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The Trajectories of Particles Suspended in Electrolytes under the Influence of Crossed Electric and Magnetic Fields

Possible Explanation of the Sensitivity of Organism to Magnetic Fields

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Abstract. We observed that particles, suspended in an electrolyte and brought into crossed magnetic and electric fields of low intensities, will deviate in the central part of the electrophoresis chamber of a standard Zeiss Cytopherometer with a component vertical to both fields. The direction and magnitude, however, were sharply at variance with what would be expected by the action of the Lorentz force (EMF) on the surface of the particles. The magnitude of the deviation depends upon the magnetic and electric field strength, the ion concentration of the suspension medium and the geometry of the chamber. The movement of the particles is due to streaming of the electrolyte which is mainly caused by inhomogeneities of the electric field in the electrophoresis chamber. The magnitude of the effect is high enough to occur under physiological conditions. Magneto-electrophoretic streaming might eventually act as a transducer mechanism which could explain the ability of some animals to orientate themselves in the geomagnetic field.

Key words: Electric field – Magnetic field – Suspended particle – Magnetic sensitivity – Organism.

Introduction

It is well established that a number of animals, e.g. insects, birds and snails [3, 11, 15] are able to orient themselves in the magnetic field of the earth. The mechanism, however, as to how these animals get information from the magnetic field is unknown. Some time ago, we made the observation that suspended μm-sized particles, or cells suspended in an electrolyte and brought into crossed magnetic and electric fields of low magnitude (50×10^{-4} T, 5 V/cm), will experience a force in a direction perpendicular to both fields [9, 12, 13]. The direction and magnitude, however, were sharply at variance with what would be predicted by the simple application of the electromagnetic force (EMF, Lorentz force) to a single charged particle in crossed electric and magnetic fields. Because of the relatively low magnetic fields, this effect may play a role in organisms for detecting the earth's magnetic field. From this point of view, it seemed worth while to us to investigate the mechanism of this effect. We will show that the effect is independent of the particles, and that the phenomenon is due to streaming of the electrolyte caused by the geometrical conditions in the chamber.

Methods

The measurements were performed with a standard Zeiss Cytopherometer [4] with a flat rectangular chamber, the central polished part of which has the dimensions 35 × 14 × 0.7 mm (Fig. 1). To both sides of the central part, the chamber converges to a cylindrical cross-section of 2 mm diameter. If not mentioned otherwise, the particle velocity was measured in the stationary plane [14] of the chamber. All ferromagnetic parts in the neighbourhood of the chamber were replaced by diamagnetic ones. As a source of the magnetic field, a current carrying coil with an inner diameter of 58 mm, an outer one of 88 mm and a depth of 20 mm made of 230 turns of No. 20 Cu wire was put on the objective of the observing microscope.

The washed blood cells, the polystyrene beads (Dow Chemical Co., Midland/Michigan; Particle Information Service, Los Altos/California), and the metallic powder were suspended to a concentration of about 10^7 particles/ml in various electrolytes (see legends of Figs.).

