Bioelectromagnetics 17:187–194 (1996)

Microwave Absorption by Magnetite: A Possible Mechanism for Coupling Nonthermal Levels of Radiation to Biological Systems

Joseph L. Kirschvink

Division of Geological and Planetary Sciences, The California Institute of Technology, Pasadena, California

The presence of trace amounts of biogenic magnetite (Fe_3O_4) in animal and human tissues and the observation that ferromagnetic particles are ubiquitous in laboratory materials (including tissue culture media) provide a physical mechanism through which microwave radiation might produce or appear to produce biological effects. Magnetite is an excellent absorber of microwave radiation at frequencies between 0.5 and 10.0 GHz through the process of ferromagnetic resonance, where the magnetic vector of the incident field causes precession of Bohr magnetons around the internal demagnetizing field of the crystal. Energy absorbed by this process is first transduced into acoustic vibrations at the microwave carrier frequency within the crystal lattice via the magnetoacoustic effect; then, the energy should be dissipated in cellular structures in close proximity to the magnetite crystals. Several possible methods for testing this hypothesis experimentally are discussed. Studies of microwave dosimetry at the cellular level should consider effects of biogenic magnetite. ©1996 Wiley-Liss, Inc.

Key words: **ferromagnetic resonance, magnetoacoustic effect, hypersound, cellular telephones, EMF bioeffects**

INTRODUCTION

One of the most challenging and controversial questions in modern biology is whether weak microwave radiation might produce biological effects via a nonthermal mechanism. Although microwave exposure standards vary widely on an international level, most national standards are based on thermal heating as the most plausible physical mechanism through which biological effects might occur [see, e.g., Guy, 1984; Barnes, 1989; Michaelson, 1991; Bernhardt, 1992].

However, a number of reports dispute this conclusion and argue for the existence of nonthermal effects of microwave radiation on both in vivo and in vitro systems [Liburdy and Magin, 1985; Liburdy and Tenforde, 1986; Liburdy et al., 1988; Stuchly et al., 1988; Tenforde and Liburdy, 1988; Cleary et al., 1992; Liburdy, 1992]. A particularly intriguing aspect of some studies is the claim that modulated microwave fields can produce biological effects under conditions where the unmodulated carrier wave of the same energy density yields no effect [Blackman et al., 1979; Adey et al., 1982; Litovitz et al., 1993]. Guy [1984] described results of this sort as "another bizarre interaction that still defies explanation . . ." although he noted that ". . . the fact that they have been observed by multiple investigators has enhanced the credibility of the findings. . . ." On the other hand, some authors have looked for effects and have found nothing [Djordjevic et al., 1983], and some direct attempts to validate previous positive studies have failed (for example, the Rafferty and Knutson [1987] attempt to investigate the Liburdy and Magin [1985] liposome effects). Trouble of this sort has led some authors [Maranie and Feirabend, 1993] to deny the existence of nonthermal effects. Recently, more concerns have been raised from an epidemiological report that suggests a link between microwave exposure from hand-held police radar and testicular cancer [Davis and Mostofi, 1993] and from a report that low-intensity microwave exposure increases the number of DNA single-strand breaks in rat brain cells [Lai and Singh, 1995].

Received for review October 25, 1994; revision received September 22, 1995.

Address reprint requests to Dr. Joseph L. Kirschvink, Caltech 170-25, Pasadena, CA 91125.

© 1996 Wiley-Liss, Inc.

No consensual theoretical explanation for the biological action of such low levels of radiation (much less that of modulated radiation) has emerged [Barnes, 1989]. This area of research appears to have a significant gap between biophysical theory and experimental results [Hilemann, 1993, 1994].

It is the goal of this paper to explore from a theoretical perspective the possibility that local absorption of microwave radiation by small crystals of biologically precipitated magnetite (Fe_3O_4) might be a mechanism that is capable of producing biological effects. Although magnetite has been known as a biochemical precipitate in animal tissues for over 30 years [Lowenstam, 1962] and has been found recently in human tissues [Kirschvink et al., 1992a,b; Dunn et al., 1995], it appears not to have been considered as an important site of interaction in past biophysical studies of microwave interaction with biological systems. This is not surprising, because the total concentration of magnetite in brain tissues is so low (~5–100 ppb) that bulk studies of the dielectric properties of tissue samples [see, e.g., Foster et al., 1979] are unlikely to have been influenced by the presence of this material. On the other hand, it is important to consider the possible influence of microwave radiation on cells that are specialized to produce magnetite, because the local concentration of this material could be as high as a few percent, and some human diseases do start from damage at the level of a single cell. Several implications of this theory and some experimental approaches for testing it are suggested here.

