ISSN 0029 - 3865

CBPF-NF-029/87

AN UPPER SIZE LIMIT TO MAGNETOTACTIC MICROORGANISM

by

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Abstract

Using some arguments based on theoretical considerations and observational analysis we obtain an upper size limit to magnetotaxis as an orientational mechanim..

Key-words: Magnetotaxis; Microorganisms; Magnetism; Behaviour; Biophysics.

Magnetotaxis is the best known orientational mechanism because the interaction between the organism and the magnetic field is well understood. It shows some particular characteristics: first, all magnetotactic microorganisms found until now have a passive orientation, that is, cells orient themselves under an external magnetic field[1]; second, in contrast with chemotaxis (or phototaxis) in which the organism needs to swim to compare changes of environmental chemical concentrations (or ligth intensities), the magnetotaxis depends only on the absolute local magnetic field (all the three components of the vector field)[1,2]; third, all the magnetotactic organisms have high density geometrical regions when observed on the electron microscope[3,4]. These regions are enveloped by a membrane and composed by magnetic material, possessing a permanent magnetic moment. In this sense, magnetotactic microorganisms are also magnetic organisms.

Mössbauer spectroscopy of *A. magnetotacticum*[5] shows that the magnetic crystals found inside the cytoplasm are magnetite crystals. Dimension measurements, X-ray analyses and electron diffraction of crystals found in many magnetotactic bacteria show that these crystals are single crystals and magnetic single domains[6,7].

The magnetotaxis phenomena is more common than believed to be some years ago, and now, we know a great number of different morphological types of microorganisms including coccus, spirillum and rod bacteria, algae, aggregates or colonies[8;9].

In this work we focuse on one question that arises when we begin to observe the magnetotactic response of microorganisms.

How large can a microorganism be to have a passive magnetic response?

Magnetic response in several species, including mammalias, has been reported by several authors[10]. This response, however, is subtle and occurs only when the organism is alive. The passive response observed in magnetotactic organisms can be explained using torques, forces, viscosity and magnetic interaction.

Magnetotaxis is seen, today, as an orientational mechanism of microorganisms; these microorganisms swim to deep regions where there are nutrients and the oxygen pressure is smaller than on the surface[2,11]. For an effecient orientation it is assumed that the magnetic interaction energy must be ten times the thermal energy, i.e., $mB/kT \gtrsim 10$, where $\underline{m}$ is the magnetic moment of the whole organism, $\underline{B}$ is the intensity of the magnetic field and kT is the thermal energy. Under this condition there is a total orientation which means that the mean migration velocity $\langle v \rangle$, is very near the instantaneous organism velocity, v_o. Assuming a statistical distribution for an ensemble of non-interacting dipole magnetic moment of microorganisms then:

$$\langle v \rangle = v_o \langle \cos\theta \rangle = v_o L(mB/kT) \qquad (1)$$

where $L(x) = \coth(x) - 1/x$ is the Langevin function of classic paramagnetism, θ is the angle between the magnetic dipole and the magnetic field, and $\langle \cos\theta \rangle$ is the mean orientation. For $mB/kT \sim 10$ we obtain $\langle v \rangle \sim 0.9\, v_o$.

The time τ_o that a microorganism takes to make the U-turn

when the field is suddenly reversed is given, by the C. Bean model[11]:

$$\tau = \frac{8\pi\eta R^3}{mB} \ln\left(\frac{2mB}{kT}\right) \qquad (2)$$

where η is the medium viscotity (for water, $\eta_{H_2O} = 10^{-2}$ Poise) and R is the effective radius of the microorganism . For the local geomagnetic field B_g the reversal time is τ_g.

The diameter of the U-turn is given, in this model, by:

$$L = \frac{8\pi^2 R^3 v_o \eta}{mB} \qquad (3)$$

We can measure, in the laboratory, the mean velocity <v>, the time τ and diameter L, using a slow-motion picture system or a dark-field photo equipament. Using eqs. (2) and (3) or fitting eq(1) for different B's, we can obtain m.

The C. Bean' model does not take into account any contribution due to the flagellar motion, water flow, fluctuations, currents, etc.... These factors contribute to a deviation from the linear trajectory adopted by this model and change the reorientation time of the organism.

For a microorganism in its habitat, the critical situation occurs when its orientation is disturbed by a perturbation of the medium, or flagellar beat, etc. and it assumes an orientation in which its magnetic moment is antiparallel to the local magnetic field. In this case the time for reorientation, within the approximations considered, is given by the U-turn time, eq. (1). The time τ_g is, then an important factor for

a magnetotactic microorganism and is dependent on the ratio between the magnetic and thermal energies, and the size of the organism.

