portionately the inhibitory tendencies postulated in connection with the various serial positions.

References

1. LEPLEY, W. M. *Psychol. Monographs*, **46**, (205), (1934).
2. HULL, C. L. *Psychol. Rev.*, **42**, 491 (1935).
3. PATTEN, E. F. *J. Psychol.*, **5**, 359 (1938).
4. HOVLAND, C. I. *J. Exptl. Psychol.*, **23**, 172 (1938).
5. *Ibid.*, **27**, 271 (1940).
6. HULL, C. L. *Am. J. Psychol.*, **45**, 730 (1933).

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An Electromagnetokinetic Phenomenon Involving Migration of Neutral Particles[1]

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Electrically neutral particles migrate in a magnetic field traversed by an electric current. The migration is perpendicular to the current and to the homogeneous magnetic field that is maintained at right angles to the current. If the electrical conductivity of the particles exceeds that of the surrounding conductive fluid, the particles migrate in the direction of the force exerted in the magnetic field upon the current. Particles of lesser conductivity than that of the surrounding fluid migrate in the opposite direction, whereas particles experience no force if their electric conductivity is equal to that of their environment.

The force of gravity, as well as the force of buoyancy exerted upon a suspended body, can be neutralized. For instance, an air bubble will not rise in acidulated water placed in a horizontal magnetic field of 10,000 oersteds traversed by a perpendicular horizontal current of 1 amp/cm^2.

Explanation of the effect. This effect is due to the establishment of a pressure gradient (analogous to the hydrostatic pressure gradient in the gravitational field) in an enclosed conductive fluid traversed by a homogeneous electric current and a homogeneous magnetic field perpendicular to that current. Each volume element of the fluid experiences a force perpendicular to the magnetic field and to the current of the magnitude

$$dF = (\mu H j)\, dV, \tag{1}$$

where μ is the magnetic permeability of the fluid, H the magnetic field strength, j the current density, and dV the fluid volume element. The force upon a finite volume V of arbitrary shape is

$$F = \int (\mu H j)\, dV = (\mu H j) V. \tag{2}$$

The expression $(\mu H j)$ corresponds to the specific weight in the hydrostatic analogy, and the force F to the weight of the volume ("electromagnetic weight," EMW). Since the fluid element V remains at rest despite the action of the force F, we conclude that an equal and opposite force is exerted upon it by the surrounding fluid. This force is comparable with the buoyancy in our hydrostatic analogy, being a consequence of the pressure field set up in the fluid by the interaction of the current with the magnetic field. We shall refer to this force as "electromagnetic buoyancy" (EMB). If the volume element V is occupied by a substance the electrical conductivity of which differs from that of the surrounding fluid, $EMW \neq EMB$ and the immersed body experiences an unbalanced force. In this case, however, a streaming of the fluid is engendered around the immersed object so that the hydrostatic forces alone do not suffice for a complete description of the effect. The following treatment is an approximation in which hydrodynamic effects are neglected.

Estimate of the force upon a sphere. The EMW of a sphere of conductivity σ_1, immersed in a fluid of conductivity σ_2 of infinite extent traversed by a homogeneous magnetic field and a perpendicular homogeneous electric current, can be estimated easily as follows: Maxwell (*Treatise on Electricity and Magnetism*, par. 313) has shown how to compute the electric field inside a sphere of conductivity σ_1 submerged in a fluid of conductivity σ_2 in which a homogeneous electric field of intensity E_2 is maintained. The electric field inside the sphere (E_1) is homogeneous and is given by the expression

$$E_1 = E_2 \frac{3\sigma_2}{2\sigma_2 + \sigma_1}. \tag{3}$$

The external field in the vicinity of the sphere is not homogeneous. Eq. (3) is valid strictly only if the sphere is negligibly small as compared to the extent of the surrounding fluid.

