1. These values are in good agreement with the observed values.

Table 2. Dependence of the displacement of erythrocyte stream line on the hematocrit[a]

Hematocrit value (%)	1.5	3.0	6.0	13.4
Displacement (μm)	180	240	400	940

[a] The flow velocity of the erythrocytes containing high-spin methemoglobin was 0.7 mm/s. The displacements were observed after letting the erythrocyte suspension flow during 150 s. The "averaged" product of the magnetic flux density and the gradient was 29 T^2/m

In addition, displacement of the stream line with a mixture of paramagnetic erythrocytes with high spin methemoglobin (50%) and diamagnetic erythrocytes with oxyhemoglobin (50%) was measured[2]. We could not observe two separated streams, but observed a single stream line which was displaced by nearly half of the displacement observed for erythrocytes with high spin methemoglobin. The result indicates that the diamagnetic erythrocytes with oxyhemoglobin are displaced together with the paramagnetic erythrocytes, and it is a direct evidence for the hydrodynamic interaction between erythrocytes mentioned above. However, using a much stronger magnetic field (and its gradient) and a long flow cell, they may be separated.

Drift due to Lorentz's force

Because the displacement described above was dependent on the magnetic moment and not on the electric charge of erythrocytes, Lorentz's force is not

2 Washed erythrocytes with high spin methemoglobin and those with oxyhemoglobin were mixed in the buffer at pH 5.7. During the experiments two kind of erythrocytes could be clearly discriminated by the difference in color

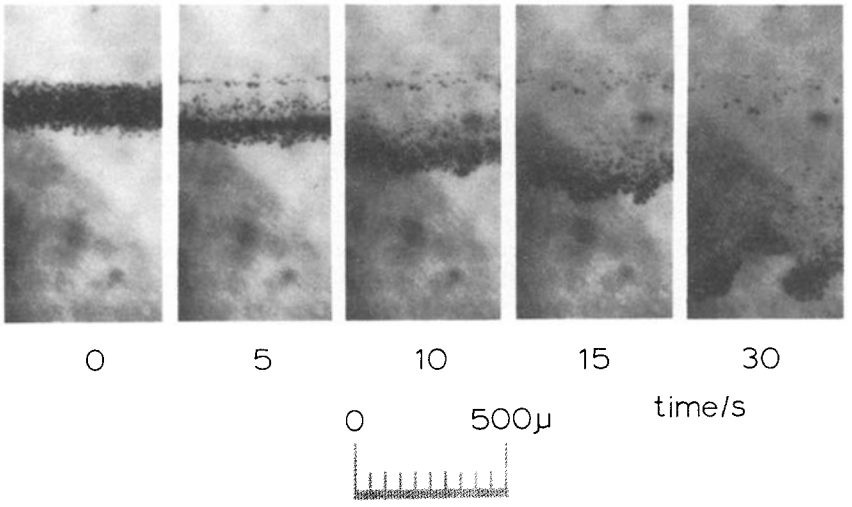

Fig. 4. Sedimentation of erythrocytes (due to gravity) after stopping a narrow horizontal stream. The glass cell (Fig. 1) was rotated 90° about z-axis to make horizontal flow. The hematocrit was 6%

the cause of this (z-direction) displacement. By rotating the observing cell by 90° about the y-axis (see Fig. 1) and using a mirror before the microscope, possible displacement due to the Lorentz's force ($-x$ direction as predicted from Eq. (2)) can be detected. The results showed that the displacement of the stream line was too small to detect in accordance with the calculated value of $5.7 \times 10^{-4}\,\mu m^3$.

Line broadening and sedimentation experiment

Distinct broadening of the stream line, due to the magnetic field, of erythrocytes containing paramagnetic hemoglobin was observed. However, quantitative measurement of the line-width broadening due to the magnetic field was not possible. In the actual stream line, the density of erythrocytes may not be perfectly homogeneous and the velocity of the flow may fluctuate. In addition, an eddy current may be formed owing to the displacement of 'the volume' of erythrocyte suspension. Because of these processes, the velocity of the displacement may differ slightly from point to point. Therefore, a broadening in the stream line of flowing erythrocytes can be expected and in fact such broadening appears in Fig. 2.