BIOPHYSICS

In tissues that do not contain ferromagnetic materials, only a small fraction of the incident microwave energy passing through a cell is absorbed, primarily through dielectric interactions of polar and charged molecules with the E vector of the microwave field. This type of interaction results in penetration depths that are generally in the centimeter to decimeter range, depending on frequency. It is easy to show that the absorption on the cellular level is small. For example, in a recent study of the ~835 MHz radiation produced from cellular telephones, Anderson and Joyner [1995] measured a tenfold decrease (90% loss) in power over a distance of approximately 5 cm in phantom models of the human head. If we assume that the typical cell is ~10 µm thick, then this attenuation would happen over ~5000 cells. If X is the fraction of energy passing by each cell to the next one in line, then 1 - X is the fraction absorbed by each cell. For an incident field with an initial power level of 1, after passage through 5000 cells, the transmitted power will be X^{5000}. Thus, $X^{5000} = 0.1$ for a 90% reduction in power, implying that the fraction of energy absorbed by each cell is $1-10^{-0.0002}$ or 0.046%. Therefore, generally, normal cells are transparent to the microwave radiation going through them.

This relative microwave transparency does not hold true for tissues or cells that contain ferromagnetic materials such as magnetite. Due to the process of ferromagnetic resonance [Kittel, 1948; Bloembergen, 1956], these materials can absorb microwave radiation strongly. At ferromagnetic resonance, the imaginary term of the susceptibility, which determines the energy dissipation within a ferromagnetic crystal, becomes infinitely large. This holds true particularly for single-domain particles, where other damping processes are minimal [for review, see Smit and Wijn, 1959, section 23]. Thus, the parameter that is important to determine is the fraction of the cross-sectional area of a cell that might contain magnetite. Typical magnetotactic bacterial cells usually contain up to 1% magnetite by volume, although some exceptional organisms, like the 8-µm-long *Magnetobacterium bavaricum* [Vali and Kirschvink, 1990; Spring et al., 1993] are in the 5–10% range.

For a simple model with 1% by volume of magnetite, consider a 10 µm cubic cell on edge containing 10^4 magnetosomes, each of which is a 0.1 mm cube. If they were arranged as a continuous square sheet in the cell, then these particles would form a 100 × 100 layer that would be 10 × 10 µm in dimension with a thickness of 0.1 µm. If it was oriented perpendicular to the incident radiation, then this sheet would be capable of screening 100% of the area of the cell. If this plane was arranged normal to the incident radiation, then a minimum of only 1% of the cell's area would be intercepted. More realistically, a random crystal arrangement would probably shield something more like 10–30% of the cell volume, which is similar to that present in published transmission electron microscopy (TEM) images of these organisms. With perfect ferromagnetic resonance, therefore, we should expect absorption efficiency of ~10–30% for this cell in contrast to the 0.046% estimated above for tissues dominated by water absorption. In practice, however, a uniform internal demagnetization field (see below) would be present only in single-domain ellipsoidal particles; fan-like dispersion near the edges of other crystal shapes would act to detune parts of the crystal volume, reducing slightly the volume of the crystal that is perfectly on resonance. Nevertheless, one should expect roughly a factor of 1000 larger energy dissipation from a magnetocyte of this sort.

It is instructive to express this absorption of microwave energy by a single 0.1 µm crystal of biogenic magnetite in terms of the background thermal energy, kT (where k is the Boltzmann constant, and T is the absolute temperature; $kT = 4 \times 10^{-21}$ Joule at 300 K). A microwave field of 10 mW/cm^2, which is near the upper limit generated by commercially available cellular telephones, corresponds to an energy flux of $2.5 \times 10^{+18}$ kT/cm^2 s. At the peak resonance for a magnetite crystal (see below), this implies that on the order of 10^{+8} kT/s is dissipated into the cellular environment around the crystal. Because the carbon-carbon bond energy is ~140 kT, and typical hydrogen bond energies are ~10 kT, there is at least the conceptual possibility that local effects of the absorbed energy could exceed thermal noise. This stands in sharp contrast to the related biophysical problem of extremely-low-frequency (ELF) radiation influencing biological systems, where the major problem is simply reaching the kT level with *any* interaction [Adair, 1991]. Magnetite also has metallic resistivity (~5×10^{-5} Ω-m), which makes it roughly 6000 times more conductive than any other biological material and broadens its interaction with microwave fields through electrical effects. Therefore, the following section will review the most probable pathway for the energy transduction with the goal of guiding future experiments.