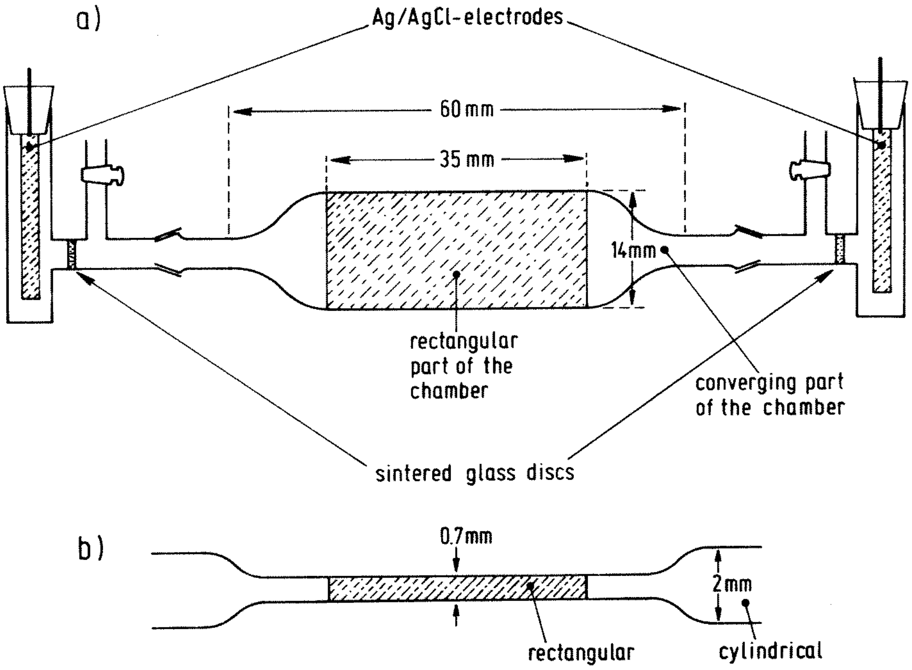

Fig. 1. Electrophoresis chamber **a)** front view, **b)** top view

Results

The standard Zeiss Cytopherometer was modified by the addition of a coil to generate a magnetic field perpendicular to the electric field. Figure 2 shows the direction of both fields and the movement of the particles with respect to the orientation of the

Table 1. Vertical and horizontal velocities of different particles in 0.1 M NaCl; E-field 6.7 V/cm, B-field 52×10^{-4} T

Particles	Velocity/E ($cm^2\ V^{-1}\ s^{-1}$) $\times 10^{-4}$	
	vertical	horizontal
Polystyrene	0.74	2.20
Au	0.79	2.01
1% Agarose	0.82	0.40
Methylcellulose	0.76	< 0.1

chamber. The component of the particle movement perpendicular to both fields will be defined as positive vertical velocity if it is oriented in direction of the z-axis. Positive horizontal velocity means the movement of particles with negative charge towards the anode. According to the EMF, the superposition of a perpendicular magnetic and electric field should give rise to a negative vertical velocity. In our chamber, however, we always observed a positive vertical velocity with a variety of different particles. Two hypotheses were investigated to explain the movement. First: The movement is due to the kind of particle suspended, and second: Streaming of the electrolyte causes the particle motion.

Concerning the particles, the deviation in the crossed magnetic and electric field was studied with

1. non-conducting particles as polystyrene beads (Table 1) of different sizes (3.5, 9.5, and 21 μm diameter), and quartz powder,
2. particles with a conducting inner part, shielded to the outside by a non-conducting membrane as erythrocytes and thrombocytes,
3. metallic particles as Au- (Table 1) [1], Fe-, Al-, and Ag-powder, and

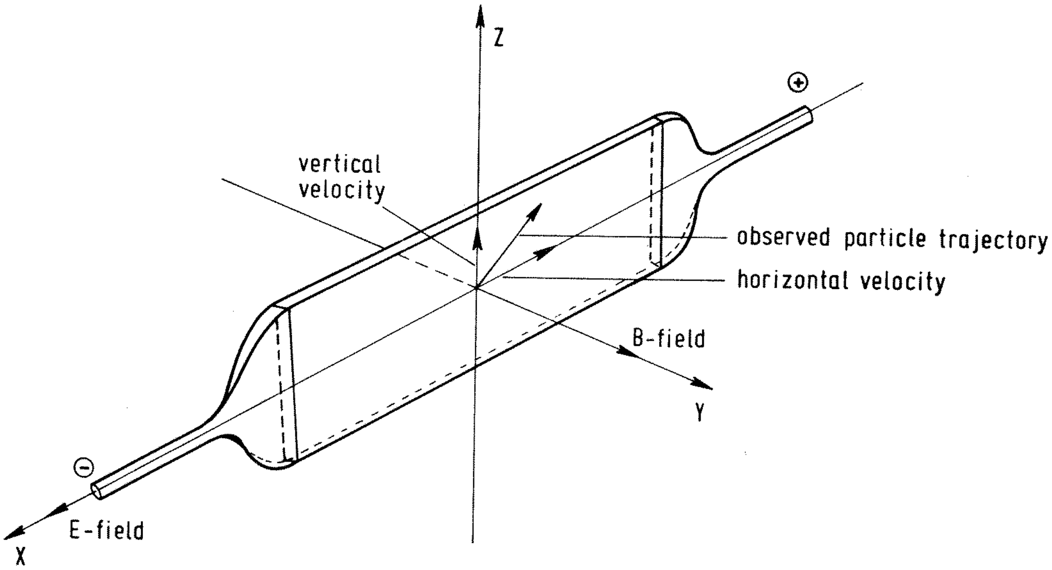

Fig. 2. Orientation of the magnetic ($\vec{B}$) and electric ($\vec{E}$) field to the electrophoresis chamber. Origin of the coordinate system in the centre of the chamber

4. particles possessing an inner conductivity, combined with a very low ζ-potential at the surface, as particles made of 1% Agarose or of methylcellulose (Table 1).