The time interval for the microorganism to return to the condition in which its magnetic moment m is parallel to the local field B must be less than the time interval between two critical perturbations of the environment. Only in this case magnetotaxis will be an efficient mechanism for orientation. We are using the term critical perturbation to characterize an intense perturbation which has conditions to reverse the microorganism orientation. In this sense a critical perturbation is related to the size of the organism. Assuming randomic perturbations, the time interval between two critical perturbations for a large microorganism is greater than for a small microorganism. Small organisms are more affected by a medium disturbance and a flagellar beat than the larger ones. Critical perturbations are not only a characteristic of the environment but, also of the specific microorganism.

Equation (2) shows that τ depends on the volume (R^3) of the microorganism linearly and is a m function of the form $\alpha m^{-1} \ln \beta m$ (where $\alpha = 8\pi\eta R^3 B^{-1}$ and $\beta = 2B\, k^{-1} T^{-1}$ are constants for a given organism, medium and magnetic field). The magnetic moment is related to the volume of magnetic material found inside the organism and depends on how the magnetic moment of each crystallite is oriented with respect to each other. We assume that the percentage of magnetite, A, inside the microorganism is constant and all the magnetic regions have parallel magnetic moments. This is not a strong assumption for A be-

cause we have observed in several different bacteria that A does not change much. With this hypothesis the total magnetic moment of a spherical organism is:

$$m = A\left(\frac{4\pi}{3} R^3\right)M \tag{4}$$

where M is the magnetization per unit volume for the magnetite (M = 480 c.g.s.). A is defined as the ratio between the total volume of magnetite and the total volume of the cell. The U-turn time is:

$$\tau = \frac{6\eta}{AMB} \ln\left[2\left(\frac{4\pi R^3}{3}\right)\frac{AMB}{kT}\right] \tag{5}$$

Eq. (4) shows that, in this case, τ varies logarithmically with the volume or $\tau \propto \ell nV$, where $V = 4\pi R^3/3$ is the total volume of the organism.

If condition expressed by eq. (3) is ignored and it is assumed that the ratio between magnetic and thermal energies is constant, i.e. (mB/kT = constant) τ is linear with V:

$$(\tau \propto V) \tag{6}$$

In both cases (i.e., A constant or mB/kT constant) the time τ increases with V. If $\tau_g > T_c$, where T_c is the typical time between two critical perturbations, then it will be impossible for the organism to reorient in the field; this means that there is an upper limit to $\tau_g \ll T_c$ and this implies that there is also an upper limit to the size (volume) of the

organism for which magnetotaxis would be efficient.

Experimental data (1,3,8,11,12) for several magnetotactic microorganisms found in sediments are presented in table 1 and we can estimate the value for A. One point must be emphasized: all measurements were made using natural samples without any chemical enrichment; if we adopt some enrichment process we do not guarantee that the magnetic moment of the organism is the same those found in its natural habitat. We note that A comes to decrease when V increases. The only clear exception is the algae *Anisonema*[13]. In this case m was calculated based on measurements made for τ_g with dead cells at magnetic fields between 0.5 to 2.0 G and fitted with the theoretical curve. This procedure is very sensible with τ and B and it could increase m and, consequently, A.

Figure 1 shows the relation between τ_g and V for $B_g = 0.25G$ (Rio de Janeiro's magnetic field). Curve (A): assuming mB_g/kT constant and equal to 1(i.e., $m = 1.6 \times 10^{-13}$ e.m.u.). Curve (B) is the least-square fitting of experimental data to a logarithm curve of the form $\tau = a + b\ell nV$ (We disregard point 9, the *Anisonema* algae, and we obtain $\tau = -1.91 + 5.20\ \ell n\ V$ with coefficient of determination equal to 0.85. This corresponds to $A \sim 10^{-4}$). Curve (C) is the limiting time curve for $\tau = T_c =$ 60 sec. The choice of T_c is somehow arbitrary since it depends on the particular habitat and on the dimensions of microorganism, etc. We can, however, estimate a value for T_c using considerations of adequability. First: magnetotactic microorganisms are found at depth of order of some tenth of centimeter (20 -50cm) in lagoons, streamlets, brooks, bays, etc...