FERROMAGNETIC RESONANCE AND MICROWAVE ABSORPTION IN MAGNETITE

Magnetite is a member of a broad class of materials called ferrites, which, over the past 40 years, have become intimately involved in the control and tuning of microwave devices. The book by Smit and Wijn [1959] provides a thorough review of the basic physical theory as well as in-depth discussions of the many forms of ferromagnetic resonance effects that were discovered in a flurry of activity in the decade after the initial prediction by Kittel [1948]. By using this work, it is possible to make a first-order estimate of the resonance frequencies expected for a magnetite crystal of known shape, size, and crystallographic orientation.

Figure 1 illustrates the basic principle of ferromagnetic spin resonance, which is most applicable to the single-domain magnetites produced biologically. Inside a ferromagnetic crystal, strong magnetic fields (H) are generated by three types of anisotropy: 1) that present in the crystallographic structure (H_a), 2) that due to the shape of the particle (H_s), and 3) that produced by stress from defects in the crystal lattice (H_d). Thus, the magnetic moment of each unpaired electron (μ_B, or Bohr magneton) of the iron atoms in the crystal will experience a torque, $\mu_B \times H$ (where H is the vector sum of H_a, H_s, and H_d), which acts perpendicular to both μ_B and H.

Because each electron also has quantized angular momentum (J) in addition to its magnetic moment, it will precess around the direction of the H vector just like a spinning top in a gravitational field. Thus, the angular precession frequency, ω, is given by

$$\omega = \gamma H \qquad (1)$$

[Smit and Wijn, 1959, p. 78, Eq. 18.4], where γ is the gyromagnetic ratio (μ_B/J) for an electron. Converting this to frequency (f) and including the value for γ, in their Equation 18.5, Smit and Wijn [1959, p. 78] provide the useful relationship

$$f = 35.2 \text{ H kHz}, \qquad (2)$$

when H is measured in A/m. Note that this has been converted from the Gaussian CGS units used by Smit and Wijn [1959] to S.I. units [1 Oe = $(1/4\pi) \times 10^3$ A/m]; in vacuum $B = \mu_o H$, where $\mu_o = 4\pi \times 10^{-7}$ Henries/m is the permeability of free space. Thus, if the total magnetic field resulting from the anisotropy and any external fields are known, then the peak resonance frequency can be found.

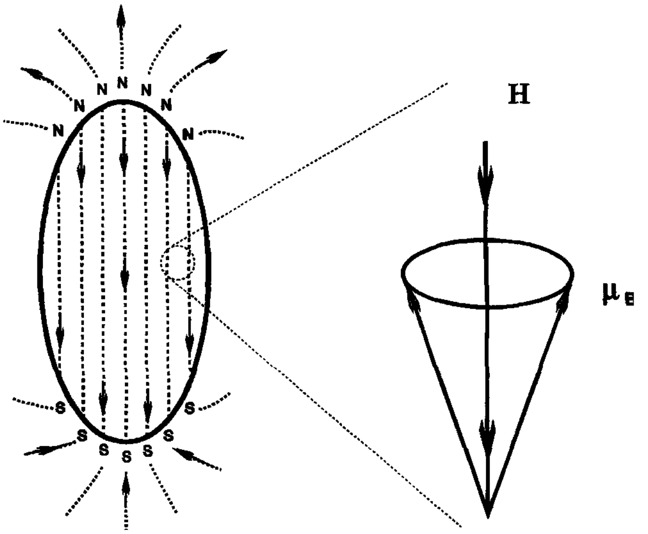

Fig. 1. Schematic representation of the precession of a magnetization vector (μ) in the demagnetization field (H). In a uniformly magnetized solid, the alignment of the Bohr magnetons at each atomic locus leads to an effective magnetic charge separation. The field external to the crystal (the magnetic induction) is precisely what would exist if it had been generated by an array of magnetic charges fixed on the surface of a particle. These effective charges also generate a real magnetic field inside of the crystal (H) that is oriented in the opposite direction from that of the magnetization; hence the name "demagnetizing field" (dotted lines on the left diagram indicate the field direction and not the magnetization direction). This demagnetization field is felt by each of the unpaired Bohr magnetons within the crystal lattice, as indicated by the right diagram. Thus, there is a torque on the magneton, μ × H, that always acts at right angles to the μ and H vectors. Thus, the tip of the μ vector precesses over the surface of circular cone with a resonance frequency, which is given by Equations 1 and 2.

