Reply to "Comment on 'Constraints on biological effects of weak extremely-low-frequency electromagnetic fields' "

Robert K. Adair
Department of Physics, Yale University, P.O. Box 6666, New Haven, Connecticut 06511
(Received 6 March 1992)

Kirschvink [preceding Comment, Phys. Rev. A **46**, 2178 (1992)] objects to my conclusions [Phys. Rev. A **43**, 1039 (1991)] that weak extremely-low-frequency (ELF) electromagnetic fields cannot affect biology on the cell level. He argues that I did not properly consider the interaction of such fields with magnetite (Fe_3O_4) grains in cells and that such interactions can induce biological effects. However, his model, designed as a proof of principle that the interaction of weak 60-Hz ELF fields with magnetite domains in a cell can affect cell biology, requires, by his account, a magnetic field of 0.14 mT (1400 mG) to operate, while my paper purported to demonstrate only that fields smaller than 0.05 mT (500 mG) must be ineffective. I then discuss ELF interactions with magnetite generally and show that the failure of Kirschvink's model to respond to weak fields must be general and that no plausible interaction with biological magnetite of 60-Hz magnetic fields with a strength less than 0.05 mT can affect biology on the cell level.

PACS number(s): 87.50.Eg, 87.22.Bt

Kirschvink [1] argues that I have left a "gaping hole" in my didactic paper [2], titled "*Constraints on biological effects of weak extremely low-frequency (ELF) electromagnetic fields*" inasmuch as he considers my discussion of the interaction of such fields with biologically produced magnetite (Fe_3O_4) inadequate. In fact there are no factual errors of commission in the two paragraphs that I devote to that subject and I hold that there are no substantive errors of omission—or gaping holes. My paper, generally, addressed the interaction of the weak 60-Hz fields of our environment with human cells and concluded that such interactions are much too weak to have biological consequences. I defined *weak magnetic fields* in my paper as "field strengths no greater than 50 μT (or 0.5 G), the strength of the earth's field." Kirschvink's arguments that the interaction of three-times larger fields (of 0.14 mT) with biological magnetite may affect biology at the cell level are then not in contradiction to my findings.

I first diverge from consideration of Kirschvink's model calculations, which I consider the heart of his *Comment,* to respond to some of his specific criticisms. In the second paragraph of his *Comment* he says, "Adair's discussion implies that only the magnetotactic bacteria are able to precipitate ··· magnetite." Such an implication can only follow from a misreading of my two paragraphs devoted to this subject. The material in those paragraphs was largely derived from my study of the review by Frankel [3] (Ref. [8] in my paper) which addressed the evidence for magnetite in other life forms at length.

Then, Kirschvink views, as "inaccurate," my statement, written in a context which refers to the weak 60-Hz fields in the environment; "After 20 years of experimentation, no significant effect of weak ELF fields at the cell level has been firmly established." He continues: "Thus, a convincing demonstration of behavioral sensitivity to weak magnetic fields in *any* animal is enough to falsify Adair's assertion" and goes on to refer to the magnetically influenced behavior of the honeybee which he says is well established and, hence, "falsifies" my statement. In my paper, I discuss known effects on the behavior of magnetotactic bacteria induced by moderately weak constant magnetic fields and refer to the effect of very weak constant electric fields on the behavior of sharks. I chose to discuss, as an example, the behavior of magnetotactic bacteria instead of honeybees for reasons that Kirschvink himself states clearly in another paper [4], "many responses ··· like honeybee waggle dances ··· have [not] yet approached the level of clarity and simplicity displayed in experiments with the magnetotactic bacteria, which is the best example of geomagnetic sensitivity in any living organism."

I find Kirschvink's section, "*Biophysical Model of Magnetite and ELF Magnetic Fields*" more to the point. Here he proposes a specific model (his Fig. 1) of biological effects of the interactions of ELF fields with cellular magnetite in an attempt to forge a proof-of-principle of his thesis that "ELF magnetic fields at the cellular or subcellular level might lead to significant effects." But his model, designed such that the interaction of an ELF field on a magnetosome will open an otherwise closed ion channel in a cell membrane, requires moderately strong fields. As he comments, "At the powerline frequency of 60 Hz, the critical ELF field for opening the channel is 0.14 Mt (1.4 G)." But I have never claimed to *prove* that fields of this magnitude cannot induce biological effects; 0.14 mT is larger by about a factor of 3 than the canonical field of 0.05 mT that I used in my paper as a representative maximum for my ineffectivity arguments and is typically 100 times larger than environmental fields that have concerned some.