Eq. (3) can also be written as follows:

$$E_1\sigma_1 = E_2\sigma_2 \left(\frac{3\sigma_1}{2\sigma_2 + \sigma_1}\right). \tag{3a}$$

Since $E_1\sigma_1 = j_1$ and $E_2\sigma_2 = j_2$ are the current densities inside the sphere and in the medium, respectively, we obtain for the current density inside the sphere

$$j_1 = j_2 \left(\frac{3\sigma_1}{2\sigma_2 + \sigma_1}\right). \tag{4}$$

According to Eq. (2) the EMW of the sphere is

$$F' = \mu H j_1 V = \mu H j_2 V \left(\frac{3\sigma_1}{2\sigma_2 + \sigma_1}\right). \tag{5}$$

If we assume for the EMB exerted upon a submerged volume V the force (F'') given by Eq. (2) we obtain

$$F'' = \mu H j_2 V. \tag{2a}$$

Thus, we can write:

$$F' = F'' \left(\frac{3\sigma_1}{2\sigma_2 + \sigma_1}\right). \tag{5a}$$

The resultant force upon the sphere is

$$F = F' - F'' = F'' \left(\frac{3\sigma_1}{2\sigma_2 + \sigma_1} - 1\right) = \mu H j_2 V \left[\frac{2(\sigma_1 - \sigma_2)}{2\sigma_2 + \sigma_1}\right]. \tag{6}$$

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In general, assuming $\sigma_1 = n\sigma_2$, we can write:

$$F = \mu H j_2 V \left[\frac{2(n\sigma_2 - \sigma_2)}{2\sigma_2 + n\sigma_2}\right] = \left(\frac{n-1}{n+2}\right) 2\mu H j_2 V. \quad (7)$$

From this equation we can determine the resultant force for various special cases. For instance: For a *dielectric sphere* $\sigma_1 = 0$, so that $n = \sigma_1/\sigma_2$ vanishes in Eq. (7). Thus, we obtain

$$F = -\mu H j_2 V \quad (8)$$

as the expression for the magnitude and direction of the electromagnetic buoyancy. For a *metallic sphere* in an electrolytic fluid we can, in most cases, consider σ_2 negligible as compared to σ_1, so that $n = \frac{\sigma_1}{\sigma_2} \gg 1$. In this instance we obtain the approximation

$$F = 2\mu H j_2 V. \quad (9)$$

In the case of living cells, the conductivity commonly differs but little from that of the environment; we can then assume in Eq. (6) $\sigma_1 \simeq \sigma_2 = \sigma$, and $\Delta\sigma = \sigma_2 - \sigma_1 \ll \sigma$. We thus obtain the following approximation:

$$F = \left(\frac{\Delta\sigma}{3\sigma}\right) 2\mu H j_2 V. \quad (10)$$

The preceding calculations do not represent an exhaustive treatment but merely an approximation which, in some cases, agrees quite closely with experimental data. A complete theory should take into account the following factors: distortion of the electric and magnetic fields caused by the inhomogeneities in σ and μ introduced by the immersed body; changes in the hydrostatic pressure distribution, as well as streaming of the liquid caused by these field distortions; and, finally, the effect of the magnetic field upon the current distribution and electrolyte concentration.

Experimental determination of the force exerted

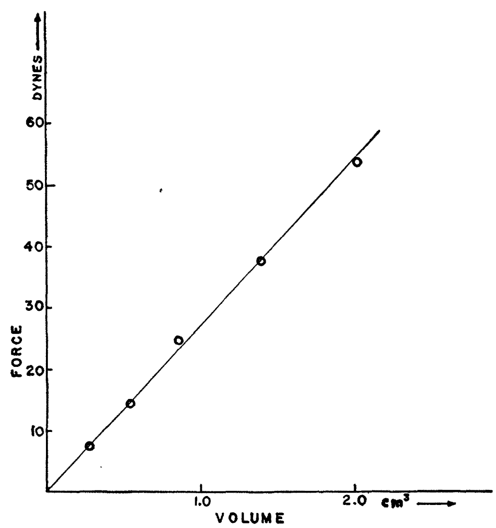

Fig. 1. Force exerted upon a glass sphere as a function of the volume of the sphere. The straight line represents predicted values; the circles indicate points determined experimentally.