The velocities of these particles were observed near the centre of the chamber at the coordinates z=x=0 and with respect to the y-axis (Fig. 2) in the stationary plane. The vertical deviation was very similar for all particles despite of their different nature. Neither the conductivity (polystyrene-Au) nor the surface charge influenced the vertical velocity, because the sequence: polystyrene-agarose-methylcellulose showed decreasing surface potential as reflected by the horizontal velocities, but no change in the vertical velocity. Further, the effect did not depend on the size of the particles in the range of 3.5—21 μm^3.

If streaming of the electrolyte chauses the motion of the particles, the velocities should significantly vary at different locations in the chamber. Furthermore, the effect should depend on the geometry of the chamber, on the strength of both fields and of the electric current through the electrolyte of the chamber.

To investigate the dependence of the particle motion on the location in the

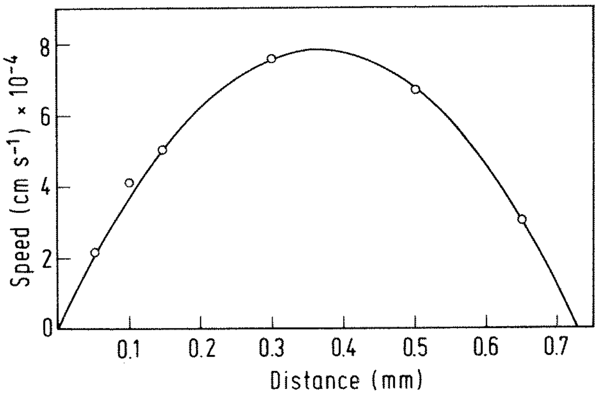

Fig. 3. Dependance of the vertical velocity of the chamber depth along the y-axis. The full line showes the parabolic curve that fits best to the measured points. Polystyrene beads of 8 μm diameter in 0.1 M NaCl, E-field 7.6 V/cm, B-field 52 x 10^{-4} T

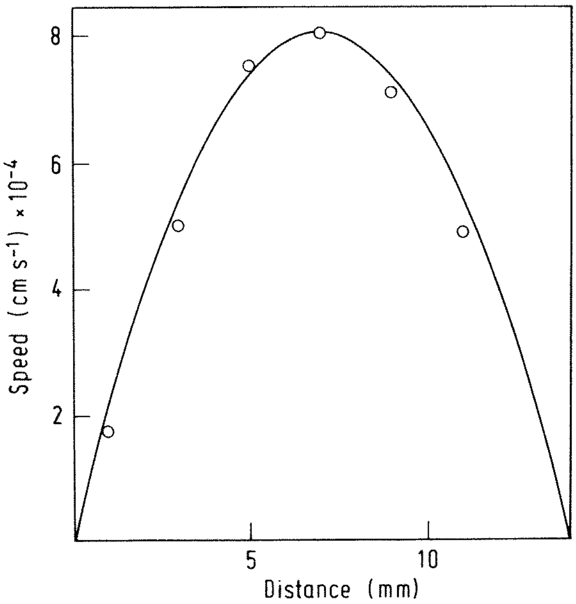

Fig. 4. Dependance of the vertical velocity of the chamber height along the z-axis. The full line showes the parabolic curve that fits best to the measured points. Polystyrene beads of 8 μm diameter in 0.1 M NaCl, E-field 7.6 V/cm, B-field 55 x 10^{-4} T

chamber, we measured the speed of the particles at different places. The first measurements, 0.5 mm right and left of the central part of the chamber along the x-axis, did not give significantly different values to the trajectories of the particles in comparison with the central point. The measurements in other parts of the chamber along the three axes, as indicated in Figure 2, showed that the vertical velocity did indeed strongly depend on the location in the chamber (Figs. 3—5).

The particle deviation was also influenced by the geometry of the chamber. If the rectangular chamber was replaced by a cylindrical one with an inner diameter of 2 mm and the same conditions of the electrolyte, particles, electric and magnetic field were used, the effect was lowered by a factor of 20.

The particle deviation finally depended on the intensity of both fields (Figs. 6 and 7), on the conductivity of the electrolyte (Fig. 8) and therefore on the current density as a function of the electric field strength and the conductivity.

