A BIOMAGNETIC HYPOTHESIS

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ABSTRACT A hypothesis is suggested to explain the inhibiting effect which magnetic fields have on the growth rate of cells. The mechanism is based on the influence a magnetic field has on the diffusion of charged particles. Electric fields originating within the cell are used to simulate an active transport mechanism. Estimates indicate that the dynamics of cells with charged cytoplasms are significantly perturbed by magnetic fields of the order of 10^5 gauss.

INTRODUCTION

Recent experimental evidence (1–9) strongly indicates that the presence of a steady magnetic field in the domain of cellular material will influence the growth dynamics of the cell. This effect has been termed by some investigators the "inhibitor effect," which is in accord with the observation that the normal growth rate is diminished. In this paper we wish to present a hypothesis which lends support to such observations.

Related mechanisms have been suggested by Bhatnagar and Mathur (10), Valentinuzzi (11), and Gross (9). The first two relate to the effects of magnetic fields on reaction rates within the cell while the latter attributes the inhibition factor to alterations in chemical bond formations due to the presence of a magnetic field.

In the present theory we assume that the growth process of cells is related to the diffusion mechanism of dissociated salts (12–14) as, for instance, across the plasma membrane from the exterior environment to and from the cytoplasm or through the nuclear membrane between the nucleus and the cytoplasm.

The discussion is divided into two parts. In the first the diffusion is depicted in its most elementary form; *i.e.,* as the free ionic diffusion across a permeable membrane. In the second approach, different types of electric fields are employed to simulate the active transport mechanism. In both cases one is most concerned with uncovering the attenuating effect on the diffusion rate which a steady magnetic field oriented normal to the direction of diffusion has. Of the various models considered, only one, that which includes a charged cytoplasm, gives positive results.

Diffusion of Ions Through a Membrane in the Presence of a Magnetic

Field. The equation governing standard diffusion processes [sometimes called Fick's law (12)] appears as

$$\frac{\partial n}{\partial t} = D\nabla^2 n \tag{1}$$

where D is the diffusion coefficient, and n is number density. If $\overline{v^2}$ is the mean square velocity of particles within the fluid and ν is their collision frequency, then to within the approximation of the above equation a good estimate for D is given by

$$D = \overline{v^2}/3\nu. \tag{2}$$

The theory holds for media whose elements are in ionized states, in which case the diffusion is of charged species such as, for instance, is the case for dissociated salts in solution. It is best suited, however, for moderate charge densities. Otherwise the phenomena of ambipolar diffusion comes into play (15).

In the event that a steady homogeneous magnetic field is embedded in the medium of transport, the diffusion process normal to the direction of the magnetic field may be strongly inhibited, owing primarily, of course, to the fact that a magnetic field will exert a force only on charged particles moving at right angles to that field. The diffusion parallel to the field, on the other hand, is unaffected.

This effect is given most simply in terms of the diffusion coefficient, 2. For diffusion normal to the fields the coefficient becomes (16, 17)

$$D_T = \frac{D_\parallel}{1 + (\Omega/\nu)^2} \tag{3}$$

where the subscript, T, denotes transverse, and $D_\parallel$, the "parallel diffusion coefficient," is given by equation (2). The Larmor frequency Ω is given by (cgs)

$$\Omega = qB/mc. \tag{4}$$

Here q is the charge of a particle, B is the magnetic field strength (gauss) and m is the mass of a particle. The collision frequency is again ν. The speed of light in vacuum is c.

A plot of $(D_T/D_\parallel)$ *vs.* B is given in Fig. 1. It is quite clear that for large enough field strength the diffusion normal to the field is greatly inhibited. It follows that

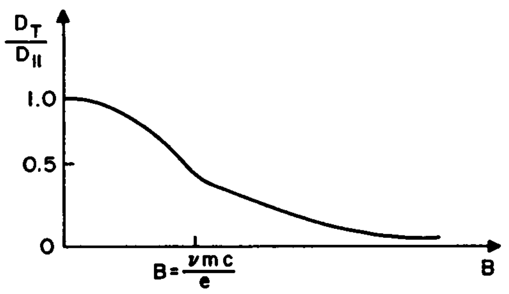

FIGURE 1 Effect of magnetic field on the transverse diffusion coefficient.

the growth dynamics of the tissue will be influenced granted that a dependence on the diffusion process exists, as stated above.