At this depth we observe that disturbances on water surface produce small disturbances at sediments. Waves, winds and tides contribute to disturb the trajectory of microorganisms and to give periodical informations about external environment. Second: we find magnetotactic microorganisms in regions which are very populated by several others microorganisms, as protozoa, algae, ... The optical observation of living samples shows an intense activity. The collisions among organisms or the disturbances due swimming organisms are frequent. If the optical observation is made at the center of the drop, a region more realistic than the end of the drop, we observe that, in addition to the collisions among organisms, we have the influence of small grits modifying the trajectory of these organisms. The mean time between these collisions is about a fraction of minute (it depends on the velocity of the organism, dimensions and shape of grits, ...) We choise T_c = 60 sec as a limiting value for the critical time. (We can argue that T_c is greater or smaller than this value but this is not important since a limiting value of τ corresponds to a limiting value for V). Figure 1 shows that T_c = 60 sec, curve (C), intercept the curve (B) at a volume approximately $1.6 \times 10^5 \mu m^3$, which corresponds to a spherical microorganism with radius about 35μm. With dimensions of this order we found swimming microorganisms belonging to several orders. At this region of volume we observe the growth of multicellular organisms and specialised colonies.

Magnetotactic response in Volvocaliae was reported in two different families: in Chlamydomonadaceaes[14] and in Volvocaceaes[15]. In the case of *Volvox*[15] the experiment shows an

intrincate response to the magnetic field without similarities with magnetotactic response. *Volvox* are large colonies with typical volume of about $10^6 \mu m^3$ and we may expect an elaborated magnetic response. In *Chlamydomanas* [14], however, we find a direct and passive response, identical to all magnetotactic microorganisms reported. These algae has volume of order of $10^2 \mu m^3$ and the reversal time is plotted in figure 1 (point 10).

Another direct conclusion is that the ratio mB/kT increases with the volume. If this does not occur, the U-turn time will increase rapidly with the increase of dimension.

In conclusion the biological efficience of magnetotaxis depends on:

a) the ratio mB/kT. Greater organisms need a greater ratio than smaller ones to respond in a time interval smaller than the critical time.

b) the fundamental parameter, the time τ. We expect this time is characteristic of the medium, or that the organisms found in different habitats can present different magnetic properties.

Acknowledgements: We wish to thank Dr. Eliane Wajnberg for valuable discussions and participation on this subject.

CAPTION FOR FIGURES AND TABLES

Figure 1 - Reversal time (τ_g) for geomagnetic field ($B_g = 0.25G$) versus volume of microorganism for several magnetotactic microorganisms found in the literature. Points 1, 2,3,4 and 6 correspond to bacteria collected in several different places[8,9]. Points 5 and 7 correspond to an unidentified colony or aggregate described in in references 1,4,8 and 9. Point 8 corresponds to a large magnetotactic microorganism reported at references 8 and 12. Point 9 corresponds to an algae *Anisonema* described in reference 13. Point 10 corresponds to an algae *Chlamydomonas* described in references 1 and 14. Curve (A) - constant ratio between magnetic and thermal energy and equal to 1. ($mB_g/kT = 1$). This corresponds to a magnetic moment $m = 1.6 \times 10^{-13}$ e.m.u..
Curve (B) - Least-square fitting of experimental points: $\tau = -1.91 + 5.20\ \ell n\, V$. This curve is in agreement with $A \sim 10^{-4}$.
Curve (C) - $\tau_g = T_c = 60$ sec.

Table 1 - Some characteristics of ten magnetotactic microorganisms found in brazilian waters. Organisms 5,7 and 8 are not classified yet. A is given by eq. (3). (The volume and τ_g presented here are different from ref. 8 and 9. In refs. 8 and 9 we aproximate the organism to a sphere with mean radius $\langle R \rangle$). τ_g is the reversal time in the geomagnetic field $B_g = .25G$. A is the percentage of magnetite defined by eq. (3).