For several reasons, biogenic magnetite presents a simple system for the application of this theory. First, virtually all crystals of biogenic magnetite that have been studied with TEM have sizes and shapes that fall within the single-domain stability field [Diaz-Ricci and Kirschvink, 1992], implying that they are uniformly and stably magnetized. This also implies that only the spin resonance needs to be considered, because other effects, like domain-wall resonance [reviewed in Smit and Wijn, 1959, section VI], should not happen. Second, high-resolution TEM (HRTEM) studies of the crystal structure of most biogenic magnetites reveals that the crystals are usually slightly elongate, with the {111} axis parallel to the long axis. This has been observed in numerous magnetotactic bacteria [Towe and Moench, 1981; Mann, 1985; Vali and Kirschvink, 1990], in salmon [Mann et al., 1988], and in many of the magnetite crystals from the human brain [Kirschvink et al., 1992a,b]. This coincidence of the "easy" direction of the magnetocrystalline and shape anisotropies implies that the internal magnetic fields they produce add together linearly, making computations easy. Finally, all of the HRTEM studies indicate that the biogenic crystals are usually free of crystal lattice defects, which allows effects from stress anisotropy to be ignored.

For magnetite at physiological temperatures, the internal field produced by the magnetocrystalline anisotropy in the {111} orientation H_a is given by

$$H_a = \frac{1}{Ms}\left[\frac{4}{3}K_1 + \frac{4}{9}K_2\right] \qquad (3)$$

[Smit and Wijn, 1959, p. 46, Table 11.I], where M_s is the saturation magnetization, and K_1 and K_2 are the magnetocrystalline anisotropy constants. Banerjee and Moskowitz [1985] give best values for these parameters of 480 emu/cm^3, -1.35 × 10^5, and -0.44 × 10^5 erg/cm^3, respectively (1 emu = 10^{-3} A-m^2 and 1 erg = 10^{-7} Joule). In the absence of shape anisotropy, Equation 2 predicts a 1164 MHz resonance frequency.

For shape anisotropy, H_s, the internal field depends on the relative value of three orthogonal demagnetization factors, N_a, N_b, and N_c, where $N_a + N_b + N_c = 4\pi$. If the particle is elongate and equant ($N_b = N_c$), then the internal field produced by the shape anisotropy, H_s, will be given by

$$H_s = (N_b - N_a)\, M_s \qquad (4)$$

[Smit and Wijn, 1959, p. 80]. Calculation of exact values for these demagnetization factors depends on the detailed shape of the particles, and closed-form expressions have been worked out for both equant rectangular prisms and ellipsoids [for a thorough summary of the earlier literature, see Diaz-Ricci and Kirschvink, 1992]. For elongate needles, however, $N_a = 0$, and $N_b = N_c = 2\pi$, yielding a maximum for H_s of $2\pi M_s$, which is equivalent to a resonance at 8445 MHz. Because $H_s = 0$ either for a perfect cube or for a sphere (where $N_a = N_b = N_c$), the shape contribution to the ferromagnetic resonance will vary from 0 to 8445 MHz.

Figure 2 shows the results of a detailed calculation of the peak resonance frequency for equant, rectangular parallelipipeds as a function of particle shape. For crystals in which the {111} axis is the elongate direction, the anisotropy fields add linearly [Smit and Wijn, 1959, p. 81], yielding a theoretical peak resonance between 1164 and 9609 MHz. Elongation of particles in other crystallographic directions would result in vector combinations of the anisotropy fields, with the outcome of slightly lower frequencies.

Calculating the width or sharpness of the ferromagnetic resonance is not a simple matter, because, in a complex fashion, it depends on the particle shape, volume, Fe^{2+} content, and packing arrangement of adjacent crystals. Although it appears that no ferromagnetic resonance parameters have been measured yet for any biogenic magnetites, there are at least two reasons to suspect that the resonance absorption will be broad. First, the