A criterion which must be satisfied in order that the stated mechanism play a role is that the Lamor radius (15) be of the order of cellular dimensions. A simple calculation indicates that a singly ionized particle of mass 30 amu at temperature 300K, will have a Larmor radius (R) of 10 μ for fields of the order of 90,000 gauss (the relation appears as (cgs) $B \approx 90/R$). These values are in the correct domain of experimental observations.

On the other hand, a measure of the effect is given by the ratio $[\Omega/\nu]$, as indicated by equation (3). In order to incorporate the fact that the domain of transport is a liquid we employ the experimental mobility of a typical ion (18) (*viz.*, 10^{-3} cm/second at 1 v/cm) and from this calculate an "effective collision frequency" (*i.e.*, if E is electric field and v is average velocity in the direction of the field, then $\nu = eE/vm$). Under similar conditions to those stated above we find that $[\Omega/\nu] \approx 10^{-9}/R$, where R (cm) is again the Larmor radius. It follows that for orbits of the order of Angstrom units the said effect becomes significant. However our previous calculation indicates that the corresponding magnetic field needed to support such a Larmor frequency becomes unreasonably large (*i.e.*, 10^{10} gauss) and the said hypothesis fails in this respect. In addition any realistic model for the diffusion mechanisms in a cell must account for the so-called active transport process which is not incorporated in this first simplified model.

In the next section we employ two types of electric fields to describe, in some small manner, the effects of an active transport mechanism.

Effects of a Magnetic Field on "Active" Diffusion Processes. Although the precise nature of the forces at play in the active diffusion process remain for the most part, uncertain, it is clear that the dominating mechanism is of an electric nature (19). To simulate such an effect in its simplest form, we consider diffusion in rod-like cells with either: (a) a uniformly charged central nucleus, or (b) a uniformly charged cytoplasm.

In both cases the Brownian motion of charged particles in the intercellular medium is examined in the presence of a steady magnetic field oriented parallel to the axis of the cylindrical shell (20) (see Fig. 2). Each example in turn has two subcases in which the Brownian particle is of like and opposite charge, respectively, compared to the charge generating the electric field.

Case a. In the problem of Brownian motion one calculates the mean square displacement $\langle r^2 \rangle$ of a particle after a time, t. In the event that a particle of charge, q, and mass, m, is moving in the vicinity of a wire of uniform charge density, ρ_L, in a viscous medium characterized by a collision frequency, ν, and in which a uniform magnetic field, B, is embedded parallel to the axis of symmetry (see Fig. 2a), the mean square displacement after an appreciable number of collisions is[1] (MKS)

[1] All subsequent diffusion rates are derived in reference 20, see also Appendix.

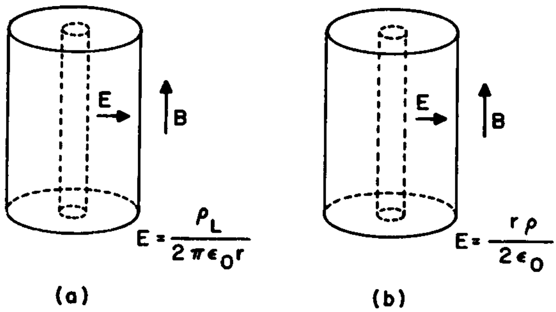

FIGURE 2 (*a*) Field orientation for uniformly charged nucleus. (*b*) Field orientation for uniformly charged cytoplasm.

$$\langle r^2 \rangle = (V^2 + C^2)t/\nu[1 + (\Omega/\nu)^2] \tag{5}$$

where:

$$V^2 \equiv q\rho_L/2\pi\epsilon_0 m \tag{6}$$

$$C^2 \equiv kT/m \tag{7}$$

$$\Omega \equiv qB/m \tag{8}$$

$$qE = mV^2/r \tag{9}$$

The permittivity of free space is ϵ_0 and t is the time. If q and ρ_L are oppositely charged then V^2 is a negative number, $-V^2$, and equation (5) becomes

$$\langle r^2 \rangle = (C^2 - V^2)t/\nu[1 + (\Omega/\nu)^2] \tag{10}$$

It follows for this subcase, that in the event the thermal speed, C, exceeds characteristic electric speed, V, the diffusion is still outward.

In either of the above two subcases we see that the mean square displacement $\langle r^2 \rangle_E$ with the magnetic field turned off is decreased by the factor

$$\langle r^2 \rangle_{EB}/\langle r^2 \rangle_E = [1 + (\Omega/\nu)^2]^{-1} \tag{11}$$

in the presence of the magnetic field. The subscript, EB, denotes that both electric and magnetic fields are in effect.