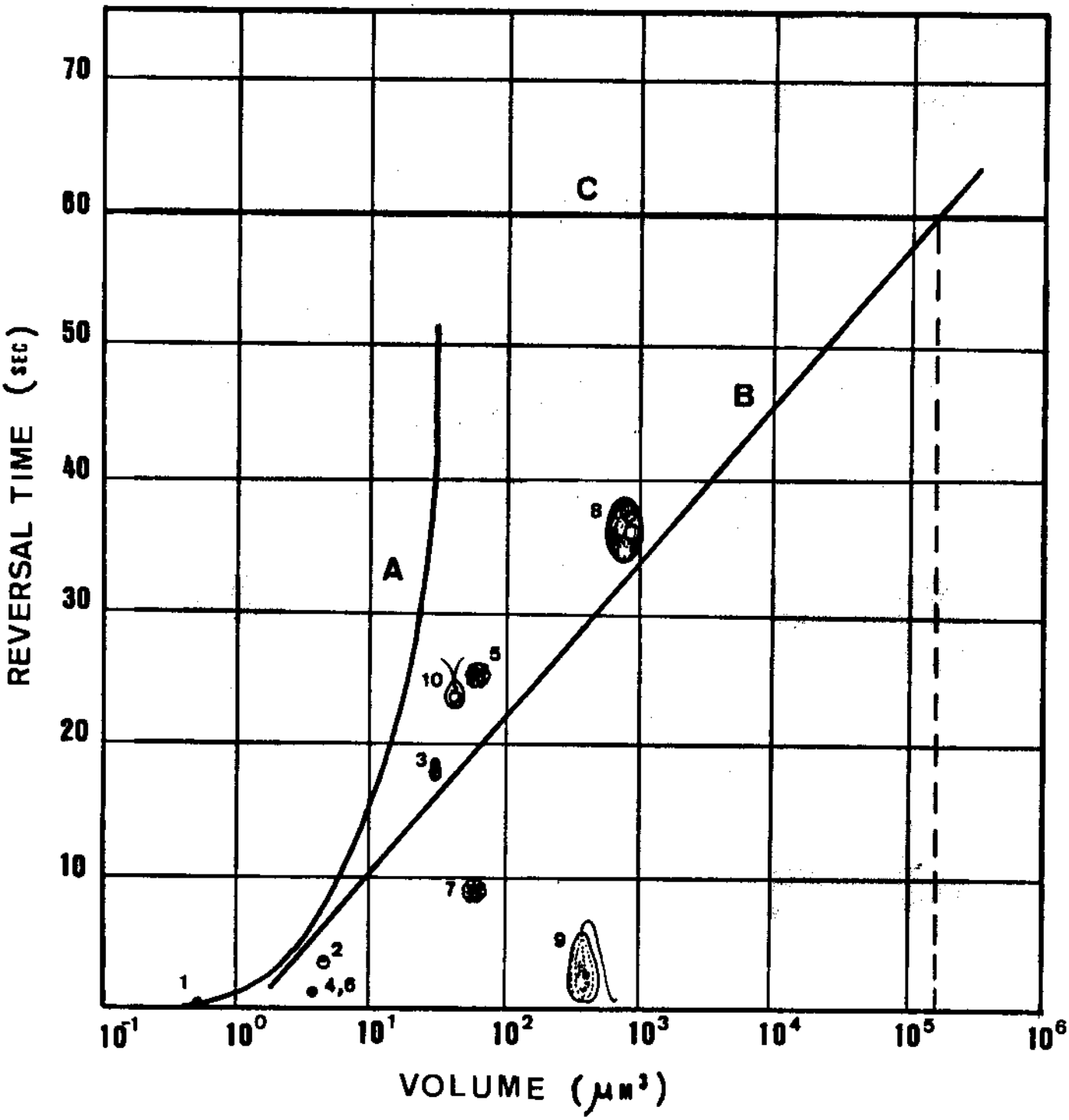
REVERSAL TIME (sec)
70
60
50
40
30
20
10
C
B
A
8
10
5
3
7
9
1
2
4,6
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
VOLUME (μm^3)

Figure 1

	CHARACTERIZATION	REFERENCE	DIMENSION (μm)	VOLUME (μm^3)	MAGNETIC MOMENT (10^{-12} emv)	τ_g (sec)	A
1	COCCUS BACTERIA	8,9	DIAMETER= 1	0.5	0.4	0.5	1.7×10^{-3}
2	COCCUS BACTERIA	8,9	DIAMETER= 2	4.2	0.6	3.6	3×10^{-4}
3	BACTERIA	8,9	3 x3 x5	35.3	1.	18.5	6×10^{-5}
4	COCCUS BACTERIA	8,9	DIAMETER= 1.8	3.1	1.4	1.5	9.4×10^{-4}
5	UNKNOWN	4,8,9	DIAMETER= 5	65.5	2.4	25.	7.6×10^{-5}
6	COCCUS BACTERIA	8,9	DIAMETER= 1.8	3.1	1.3	1.5	8.7×10^{-4}
7	UNKNOWN	4,8,9	DIAMETER= 5	65.5	8.	8.9	2.5×10^{-4}
8	UNKNOW	8,9	10x10x18	706.	54.	37.	1.6×10^{-4}
9	ANISONEMA	13	4x12x20	3376.	1550.	3.	8.6×10^{-3}
10	CHLAMYDO-MONA	1,14	DIAMETER= 6	113.	4.7	24.	8.7×10^{-5}

Table 1

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