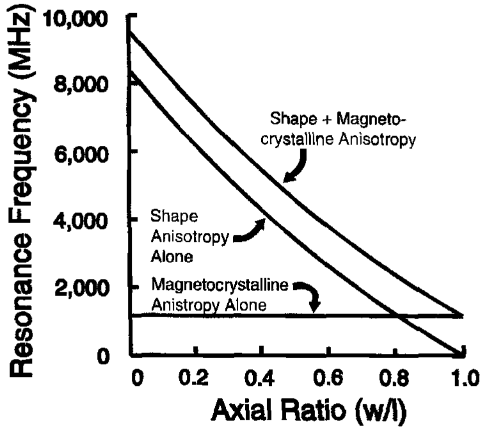

Fig. 2. Theoretical peak ferromagnetic resonance frequencies for rectangular single-domain crystals of magnetite. The magnetocrystalline anisotropy alone, as described in the text, leads to a constant resonance frequency of 1165 MHz. The shape anisotropy (neglecting magnetocrystalline anisotropy) leads to frequencies between 0 and 8445 MHz. If the {111} axis of magnetite is aligned with the particle elongation (which is the case in many biogenic magnetites), then the two anisotropy fields will sum, yielding peak resonance frequencies up to 9609 MHz. Note that these are only the peak of the resonance curves, which, as described in the text, ought to be rather broad.

intrinsic width of the absorption peak increases with the Fe^{2+} content in ferrites due to electron hopping between adjacent Fe^{2+} and Fe^{3+} centers and to the increased dielectric constant [Smit and Wijn, 1959, p. 292]. Second, all known biogenic magnetites have been found either in linear chains, like those in magnetotactic bacteria, algae, and salmon, or in clusters, like those in chiton teeth [Kirschvink and Lowenstam, 1979; Nesson and Lowenstam, 1985], although additional arrangements may also exist [Ghosh et al., 1993; Kobayashi and Kirschvink, 1993; Kobayashi-Kirschvink et al., 1994]. Although the average concentration of biogenic magnetite in human tissues is small (5–100 ppb), magnetic interaction data [Kirschvink et al., 1992b] imply that the crystals are in interacting clumps of some sort, which would be expected if they were localized in specialized cells, as noted earlier.

Because the magnetic field of a neighboring grain will add vectorially to the internal field controlling the precession frequency of each Bohr magneton in the crystal, a random assortment of magnetically interacting particles should act to broaden the resonance. Note that the initial state of an interacting assemblage of semimobile magnetosomes should be such that the external magnetization would be near zero. Exposure to a strong external field (e.g., from an MRI device) will leave a net remanence on an interacting cluster, potentially changing the resonance characteristics. This could be tested experimentally.

Once energy has been absorbed through the process of ferromagnetic resonance in a magnetite crystal, it is important to follow how it is transduced and ultimately dissipated as thermal energy in the surrounding tissues. A simple calculation illustrates that local thermal heating effects around a magnetosome, or even around a cell containing thousands of magnetosomes, are not likely to be responsible for any significant biological effects for low levels of radiation. The fundamental law of heat conduction is given by

$$\frac{dQ}{dt} = -kA\frac{dT}{dx} \tag{5}$$

where dQ/dt is the time rate of heat transfer across an area A, dT/dx is the spatial temperature gradient, and *k* the thermal conductivity of the medium. If area A is the surface area of a spherical magnetite crystal of radius r, and if we assume that the equilibrium heat flux out of the surface is equal to the total power, P, in the microwave field that is intercepted by the crystal (100% absorption by the cross-sectional area of the crystal), then we can integrate Equation 5 to find the equilibrium temperature increase, ΔT, as

$$\Delta T = \frac{P}{4\pi kr} \tag{6}$$

For a spherical magnetosome with a radius of 0.05 µm in a 10 mW/cm^2 microwave field, $P = 7.8 \times 10^{-13}$ J/s. By using a value of *k* similar to that of organic liquids (like toluene at body temperature; $k = 1.34$ mW/cm K), we find a ΔT of about 10^{-5} K. A similar calculation demonstrates that even a 5-µm-diameter cell (e.g., a lymphocyte) absorbing 100% of the energy flux through it would have a maximal temperature rise of about 5×10^{-4} K. Hence, even with maximal absorption through ferromagnetic resonance, local thermal heating is unlikely to produce significant biological effects.

On the other hand, microwave energy absorbed through ferromagnetic resonance is not converted immediately into heat. Because all of the Bohr magnetons in the crystal are precessing in phase at the driving frequency of the microwave field and are aligned and interacting strongly through the super exchange coupling with the crystal lattice, the energy is dumped first into crystal lattice vibrations at precisely the carrier frequency. This is the well-known process of magnetoacoustic resonance through which microwave action on ferromagnetic and antiferromagnetic materials produces hypersound phonons within the crystal [for review, see Belyaeva et al., 1992; for more recent microwave applications, see Romanov et al., 1993; Svistov et al., 1994]. Biological molecules with rotational or collisional time constants in the GHz band could be influenced strongly, particularly those in the magnetosome membranes that envelop the magnetite crystal.