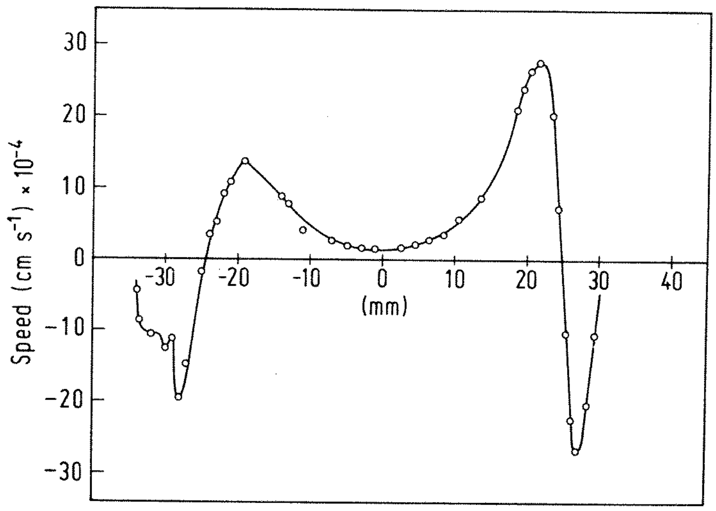

Fig. 5. Dependance of the vertical velocity of the chamber length along the x-axis. Polystyrene beads of 8 μm diameter in 0.1 M NaCl, electric current 1 mA, B-field 63 × 10^{-4} T

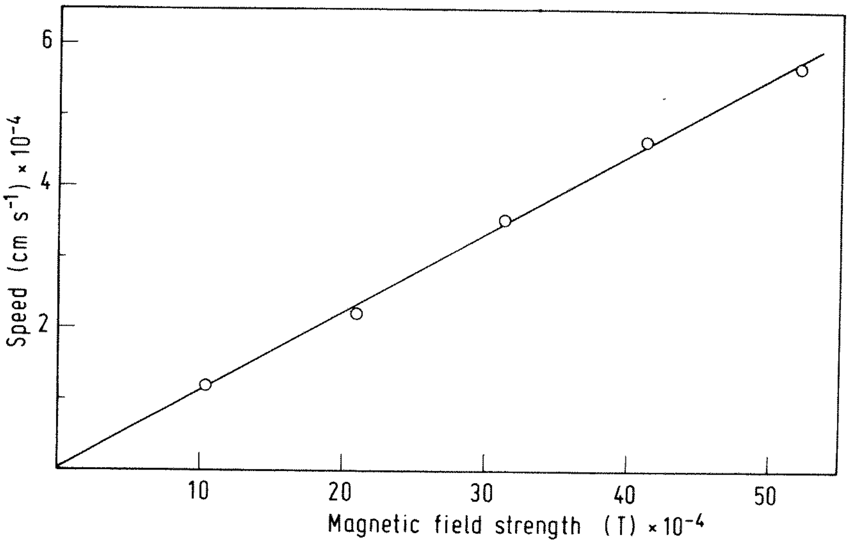

Fig. 6. Vertical velocity versus B-field. Polystyrene beads of 8 μm diameter in 0.1 M NaCl, E-field 7.6 V/cm

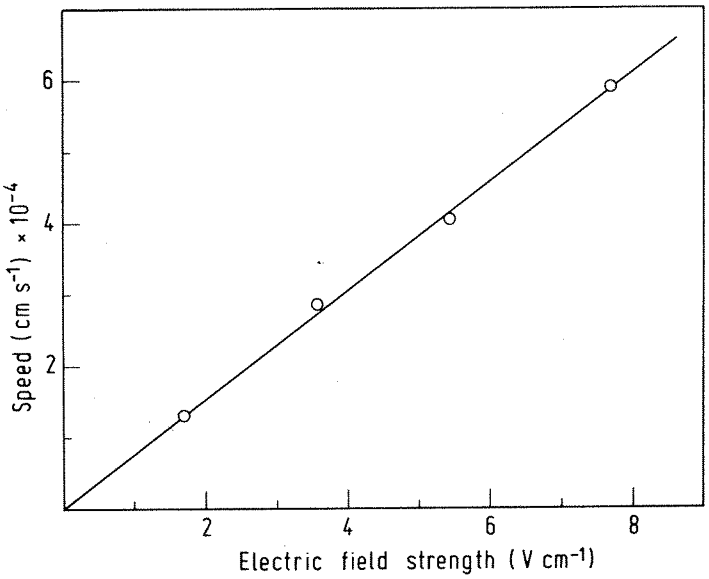

Fig. 7. Vertical velocity versus E-field. Polystyrene beads of 8 μm diameter in 0.1 M NaCl, B-field 52 × 10^{-4} T