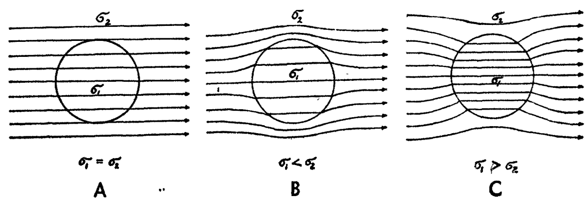

Fig. 2. Refraction of electric current lines. Distribution of current density (*A*) for a sphere with conductivity equal to that of its environment, (*B*) for a sphere of lower conductivity, (*C*) for a sphere of higher conductivity. In all cases shown the current density inside the sphere is uniform. It is decreased in case (*B*) and increased in case (*C*) as compared to *j* outside the sphere.

upon a sphere. Fig. 1 illustrates the agreement between the prediction (Eq. [8]) and experimental determination of the force exerted upon glass spheres. The spheres were suspended from a balance arm in a solution of copper sulfate, through which a horizontal current was passed ($j = 0.146$ amp/cm²) at right angles to a horizontal magnetic field ($H \doteq 1857$ oersteds). The straight line represents the predicted *EMB*. The circles indicate experimentally obtained points. The experimental values of the force agree with the predicted values within the limits of experimental error.

The checking of Eq. (9) by suspending metallic spheres in an electrolytic solution is much more difficult. A copper sphere, for instance, suspended in a solution of $CuSO_4$, experiences a force in the predicted direction—namely, opposite to the force exerted upon a glass sphere. But the magnitude of the force does not remain constant. Rather, it drops to zero within a few seconds for a current density of 0.5 amp/cm². A sustained force can be obtained using a zinc sphere in an acidulated solution of $ZnCl_2$. The value found fluctuates, however, about 60% of the value predicted by Eq. (9). The results obtained with Cu and Zn may be due to an electrolytic "fatigue effect" of the following kind.[3] Fig. 2 shows the current distribution (*A*) in the case of a sphere with conductivity equal to that of the surroundings ($F = 0$), (*B*) for a sphere of lesser conductivity than the environment, and (*C*) for a sphere with conductivity exceeding that of the surrounding fluid. Electrochemical processes on the surface of the sphere (such as liberation of gas) which tend to change the current distribution from the one pictured in Fig. 2 *C* to that of Fig. 2 *A* would tend to diminish the force exerted upon the sphere. The fatigue effect would be greatest in the region of the highest current density.

Transport of neutral bodies. The migration of bodies suspended in a conductive fluid can be demonstrated quite effectively by suspending mustard seeds and whitefish eggs in a concentrated solution of sucrose containing a small amount of an electrolyte.[4] When

[3] Effects of electrolytic processes upon the current distribution in metallic bodies submerged in current-carrying electrolytes have been described by J. Stark (*Ann. Physik*, **66**, 245 [1898]). He found that polarization may cause a redistribution of currents entering the metallic body.

[4] In order to maintain the seeds and eggs in suspension, a density gradient was created by pouring a solution free of sucrose on top of the sucrose-electrolyte solution.

TABLE 1

Radius in cm	Terminal speed in cm/sec
10^{-4}	10^{-4}
10^{-3}	10^{-2}
10^{-2}	1
10^{-1}	10^{2}

the conductivity of the solution is less than that of the fish eggs, one can see the eggs and the seeds migrate in opposite directions with a speed of the order of magnitude of 1 cm/sec at a current density of 0.1 amp/cm^2 in a magnetic field of about 2000 oersteds. Their direction of migration can be reversed by reversing the electric current or the magnetic field. The direction of migration of the fish eggs coincides with the direction of the force exerted upon the current. The direction of this migration can be reversed by increasing the conductivity of the solution sufficiently.

Table 1 shows computed values of the velocity of migration of nonconductive spheres of different sizes in an aqueous electrolytic solution in a magnetic field of 5000 oersteds at a current density of 1 amp/cm^2. The figures were obtained by substituting the value of F given by Eq. (8) in Stokes' law,

$$F = 6\pi\eta R v. \quad (11)$$

We obtain

$$v = \frac{1}{45}\frac{Hj}{\eta}R^2 \quad (12)$$

for the terminal velocity of a sphere of radius R (j is measured in amp/cm^2, and in Table 1 η is assumed to be $= 10^{-2}$ poise).

The observation of the migration of microscopic particles is much more difficult than that of macroscopic ones. This is mainly due to the difficulty of obtaining a perfectly homogeneous magnetic field. A circulation that drags mostly the smallest particles along is engendered in the electrolytic cell if the magnetic field throughout it is not sufficiently homogeneous, or if the current density is not uniform. A simple, satisfactory cell for microscopic observation can be made by drilling a narrow channel into lucite and sealing it at both ends with screws, which serve as electrodes. Placing such a cell vertically in the gap of a magnetron magnet, one can easily observe and measure the speed of migration of commercially obtainable polystyrene spheres of the order of magnitude of 10^{-2} cm in diameter.