Several authors have suggested that their reported nonthermal effects of microwave radiation might be due to the similarity in characteristic rotational time constants of the tail groups of phospholipids in membranes with those of the carrier wave, but a plausible mechanism for this energy conversion has not been suggested [Liburdy, 1992]. Magnetosomes or other ferromagnetic contaminants in the cell preparations may offer a more plausible mechanism for directly coupling this energy to adjacent structures. Note that there is no size dependence upon the ferromagnetic absorption, because it occurs at an atomic level; thus, it is independent of whole-animal body size. Also, as the energy of hypersound phonons is dissipated rapidly in liquids due to the effects of transverse viscosity, biological effects (if any) should be localized to structures that are in close contact with the magnetosomes. These include the magnetosome membrane itself and perhaps the membrane-bound proteins and associated cytoskeletal elements. Intracellular summation of hypersound phonons from multiple crystals is also unlikely.

Although it appears that, as of this writing, there are no direct measurements of ferromagnetic absorption in any biogenic magnetites, numerous studies have been made on natural magnetites. In a qualitative study, Chen et al. [1984] reported that magnetite is relatively opaque to the transmission of 2.45 GHz microwave radiation. Walkiewicz et al. [1988] conducted microwave heating studies on a variety of materials in a 1 kW, 2.45 GHz oven. A 25 g sample of magnetite powder reached 1258 °C in only 2.75 min, making it one of the best microwave absorbers of the 150 reagent-grade elements, compounds, and natural minerals tested. By using an average specific heat capacity for magnetite of about 0.9 J/g K over this temperature range [Robertson, 1988], the magnetite is absorbing a minimum of about 15% of the available energy. Because this ignores heat loss through the crucible and a rather short penetration depth of the microwaves in the sample, the true absorption should be higher. Magnetite was such a good absorber that they recommended adding it to microwave-transparent materials to improve their heating ability. This work has led to the subsequent development of microwave sintering of iron ore, wherein the rapid thermal expansion of magnetite cracks the surrounding rock matrix, reducing the energy required in the ore-grinding process [Walkiewicz et al., 1991].

PROPOSED EXPERIMENTAL TESTS OF THE MAGNETITE ABSORPTION THEORY

Several rather obvious experiments and measurements could be done to test the model outlined here, a few of which are outlined here.

The properties of microwave absorption need to be measured directly for a variety of biogenic magnetites and inorganic contaminants. If their absorption spectra bear no relationship to microwave exposures implicated in nonthermal effects (or even through epidemiological associations), then a ferromagnetic mechanism would be unlikely.

There may be a simple experimental technique with which to test the hypothesis that ferromagnetic resonance of ultrafine-grained magnetite may be responsible for a particular nonthermal biological effect. From Equation 1, the resonance frequency is directly proportional to the internal demagnetizing field, H. However, because single-domain particles are essentially at saturation, the application of a strong, external magnetic field will shift the resonance linearly, particularly if the applied field exceeds the maximal coercivity of magnetite (0.3 T). Numerous commercially available rare-earth magnets produce surface fields of this strength, and pairing them with nonmagnetic metals would allow full experimental blinding. Static fields of this magnitude should not perturb the dielectric properties of water or of other biological materials that form the bulk of microwave energy dissipation in tissues. This approach is most powerful if the resonance spectra of the magnetic materials are known.

It should be possible to look for the disruption effects of the phospholipid membrane of aqueous suspensions of bacterial magnetosomes. TEM examination of the crystal surface should reveal the fraction of intact membranes [Gorby et al., 1988; Vali and Kirschvink, 1990], and this could be done as a function of exposure intensity, duration, and frequency.

Experiments aimed at looking for microwave-induced mutations or other damage to DNA could be performed on the magnetotactic bacterium *Magnetospirillum magnetotacticum* and, as a control, on its nonmagnetotactic mutant, NM-1, both of which are available from the American Type Culture Collection. This would be the worst-case scenario, because the bacterial DNA in this organism is in close proximity to the magnetosomes.