Moreover, I note that Kirschvink has used some assumptions in his model that raise doubts as to whether even 0.14-mT fields can affect biology and suggests that the design of a more sensitive model will be difficult indeed. In particular, he uses as a gate opener a very large magnetosome with a very large magnetic moment of 2×10^{-15} A m^2. This is about a factor of 10 greater than that for the largest stable magnetite single domain as calculated by Butler and Bannerjee [5]. Also, the energy difference between the open and closed-gate configuration is only about $1.85kT$. Hence, in the absence of an external ELF, one might expect that the gate would be open about $e^{-1.85}/(1+e^{-1.85})\approx 13\%$ of the time, which is comparable to the open time of about 25% that might be expected from the action of the ELF field on the model system with no noise.

Since the energy of displacement varies as the square of the magnitude of the external ELF field in Kirschvink's model, the mean energy will be equal to about $0.13kT$ for an ELF field equal to the earth's field of 0.5 mT. For a field of 10 μT (or 100 mG), which is near the maximum, one ordinarily finds in the environment [6] that the interaction energy is about $0.005kT$. Hence, his model supports the thesis that thermal noise can be expected to overwhelm the interactions of the weak fields of the environment with any magnetite to be found in human cells.

Therefore, the results of Kirschvink's calculations contradict his remark to the effect that his model shows that, "in direct contradiction to the statements of Adair, it may be possible for weak, ELF magnetic fields to produce biological effects at the cellular level through a nonsensory process." Indeed, in light of differences greater than 1000 between the interaction energies required for this model and the interaction energies from the environmental fields of about 5 μT—or less—that have been of concern, his statements implying that he has shown that weak environmental fields "could lead plausibly to $\cdots$ chromosome nondisjunction and consequences of this sort" are misleading.

By considerations that include Kirschvink's model as a special case, I show generally that no plausible interaction of a weak 60-Hz magnetic field with magnetite in cells or other small structures can be expected to have biological consequences. I proceed in the manner of Kirschvink by considering the kinetic and potential energies induced in a magnetite structure by the interaction of a perturbing field where the *kT noise is neglected.* If those energies are very much smaller than kT, I conclude that the thermal noise will overwhelm the signal and the interaction cannot be expected to have any biological effect. This procedure has the advantage of simplicity of exposition and should be adequate to set lower limits on the magnitude of fields that might affect biology through interaction with biological magnetite.

So as to consider a maximum effect, I assume that the unbound magnetite structure is aligned by the earth's field and is subject to a 60-Hz field of amplitude B_{ELF} directed at right angles with respect to the earth's field. That field will induce an alternating torque on the magnetosome structure that will cause it to oscillate. If the alternating field is to generate biologically significant signals, the field must perturb the magnetite system to an extent greater than the natural perturbations from thermal fluctuations. In particular, either the kinetic or potential energies generated by the action of the imposed field must be as large as kT.

The torque on a free magnetic element with a magnetic moment μ will be made up of a resistive torque, $T_r=-C\dot{\theta}$, a binding torque, $T_b=-B_{\mathrm{earth}}\mu\theta$, and a driving torque, $T_d=B_{\mathrm{ELF}}\mu\cos\omega t$, where θ is the angle of rotation and $\omega=\dot{\theta}=377$ radians per second. (I use Kirschvink's notation.) The equation of motion, valid for small vibrations, takes the form

$$I\ddot{\theta}=-C\dot{\theta}-B_{\mathrm{earth}}\mu\theta+B_{\mathrm{ELF}}\mu\cos\omega t\ , \tag{1}$$

where I is the moment of inertia of the element. Writing $\theta(t)=\theta_0\cos(\omega t+\phi)$, for $\theta_0<20°$, which will generally hold for the small fields B_{ELF} we are considering,

$$\theta_0^2=\frac{(B_{\mathrm{ELF}}\mu)^2}{(B_{\mathrm{earth}}\mu-I\omega^2)^2+C^2\omega^2}\ . \tag{2}$$

This equation is fundamentally the same as Kirschvink's Eq. (3) though I use a small angle approximation and retain the inertial effect of I.