The result given by equation (5) indicates that in the present instance the macroscopic formalism of which equation (1) is a part, is still applicable. The classical Einstein relation between $\langle r^2 \rangle$ and D appears as (21)[2]

$$\langle r^2 \rangle = 4Dt. \tag{12}$$

Recalling equation (11) we see that the effect which the imposed magnetic field has on the transverse diffusion is the same as was derived for the much simpler ex-

[2] In one dimension, $\langle r^2 \rangle$ is $2Dt$, in two, $4Dt$, and in three, $6Dt$.

ample considered in the Introduction, (*cf.* equation (3)—note also that the cgs and MKS systems agree in the units of time) whence the conclusions of that investigation also apply. The magnitude of the magnetic field needed to produce results are unreasonably high.

Case b. Again we consider a rod-like cell (see Fig. 2*b*). However, in the present instance, the cytoplasm is assumed to be uniformly charged thereby creating a radial electric field, E,

$$E = (m/2q)\omega_p^2 r \tag{13}$$

$$\omega_p^2 \equiv q^2 n/\epsilon_0 m \tag{14}$$

The number density of the charged medium (number per cubic meter) is n. If a magnetic field, B, is embedded in the medium of transport parallel to cylindrical axis of symmetry then the mean square displacement, after a sufficient number of collisions becomes

$$\langle r^2\rangle = [C^2(\nu^2 + \Omega^2)/\omega_p^4 \nu t] \exp\{\omega_p^2 \nu t/(\nu^2 + \Omega^2)\} \tag{15}$$

In the subcase of Brownian particle and medium of transport oppositely charged, the particle migrates to, but not further than, a Debye distance, $C^2/|\omega_p{}^2|$ from the axis of symmetry.

Returning to the more pertinent case of particle and medium similarly charged, one notes that the mean square displacement is diminished by the factor

$$\Delta \equiv \langle r^2\rangle_{BB}/\langle r^2\rangle_B = (1 + (\Omega/\nu)^2) \exp\{-(\omega_p/\nu)^2(\Omega/\nu)^2 \nu t/[1 + (\Omega/\nu)^2]\}. \tag{16}$$

Our previous considerations indicate that for the media of interest $(\Omega/\nu) \sim B \times 10^{-11}$. For a B field of the order of 10^5 gauss, $(\Omega/\nu) \sim 10^{-6}$, still a very small number, so that Δ is well approximated by

$$\Delta \simeq \exp\{-(\omega_p/\nu)^2(\Omega/\nu)^2 \nu t\}. \tag{17}$$

A very conservative estimate for the plasma frequency of such a charged medium is $\sim 10^{17}$ sec^{-1}.[8] Inserting these values into Δ gives $\Delta \sim \exp\{-10^{-2}\nu t\}$, so that after $\sim 10^2$ collisions $\langle r^2\rangle_B$ is reduced by the factor e^{-1}, due to a magnetic field of 10^5 gauss.

Of all the models considered this latter one is most significantly influenced by the application of a magnetic field. On the other hand it is also the model which would be most difficult to conceive of in practice. As is well known, an inhomogeneous aggregate of charge embedded in a material of conductivity, σ, and dielectric constant, ε, will relax to a uniform array in the time, ε/σ. For distilled water this relaxation time is 10^{-6} second, and for petroleum, $\sim 10^4$ second. For a reasonably good conductor the relaxation time is exceedingly small (sea water $\sim 10^{-10}$ second). If the said effect is to play a role in the dynamics of the cell, the charged medium

[8] A smaller collision frequency would give more positive results.

should not change appreciably in the time it takes for Δ to diminish, which by the above calculation can be as small a time as 10^{-10} seconds, whence this criterion is reasonably well satisfied.

Conclusions and Suggested Experiments. Of the three models discussed in the previous sections the one which most satisfies the imposed criteria is that of a cylindrical cell whose cytoplasm carries some amount of net charge. A magnetic field oriented parallel to the symmetry axis of the cell may greatly inhibit the diffusion of dissociated salts through such a medium. Although data with regard to electrical properties of such material are obscure, a significant effect is seen to persist over a wide range of values (*e.g.,* conductivity, permittivity, collision frequency, etc.) for a magnetic field of the order of 10^5 gauss.