Effect of shape and orientation of suspended bodies. A rigorous calculation of the force exerted upon the submerged body would be difficult to carry out, except for a few special cases of favorable shape and orientation. A complicating factor is the evaluation of the effect of the electromagnetically engendered streaming of the fluid upon the immersed body. So far, the effects of shape and orientation have been investigated in a purely experimental fashion.

Fig. 3 shows how the current distribution in the case of a sphere of higher conductivity than its environment (shown in Fig. 2 *C*) is altered when the sphere is distorted into a prolate (Fig. 3 *A*) or an oblate spheroid (Fig. 3 *B*). In the former case the excess of the current density inside the body over its value in the surrounding fluid is larger than for a sphere (Fig. 2 *C*), whereas in the latter case it is smaller. This excess becomes vanishingly small for a disk the thickness of which is negligible as compared to its diameter (Fig. 3 *C*). In this case the refraction of the current lines can be disregarded except near the edges of the disk (not shown in the figure). Since the current density inside the disk is nearly the same as in the surrounding fluid, we expect the force to be vanishingly small. This is confirmed by experiment. The force upon a Zn disk of $R = 0.65$ cm and thickness $h = 0.23$ cm immersed in a solution of $ZnCl_2$ was found to be imperceptible when oriented as described above.[5] When the disk was rotated through

[5] The fact that the diameter of the disk was not small as compared to the diameter of the vessel containing the fluid is partly responsible for the smallness of the observed force.

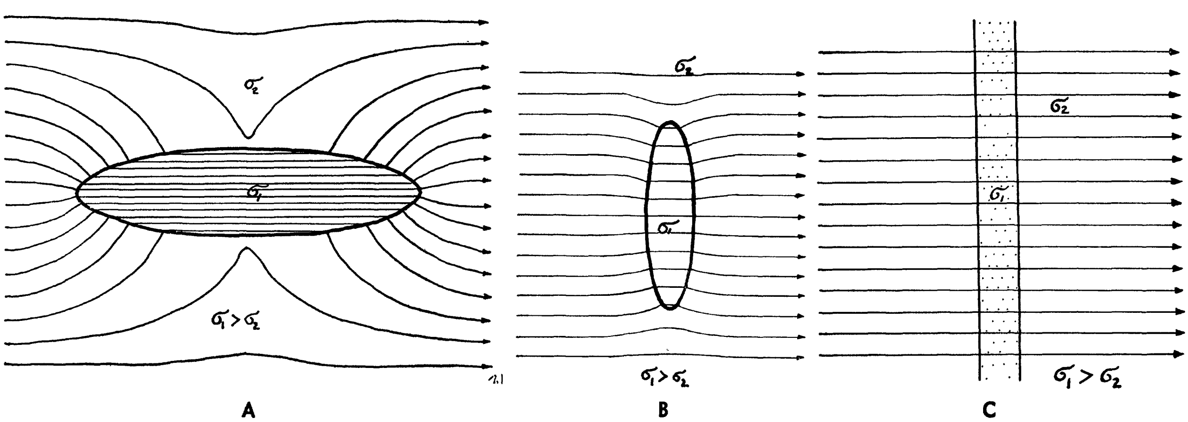

FIG. 3. Effect of shape upon the current density inside an immersed body for $\sigma_1 > \sigma_2$. In all cases shown above the current density inside the body is uniform. (*A*), prolate spheroid: The current lines are strongly refracted at the boundary of the spheroid. The current density inside is greatly increased over the value outside the spheroid. (*B*), oblate spheroid: The internal current density is only slightly increased. (*C*) Infinitely wide disk (lateral view): No refraction of current lines. Current density inside the disk is the same as outside.