Figure 4 shows a sedimentation experiment of a narrow stream line of erythrocytes, which is stopped abruptly. For this experiment, the observing cell (Fig. 1) was set to make the flow horizontal and the wide plane of the cell to face to the magnetic poles. A surface mirror was equipped for the observation. Some interesting phenomena are demonstrated: (1) a large part of the erythrocytes are concentrated at the front end and sedimented fast; (2) a minor part of the erythrocytes are left behind at a density much smaller than the original hematocrit and sedimented slowly. Calculated sedimentation rate for a single erythrocyte (Fahraeus 1929; for recent treatment see Oka 1985) is about $1.1\,\mu m/s$[4], while the observed sedimentation rate (for "the dense volume" of erythrocytes) of about $20\,\mu m/s$ is much larger than this calculated value.

The ratio between these two rates of sedimentation was in the same order as the ratio between the calculated rate of displacement for a single paramagnetic erythrocyte and the observed displacement rate for the actual erythrocyte stream line in the inhomogeneous magnetic field. Therefore, it is concluded that erythrocytes move collectively by a weak force, such as gravity or interaction with an inhomogeneous magnetic field.

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References

Adey WR (1981) Tissue interactions with nonionizing electromagnetic fields. Physiol Rev 61:435–514

Alpert Y, Banerjee R (1975) Magnetic susceptibility measurements of deoxygenated hemoglobin and isolated chains. Biochim Biophys Acta 405:144–154, and references therein

Brody AS, Sorette MP, Gooding CA, Listerud J, Clark MR, Mentzer WC, Brasch RC, James TL (1985) Induced alignment of flowing sickle erythrocytes in a magnetic field: a preliminary report. Invest Radiol 20:560–566

3 In the calculation -6.4×10^{-16} C for the charge on the ζ surface of the erythrocyte (Eylar et al. 1962) was used, and the electric field due to Hall effect was neglected

4 The specific gravities of erythrocyte and the buffer solution are 1.097 and 1.023, respectively. Hydrodynamic radius of 3 μm for erythrocyte was used

Cerdonio M, Morante M, Vitale S (1981) Magnetic Susceptibility of Hemoglobins. In: Eraldo A, Rossi-Bernardi L, Chiancone E (eds) Hemoglobins (Methods in enzymology vol. 76). Academic Press, New York, pp 354–371

Chen IIH, Saha S (1984) Analysis of an intensive magnetic field on blood flow. J Bioelectricity 3:293–298

Chen IIH, Saha S (1985) Analysis of an intensive magnetic field on blood flow: part 2. J Bioelectricity 4:55–61

Coryell CD, Stitt F, Pauling L (1937) The magnetic properties and structure of ferrihemoglobin (methemoglobin) and some of its compounds. J Am Chem Soc 59:633–642

Costa-Ribeiro P, Davidovich MA, Wajnberg E, Bemski G, Kischinevsky M (1981) Rotation of sickle cells in homogeneous magnetic field. Biophys J 36:443–447

Eylar EH, Madoff MA, Brody OV, Oncley JL (1962) The contribution of sialic acid to the surface charge of the erythrocyte. J Biol Chem 237:1992–2000

Fahraeus R (1929) The suspension stability of blood. Physiol Rev 9:241–274

Ferraro VCA, Plumpton C (1966) An introduction to magnetofluid mechanics, 2nd edn. Clarendon Press, Oxford

Frankel RB (1984) Magnetic guidance of organisms. Annu Rev Biophys Bioeng 13:85–103

Iizuka T, Kotani M (1969) Analysis of thermal equilibrium between high-spin and low-spin states in ferrihemoglobin complexes. Biochim Biophys Acta 194:351–363

Kittel C (1966) Introduction to solid state physics, 3rd edn. John Wiley, New York, p 429

Melville D, Paul F, Roath S (1975) Direct magnetic separation of red cells from whole blood. Nature 255:706

Murayama M (1965) Orientation of sickled erythrocytes in a magnetic field. Nature 206:420–422

Nakano N, Otsuka J, Tasaki A (1972) Paramagnetic Anisotropy on a single crystal of deoxyhemoglobin. Biochim Biophys Acta 278:355–371

Oka S (1985) A physical theory of erythrocyte sedimentation. Biorheology 22:315–321

Paul F, Roath S, Melville D (1978) Differential blood cell separation using a high gradient magnetic field. Br J Haematol 38:273–280

Pauling L, Coryell CD (1936) The magnetic properties and structure of hemoglobin, oxyhemoglobin and carbomonoxyhemoglobin. Proc Natl Acad Sci USA 22:210–216

Shalygin AN, Norina SB, Kondorsky EI (1983) Behavior of erythrocytes in high gradient magnetic field. J Magn Magn Mater 31:555–556

Tenforde TS (1979) Magnetic effect on biological systems. Academic Press, New York

Vardanyan VA (1973) Effect of a magnetic field on blood flow. Biofizika 18:491–496