An interesting experiment which naturally suggests itself is to measure the effects on the growth of such cylindrical cells due to a magnetic field of constant strength but imposed at different angles to some chosen axis of the cell. In Fig. 3 if the

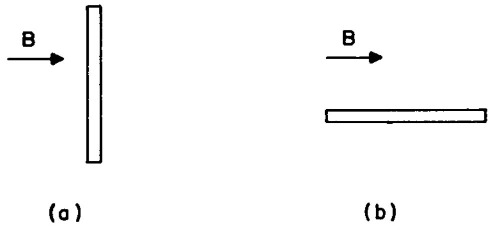

FIGURE 3 Orientation of plasma membrane with respect to magnetic field.

object shown is the plasma membrane then the B field, whose direction is given by the arrow, has little effect on diffusion rates in Fig. 3*a,* but greatly inhibits diffusion in Fig. 3*b*. This effect may, under certain conditions, exhibit a selection amongst the cells which would result in a net perpendicular orientation with respect to the field after a few generations. Inasmuch as the experiment involves cells, *in vitro,* it should be noted that similar observations would be found for properly prepared cellular tissue. In this case the diffusion process is intracellular, through the plasma membrane. Positive results would, of course, lend strong inductive support to the included hypothesis.

APPENDIX

OUTLINE OF DERIVATION OF MEAN SQUARE DISPLACEMENT FACTORS

The equation of motion of an isolated "test" charge in a viscous medium in which electric and magnetic fields are embedded appears as

$$m\ddot{\mathbf{r}} = q\dot{\mathbf{r}} \times \mathbf{B} + q\mathbf{E} - \nu m\dot{\mathbf{r}} + \mathbf{\Gamma} \tag{1}$$

In this equation dots represent time derivatives, m and q are the mass and charge of the Brownian particle respectively, and $\mathbf{E}$ and $\mathbf{B}$ are the imposed fields. The magnetic field is taken to be in the "z" direction, while $\mathbf{E}$ is radial. The interaction between the particle and the medium is given in terms of the collision frequency, ν, and the stochastically fluctuating field, $\mathbf{\Gamma}$, characteristic to Brownian motion.

It is readily shown that equation (1) implies,

$$(r^2)'' - 2\dot{r}^2 + \alpha(r^2)' - 2(q/m)\mathbf{E}\cdot\mathbf{r} - 2\mathbf{\Gamma}\cdot\mathbf{r} + \left(\frac{2\Omega}{\nu}\right)\mathbf{b}\cdot\{(q/m)\mathbf{r}\times\mathbf{E} + \mathbf{r}\times\mathbf{\Gamma} + (1/m)\mathbf{F}\times\mathbf{r}\} = 0 \quad (2)$$

In this equation, primes have replaced dots,

$$r^2 \equiv \mathbf{r}\cdot\mathbf{r}, \quad (2a)$$

$$\alpha\nu \equiv \nu^2 + \Omega^2, \quad (2b)$$

$$\Omega \equiv qB/m, \quad (2c)$$

and $\mathbf{F}$ is the instantaneous force field,

$$\mathbf{F} = m\ddot{\mathbf{r}}. \quad (2d)$$

The unit vector, $\mathbf{b}$, is in the direction of $\mathbf{B}$. Since the electric field is radial, $\mathbf{E}$, at the point, $\mathbf{r}$, is in the direction of, $\mathbf{r}$, whence $r \times \mathbf{E}$ vanishes, while $\mathbf{E}\cdot\mathbf{r} = Er$. Equation (2), still in exact form then reduces to,

$$(r^2)'' - 2\dot{r}^2 + \alpha(r^2)' - 2(q/m)Er - 2\mathbf{\Gamma}\cdot\mathbf{r} - (2\Omega/\nu)\mathbf{b}\cdot[(\mathbf{r}\times\mathbf{\Gamma}) + (1/m)(\mathbf{F}\times\mathbf{r})] = 0 \quad (3)$$

Our primary interest at this point involves the mean square displacement.

$$\delta \equiv \langle r^2\rangle = \frac{1}{t}\int_0^t r^2(\eta)\,d\eta, \quad (4)$$

in the limit $\nu t \gg 1$; *i.e.*, after many "collisions" have taken place. The inverse of the latter equation is

$$(t\delta)' = r^2, \quad (5)$$

so that although r^2 is uniquely determined by δ, knowing r^2 determines δ, only to within an additive factor K/t where K is any constant.