Neglecting the inertial effects, which is a good approximation for the situations considered here, Eq. (2) can be written

$$\theta_0^2=\left[\frac{B_{\mathrm{ELF}}}{B_{\mathrm{earth}}}\right]^2\frac{1}{1+(\omega\tau)^2}\ ,$$

where

$$\tau=\frac{C}{B_{\mathrm{earth}}\mu} \tag{3}$$

is a relevant time constant. If the time constant is long compared to $\frac{1}{60}$th of a second, the response of the magnetite system to the perturbing field will be severely damped.

The mean kinetic energy W_T and mean potential energy W_V can be written as

$$W_T=\frac{I\omega^2\theta_0^2}{4}\ ,$$

and

$$W_V=\frac{B_{\mathrm{earth}}\mu\theta_0^2}{4}\ . \tag{4}$$

It is important to couch conclusions in term of some particular simple structure in order to provide insights into general behaviors. Hence, I state energies in units of kT and magnetic moments μ in terms of the magnetic energies $B_{\mathrm{earth}}\mu$, also in units of kT. For moments of inertia and viscous effects I use a sphere of radius r as a surrogate for more generally shaped bodies of a given volume. I take the density of the nonmagnetite material of the sphere as that of water and, for purposes of estimating the moment of inertia, assume the heavy magnetite is spread evenly through the sphere. The resistive torque is taken as $C=6\eta v$, where v is the volume of the body and η the viscosity. With this evaluation of C, the characteristic time constant τ can be written as $\tau=(6\eta v)/(B_{\mathrm{earth}}\mu)$.

Here, I discuss two different models of the effects of 60-Hz magnetic fields on magnetite elements. Following

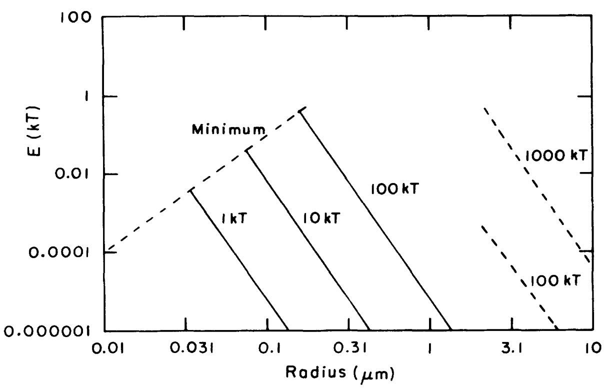

FIG. 1. The potential energy, measured in units of kT, induced by the interaction of 60 Hz, 50 μT, fields with magnetite elements that might be found in cells. The solid lines show the energies as a function of radius for spherical magnetic elements that are assumed to act internal to the cell where the viscosity of the cytoplasm is taken as $\eta \approx 0.1$ N s/m^2. Each line presents the values of the potential energy for elements with different magnetic moments expressed as $B_{\text{earth}}\mu$. The dashed lines are meant to describe the rotations of whole spherical cells which hold magnetite elements rigidly within the cell. Here the viscosity is assumed to be that of water, $\eta = 0.001$ N s/m^2. The line labeled minimum defines the limiting size when the magnetite occupies the whole volume.

Kirschvink [1], I consider the motion of single-domain magnetosomes within the cell and assume that such structures will generally be smaller than $r = 0.5$ μm and will have a magnetic moment μ such that $B_{\text{earth}}\mu < 50kT$. For this environment , I take the effective viscosity as that of cytoplasm taken [1,7] as $\eta = 0.1$ N s/m^2. Then I use Eqs. (2) and (4) to calculate the energies induced by perturbative 60-Hz magnetic fields, B_{ELF}. The solid lines of Fig. 1 show the variation of potential energy as a function of r for different magnetic moments μ, expressed in terms of energies $B_{\text{earth}}\mu$ in units of kT, and for a perturbing field $B_{\text{ELF}} = 50$ $\mu\text{T} = B_{\text{earth}}$, which is the limiting value used in my paper [2]. The line labeled "minimum" shows the limit of sizes reached when the structure is wholly Fe_3O_4. The kinetic energies are much smaller and are not plotted.