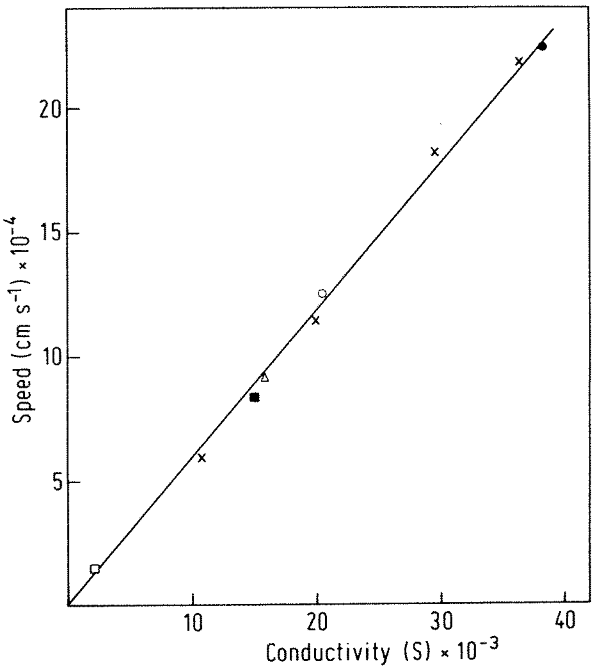

Fig. 8. Vertical velocity versus conductivity of the electrolyte. Polystyrene beads of 8 μm diameter in NaCl (×), HCl (●), NaOH (○), ampholine (□); human erythrocytes in NaCl (■); Ag-suspension in Na_2SO_4 (△). E-field 7.6 V/cm, B-field 56 × 10^{-4} T

Discussion

1. Experimental Results

All the results are compatible with streaming of the electrolyte: Neither the size nor the surface charge nor the inner conductivity of the particles influenced the particle deviation. Therefore the vertical velocity is independent of the properties of the particles. However, the vertical velocity changed considerably with the geometry and the location in the chamber. Near the glass walls, where the friction due to the viscosity of the electrolyte should reduce the speed of streaming, the vertical velocity indeed decreased towards zero, whereas it was maximal in the centre of the chamber

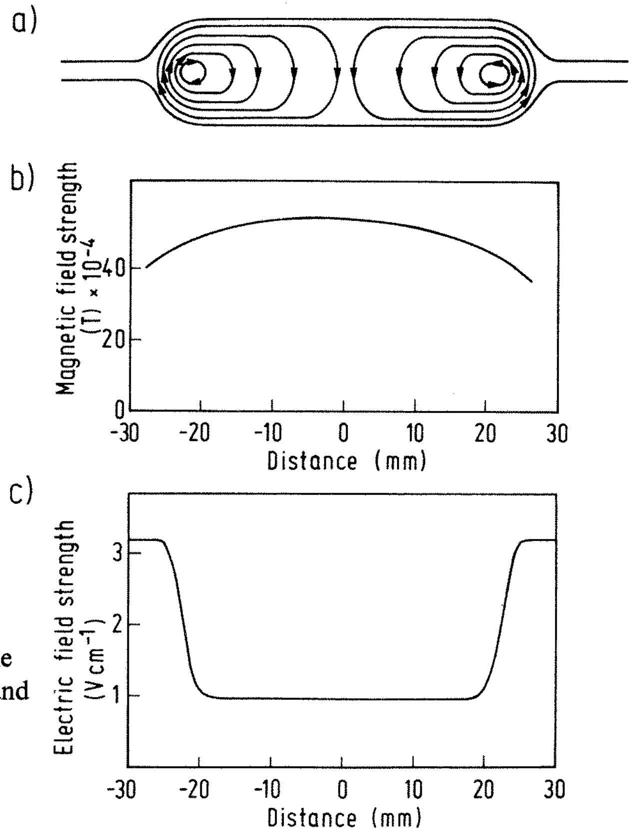

Fig. 9. Streaming model with the centres of circular streams in the converging part of the chamber (**a**). Variation of the magnetic (**b**) and the electric field (**c**) along the x-axis (0.1 M NaCl, 7 mA)

in the y- and z-direction (Figs. 3 and 4). If streaming is responsible for the movement in question, there should be a reflux in the opposite direction somewhere in the chamber. The reflux was found at the outer part of the chamber, where the cross-section of the chamber decreases rapidly (Fig. 5). The curve in Figure 5 shows marked assymmetry outside of the polished part of the chamber. This is probably explained by the unequal distances of the inner glass walls in the unpolished part of the chamber, which caused the irregularities in the speed. The measurements of the velocity at different places in the chamber are consistant with a streaming model with the centres of circular streams in the converging parts of the chamber (Fig. 9a).