Inserting equation (5) into equation (3) gives,

$$(t\delta)''' + \alpha(t\delta)'' - 2(q/m)Er = 2(t\langle\dot{r}^2\rangle)' + 2(\Omega/\nu)[(t\langle\mathbf{b}\cdot\mathbf{r}\times\mathbf{\Gamma}\rangle)' - (1/m)(t\langle\mathbf{b}\cdot\mathbf{r}\times\mathbf{F}\rangle)'] + 2(t\langle\mathbf{\Gamma}\cdot\mathbf{r}\rangle)' \quad (6)$$

This equation together with the relation (4), is still in exact form. Due to the vector products however, it is not self-contained. But clearly the random property of $\mathbf{\Gamma}$ implies that it exerts no net average torque about the origin. Therefore $\langle\mathbf{b}\cdot\mathbf{r}\times\mathbf{\Gamma}\rangle = 0$. More generally if $\mathbf{\Gamma}$ and $\mathbf{r}$ are assumed to have random phases then, $\langle\mathbf{r}\cdot\mathbf{\Gamma}\rangle$ also vanishes. In addition, the diffusing particle does not have a preferred sense of rotation about the origin whence $\langle\mathbf{b}\cdot\mathbf{r}\times\mathbf{F}\rangle$ also vanishes. Finally replacing $\langle\dot{r}^2\rangle$, with the mean square thermal speed, C^2, (a valid approximation only if the mean electric energy gained between collisions is small compared with kT) gives,

$$(t\delta)''' + \alpha(t\delta)'' - 2(q/m)Er = 2C^2 \quad (7)$$

This is the desired starting equation. Application to two relevant cases follows.

Motion About a Charged Axis. In this first example we consider the Brownian motion of charged particles about a straight uniformly charged wire which is parallel to a constant uniform magnetic field. If ρ_L is the charge density of the line (coulombs per meter) then equation (7) takes the form,

$$(t\delta)''' + \alpha(t\delta) = 2\beta^2 \equiv 2[(q\rho_L/2\pi\epsilon_0 m) + C^2] \equiv 2[V^2 + C^2] \quad (8)$$

The solution is

$$t\delta = A + Fe^{-\alpha t} + (\beta^2/\alpha^3)[(\alpha t)^2 + D(\alpha t)] \quad (9)$$

where A, F, and D are constants of integration. If one imposes the initial condition that the particle move uniformly in early times, equation (9) reduces to,

$$(\alpha^2/2\beta^2)\delta = (1/y)(1 - e^{-y}) + \frac{(y-2)}{2} \quad (10a)$$

$$y \equiv \alpha t \quad (10b)$$

In the limit as $\nu t \gg 1$, $\alpha t \gg 2$ and equation (10) becomes, in explicit form,

$$\langle r^2 \rangle \simeq (V^2 + C^2)t/\nu[1 + (\Omega/\nu)^2] \quad (11)$$

which is equation (5) in the text.

Motion in a Uniformly Charged Cylindrical Medium. In this second example the cylindrical geometry is uniformly filled with a viscous medium of constant charge density. A steady magnetic field oriented parallel to the axis of symmetry permeates the medium. Equation (7) appears as,

$$(t\delta)''' + \alpha(t\delta)'' - \omega_p^2(t\delta)' = 2C^2 \quad (12a)$$

where ω_p is an effective plasma frequency and is given by,

$$\omega_p^2 \equiv q^2 n/\epsilon_0 m. \quad (12b)$$

The number density of the medium of transport is n, while for convenience, the unit of charge of the medium, q, is taken to be the same as that of the test particle.

The solution to equation 12 is,

$$(\omega_p^2/C^2)(t\delta) = A(e^{D_+ t} - 1) + F(e^{D_- t} - 1) - t \quad (13)$$

where the exponents are the roots,

$$2D_\pm = -\alpha \pm \sqrt{\alpha^2 + (2\omega_p)^2} \quad (14)$$

Imposing the initial condition that the particle move uniformly in early times, determines the constants, A and F,

$$A = \frac{D_-}{D_+(D_- - D_+)} \quad (15a)$$

$$F = \frac{D_+}{D_-(D_+ - D_-)} \quad (15b)$$

Again going to the limit $\nu t \gg 1$, equation (13) reduces to,

$$\langle r^2 \rangle \simeq (C^2\alpha/\omega_p^4 t) \exp \{\omega_p^2 t/\alpha\}, \tag{16}$$

which is equation (15) in the text.

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