TABLE 2

Body	Diameter (cm)	Height (cm)	Orientation of cylinder axis	Force measured in dynes	Computed *EMB* in dynes
Bakelite disk	1.55	0.3			
			$\parallel H$ and $\perp j$	16.1 ± 1.0	15.5
			$\parallel j$ and $\perp H$	12.0 ± 1.0	15.5
Bakelite cylinder	0.53	2.12			
			$\parallel j$ and $\perp H$	13.3 ± 0.5	12.8
			$\perp H$ and $\perp j$	9.4 ± 0.5	12.8
			$\parallel H$ and $\perp j$	1.1 ± 0.5	12.8

90° so that the magnetic lines of force entered its circular faces at right angles, a force $F = 49.0$ dynes was exerted upon it. The force computed from Eq. (9) for a metal sphere of equal volume under the same conditions is 16.7 dynes. In the latter position the disk experiences a torque that tends to set its cylinder axis parallel to the current.

With an elongated Zn cylinder, with dimensions $L = 1.70$ cm, $2\ R = 0.21$ cm (similar to *a* of Fig. 3), suspended in a solution of $ZnCl_2$, the following results were found: (*a*) When the long side is oriented parallel to the current, $F = 41.0$ dynes; (*b*) when the long side is oriented parallel to the magnetic field, $F = 0$. Force computed for a metal sphere of this volume, $F = 3.88$ dynes.

We see that the force in case (*a*) greatly exceeds the force upon a sphere of equal volume, whereas in case (*b*) it vanishes. The cylinder experiences a torque orienting its axis parallel to the magnetic field, about which it persistently oscillates.

Similar experiments were carried out with dielectric disks and cylinders. Table 2 illustrates the behavior of a disk and of a cylinder at $H = 1857$ oersteds and $j = 0.146$ amp/cm^2.

Table 2 shows that, for certain orientations of the cylinder and of the disk, the force is the same as upon a sphere of equal volume, whereas for others the discrepancy may be quite large, as indicated most strikingly by data on the last line.

The dependence of the force upon the shape and orientation is of importance in considering migration of nonspherical bodies. Such bodies tend to be oriented $\parallel H$ or $\perp H$ in a liquid even at $j = 0$ if their magnetic permeability differs from that of the liquid medium. In addition, we have the orienting torque referred to above at $j \neq 0$.

Use of alternating fields. In order to avoid undesirable electrochemical reactions at the electrodes and at the interface between the solution and the suspended particles, alternating currents have been used in conjunction with an alternating magnetic field. It is desirable that the current be as nearly as possible in phase with the magnetic field. In this case the force will not reverse direction as the magnetic field and the current do so. A reversal of the phase of the current or of the field reverses the direction of migration of the particles.

Some possible uses of this effect. Among the possible applications of this effect might be mentioned the separation of particles of nearly equal density but distinctly different electrical conductivity; for instance, cells of different tissues, algae, bacteria, and possibly viruses. In the case of two kinds of cells of different conductivity, by adjusting the conductivity of the surrounding fluid to an intermediate value, the two species can be made to migrate in opposite directions. Particles of different shapes (e.g., spherules, rodlets, and platelets) may be separated even when their densities, volumes, and electrical conductivities are the same.

The electrical conductivity of irregular bodies and of microscopic particles may be measured by finding the conductivity of a solution in which they experience no electromagnetic force. This offers the possibility of measuring the electrical conductivity of various tissues and of isolated living cells. The electrical stimulation of the cells could be avoided by using alternating fields and currents of sufficiently high frequency.[6] Such observations of variation in the electrical conductivity of active cells would be of interest in studies of changes in cell membrane permeability in response to various stimuli. Similar electromagnetic forces should be observable in high-frequency electromagnetic fields with suspensions in dielectric media.

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[6] The use of high frequencies would also be desirable for the purpose of minimizing cell membrane impedance in measurements of the cell resistance.

Intra-Ocular Hemorrhagic Reaction Induced by Ectoplacental Trophoblast in Hypophysectomized Mice

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Tubal eggs, whole blastocysts, or isolated ectoplacental trophoblast of the mouse will produce a vigorous hemorrhagic reaction when implanted into the eyes of immature or adult animals of either sex (*1–3*). The occurrence of the reaction in immature and male animals indicates that it does not have the same hormonal requirements as the marked endometrial hyperemia occurring at the normal implantation site. The question may be asked, however, whether the reaction has some other hormonal background that would be disrupted by hypophysectomy.

The ectoplacental region of 8-day C × C3H mouse embryos (early somite stages) was implanted into the right eye of 18 hypophysectomized and 10 normal