The small values for the induced energies can be understood in terms of the large magnitudes of the time constants τ. For example, for a magnetite system in the interior of the cell with a radius of 0.5 μm carrying a large magnetic moment μ such that $B_{\text{earth}}\mu = 25kT$, the time constant, calculated from Eq. (4), will be 3 s, and $(\omega\tau)^2 = 1.33 \times 10^6$.

Although we plot the calculated energies for single-domain elements with magnetic moments as large as $B_{\text{earth}}\mu \rightarrow 100kT$, we note that the magnetostatic energy for single-domain systems such that $B_{\text{earth}}\mu > 3kT$ is such as to favor the division of such large magnetite domains into several nonaligned domains, thus sharply reducing the magnetic moment of the magnetosome.

In some cases, strings of magnetosomes, aligned magnetically, are rigidly held in cells and the field can then cause the whole cell to rotate. These strings of separated individual domains are not subject to the magnetostatic energy factors that constrain the size of single domains hence large total magnetic moments μ such that $B_{\text{earth}}\mu \approx 1000kT$ may occur. For the rotation of these cells, I assume that the viscosity of the cell medium may be as small as that of water and take $\eta = 0.001$ N/m^2 Generally, the cell will be of the size $r > 5$ μm. For such a cell, with $r = 5$ μm and $B_{\text{earth}}\mu = 1000kT$, rotating in a medium with the viscosity of water, $\tau \approx 0.75$ s. The dashed lines show the potential energies generated by 60 Hz, 50 μT, fields in the excursions of these cells. Again, the kinetic energies are insignificant.

From the plots of Fig. 1, the induced energies are seen to be smaller —and excepting the implausible very large single-domain elements presumed to act within the cell, very much smaller— than kT. Hence, I conclude that 60-Hz magnetic fields weaker than 50 μT cannot generate significant biological effects through action on magnetite. However, since the induced energies vary as B_{ELF}^2, these simple arguments do not preclude biological effects for 60-Hz fields appreciably larger than the earth's field, $B_{\text{earth}} = 50$ μT. Conversely, energies induced by maximal long-time environmental fields of 5 μT are 100 times smaller.

Hence, these calculations, including Kirschvink's results, support my statement, quoted in his *Comment*, that, "There are very good reasons to believe that weak ELF fields can have no significant effect at the cell level—and no strong reason to believe otherwise."

[1] J. L. Kirschvink, preceding paper, Phys. Rev. **46**, 2178 (1992).

[2] R. K. Adair, Phys. Rev. A **43**, 1039 (1991).

[3] R. B. Frankel, in *CRC Handbook of the Biological Effects of Electromagnetic Fields*, edited by C. Polk and E. Postow (Chemical Rubber Co., Boca Raton, FL, 1986).

[4] J. L. Kirschvink and A. Kobayashi-Kirschvink, Am. Zool. **31**, 169 (1991).

[5] R. F. Butler and S. K. Banerjee, J. Geophys. Res. **80**, 4049 (1975).

[6] The magnetic-field strengths in the environment from common sources are discussed—with references—in I. Nair, M. G. Morgan, and H. K. Florig, U.S. Congress, Office of Technology Assessment Report No. OTA-BP-E53, 1989 (unpublished). Typical maximum fields listed in Table 2-2 are from: house wiring,—10 mG; ground currents, 5 mG; distribution lines, 10 mG. It is these—largely unavoidable— fields that have been linked by the OTA, in this report, and by others, to health effects. The electric motors in appliances generate fields as great as 25 G very near the stator magnets but these fields fall off sharply with distance to levels less than 25 mG at 1 m. Hence, exposure to such fields are characteristically limited in spatial extent as well as duration and are generally avoidable.

[7] W. J. Moody and M. M. Bosma, J. Membrane Biol. **107**, 179 (1989).