From the results, it is evident that the particle motion is due to streaming of the electrolyte in the electrophoresis chamber, but the question is still open, how the streaming originates. In cell electrophoresis without a magnetic field, the electroendosmotic streaming complicates the measurement of the electrophoretic mobility of the particles. The potential difference of the glass walls to the electrolyte causes an electrical double layer on the glass surface, which gives rise to a well ordered convection parallel to the electric field along the glass walls. It returns in the middle of the chamber. In the two planes between the forward flow and the backward flow, the stationary planes, the endosmotic convection is zero and the electrophoretic mobility of the particles can be determined [14]. The endosmosis can be suppressed when the glass surface is coated with methylcellulose [6]. If a perpendicular magnetic field was applied now, the vertical velocity persisted. This proves that the particle deviation by the crossed electric and magnetic fields in the Cytopherometer is not generated by the electroendosmosis.

Streaming of electrolyte caused by crossed electric and magnetic fields has been studied by Kolin [8], Gak [5] and Mohanta [10] and is practically used to generate a stabilizing rotation of the buffer in electrophoretic continuous flow fractionation. The experimental conditions are, however, too different to compare them with the electrophoresis chamber in the cytopherometer. Our experimental arrangement is more similar to the rectangular chamber filled with electrolyte considered theoretically by Kolin [7]. Streaming due to crossed electric and magnetic fields should occur if at least one of the fields is inhomogeneous. In our experiments, the magnetic field was essentially homogeneous in the central part of the chamber and falls off by 20% within the converging part of the chamber (Fig. 9b). The electric field was homogeneous in the rectangular part of the chamber (Fig. 9c), but strongly inhomogeneous in the converging section. Maximally, the change of the electric field strength per cm in the area was 1.6 times the mean electrical field in the rectangular part. Consequently the streaming should predominantly be originated in these parts of the chamber in the direction predicted by the EMF (Fig. 9a). This was in fact the case as can be seen from Figure 5. The locally displaced electrolyte comes back to the origin of streaming in two circular streams which meet in the centre of the electrophoresis chamber (Fig. 9a).

A similar effect is expected if the magnetic field is inhomogeneous with respect to the x-z-plane (see Fig. 2). Our arrangement with a magnetic coil in front of the chamber will not produce a completely homogeneous magnetic field, but measurements of the magnetic field strength in the x-z-plane show that its deviation within the electrophoresis chamber did not exceed 20%. Moreover the movement of the magnetic coil in the x-z-plane did not change the vertical velocity of the particles. Possible influence of the inhomogeneity in y-direction on the vertical velocity could be excluded by a Helmholz arrangement of two identical coils, which produce a field without a gradient in their centre.

2. *Possible Biological Relevance*

It seems to be accepted that some animals are capable to orientate their activities in dependence of the direction of the magnetic field of the earth. No particular organ is known so far to be the receptor. Furthermore, the mechanism as to how a magnetic field is perceived by the organism, is obscure [11]. It is therefore of interest to consider if a streaming phenomenon as described above could eventually be responsible as mediator for perception, similarly as streaming e.g. is responsible for movement perception in the inner ear. The total magnetic field in central Europe is about 0.5×10^{-4} T and approximately 100 times smaller than the magnetic field in our experiments. Since the streaming is proportional to the electric current and the magnetic field, an increase of the electric current to 0.1 A/cm^2 would compensate and should yield, under the conditions of our chamber, particle velocities up to 12 μm/min.

During excitation of certain nerve cells, a sodium inflow, which equals up to 50 mA/cm^2 for about 1 ms, is observed [2]. The combination of such an electric current within a cell of suitable geometrical conditions, i.e. electrically anisotropic membrane, may produce a streaming of the inner fluid under the influence of the geomagnetic field. From these considerations, it seems important to investigate in more detail, if magneto-electric streaming occurs in cells and if it can play a mediator function in the perception of the earth's magnetic field by living organisms.

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