DISCUSSION

Although magnetite has been known as a biochemical precipitate in animal tissues for over 30 years [Lowenstam, 1962; for review, see Kirschvink et al., 1985], apparently it has not been considered in biophysical analyses, including those in the field of microwave dosimetry. This author has not found any mention of ferromagnetic resonance ever having been considered in biophysical analyses of microwave interaction with biological materials, much less in the context of human health issues. It should be clear from the analyses and review in this paper that magnetite is the best absorber of microwave radiation of any biological material in the 0.5–10.0 GHz frequency range by several orders of magnitude. This includes the frequencies that are normally used in the cellular telephone industry, 0.8–2.0 GHz. Hence, the recent confirmation that magnetite is also present in human tissues [Kirschvink et al., 1992a,b; replicated independently by Dunn et al., 1995] implies that its should be included in dosimetry studies. Even though the absolute concentrations of magnetite are low, a damaging effect at the level of one cell can have global consequences. From a biomedical perspective, it is obviously important to know which human tissue types contain magnetite, which cell types precipitate it, how the particles are arranged in each cell, and, ultimately, what the biological functions are.

A related issue concerns the numerous in vitro studies of the biological effects of microwave radiation, a few of which were mentioned above. Ferromagnetic resonance is not restricted to biological magnetites. Any ferromagnetic or antiferromagnetic materials could yield similar effects if they happen to be present. Hence, the observation that these contaminants are often present in many laboratory plastics, culture media, and reagents [Walker et al., 1985; Kobayashi et al., 1995] is a potential complication for all previously published in vitro microwave studies. Therefore, the conclusion of Kobayashi et al. [1995] that ferromagnetic contamination compromises in vitro biological studies in ELF electromagnetic radiation must be extended up to the 10 GHz microwave range as well. Once the appropriate procedures are developed to test for the involvement of magnetite in in vivo experiments, then critical published experiments should be reexamined to determine whether magnetite could have played a causal role.

Another puzzle in the biomagnetic literature has been the claims that ELF modulation of a microwave carrier field can sometimes elicit an effect in situations where an unmodulated carrier wave of comparable energy density yields nothing [Blackman et al., 1979; Adey et al., 1982; Litovitz et al. 1993]. Again, magnetite might provide a solution. In a modulated microwave field, the amplitude of the crystal vibrations will vary according to the modulation. Thus, the acoustic wave that is generated will contain components at both the carrier-wave and the modulating frequencies. These ought to propagate quite differently through the surrounding intracellular medium and could reasonably lead to different effects. The magnetite could be of either biogenic or exogenous origin.

A final and currently speculative question arises whether the ferromagnetic absorption processes discussed here might plausibly lead to cellular damage, particularly to DNA. One very speculative possibility is that the microwave acoustic oscillations might increase the membrane porosity by the transient opening of hydrophilic pores in the magnetosome membrane, thereby exposing the "naked" surface of the magnetite to the cell's cytoplasm. Under these conditions, weak concentrations of hydroxyl radicals can form by oxidation of Fe^{2+} ions in the magnetite via the iron-catalyzed Haber-Weiss process [for review, see Grady and Chasteen, 1991]. Hydroxyl radicals are highly damaging to DNA. Presently, it is not known whether eukaryotic magnetosomes are ever located within the nucleus, although there is at least one report of ferromagnetic inclusions in nucleic acid samples [Schulman et al., 1961]. However, those authors described no precautions against ferromagnetic contamination. Other effects, such as the opening of these transient pores in the cell membrane to allow Ca^{2+} and other hydrophilic molecules to pass through, are also worth investigating.

ACKNOWLEDGMENTS

The author is grateful for support from EPRI project WO 4307-03 and NIH grant ES-06652 during the development of these ideas. Helpful discussions with many friends and colleagues are also acknowledged along with the lengthy comments of three referees and the Assistant Editor.

REFERENCES

Adair RK (1991): Constraints on biological effects of weak extremely-low frequency electromagnetic fields. Phys Rev A 43:1039–1048.

Adey WR, Bawin SM, Lawrence AF (1982): Effect of weak amplitude-modulated microwave fields on calcium efflux from awake cat cerebral cortex. Bioelectromagnetics 3:295–307.

Anderson V, Joyner KH (1995): Specific absorption rate levels measured in a phantom head exposed to radio frequency transmissions from analog hand-held mobile phones. Bioelectromagnetics 16:60–69.

Banerjee SK, Moskowitz BM (1985): Ferromagnetic properties of magnetite. In Kirschvink JL, Jones DS, MacFadden BJ (eds): "Magnetite Biomineralization and Magnetoreception in Organisms: A New Biomagnetism." New York: Plenum Press, pp 17–41.

Barnes FS (1989): Radio-microwave interactions with biological materials. Health Phys 56:759–766.

Belyaeva OY, Karpachev SN, Zarembo LK (1992): Magnetoacoustics of ferrites and magnetoacoustic resonance. Uspekhi Fizicheskikh Nauk 162:107–138.

Bernhardt JH (1992): Nonionizing radiation safety: Radiofrequency radiation, electric and magnetic fields (review). Phys Med Biol 37:807–844.

Blackman CF, Weil CM, Benane SG, Eichinger DC, House DE (1979): Induction of calcium-ion efflux from brain tissue by radio frequency radiation: Effects of modulation frequency and field strength. Radio Sci 14:93–98.

Bloembergen N (1956): Magnetic resonance in ferrites. Proc IRE 44:1259–1269.

Chen TT, Dutrizac JE, Haque KE, Wyslouzil W, Kashyap S (1984): The relative transparency of minerals to microwave radiation. Can Metallurg Q 23:349–351.

Cleary SF, Liu LM, Cao GH (1992): Effects of RF power absorption in mammalian cells. Ann NY Acad Sci 649:166–175.

Davis RL, Mostofi FK (1993): Cluster of testicular cancer in police officers exposed to hand-held radar. Am J Indus Med 24:231–233.

Diaz-Ricci JC, Kirschvink JL (1992): Magnetic domain state and coercivity predictions for biogenic greigite (Fe_3O_4): A comparison of theory with magnetosome observations. J Geophys Res 97:17309–17315.

Djordjevic Z, Lolak A, Djokovic V, Ristic P, Kelecevic Z (1983): Results of our 15 year study into the biological effects of microwave exposure. Aviat Space Environ Med 54:539–542.

Dunn JR, Fuller M, Zoeger J, Dobson JR, Heller F, Hammann J, Caine E, Moskowitz BM (1995): Magnetic material in the human hippocampus. Brain Res Bull 36:149–153.

Foster KR, Schepps JR, Stoy RD, Schwan HP (1979): Dielectric properties of brain tissue between 0.01 and 10 GHz. Phys Med Biol 24:1177–1187.

Ghosh P, Jacobs RE, Kobayashi-Kirschvink A, Kirschvink JL (1993): NMR Microscopy of Biogenic Magnetite. Abstracts, 12th

Annual Meeting of the Society for Magnetic Resonance Imaging, New York, NY, p 938.

Gorby YA, Beveridge TJ, Blakemore RP (1988): Characterization of the bacterial magnetosome membrane. J Bacteriol 170:834–841.

Grady JK, Chasteen ND (1991): Some speculations on the role of oxyradicals in the conversion of ferritin to hemosiderin. In Frankel RB, Blakemore RP (eds): "Iron Biominerals." New York: Plenum Press, pp 315–323.

Guy A (1984): History of biological effects and medical applications of microwave energy. IEEE Trans Microwave Theor Tech MIT 32:1182–1200.

Hilemann B (1993): Health effects of electromagnetic fields remain unresolved. Chem Eng News 71:15–29.

Hilemann B (1994): Findings point to complexity of health effects of electric, magnetic fields. Chem Eng News 72:27–33.

Kirschvink JL, Lowenstam HA (1979): Mineralization and magnetization of chiton teeth: Paleomagnetic, sedimentologic, and biologic implications of organic magnetite. Earth Planetary Sci Lett 44:193–204.

Kirschvink JL, Jones DS, MacFadden BJ (1985): "Magnetite Biomineralization and Magnetoreception in Organisms: A New Biomagnetism." New York: Plenum Press, 682 pp.

Kirschvink JL, Kobayashi-Kirschvink A, Woodford BJ (1992a): Magnetite biomineralization in the human brain. Proc Natl Acad Sci USA 89:7683–7687.

Kirschvink JL, Kobayashi-Kirschvink A, Diaz-Ricci J, Kirschvink SJ (1992b): Magnetite in human tissues: A mechanism for the biological effects of weak ELF magnetic fields. Bioelectromagnetics (Suppl) 1:101–114.

Kittel C (1948): On the theory of ferromagnetic resonance. Phys Rev 73:155–161.

Kobayashi AK, Kirschvink JL (1993): Rock magnetism, TEM and MRI microscopy of human Magnetoleukocytes: The first magnetocyte. E S Trans Am Geophys Union, 1993 Fall Meeting, p 203.

Kobayashi AK, Kirschvink JL, Nesson MH (1995): Ferromagnets and EMFs. Nature 374:123–123.

Kobayashi-Kirschvink A, Kirschvink JL, Ghosh P, Jacobs RE (1994): Magnetic resonance imaging microscopy of magnetocytes. Abstracts, 16th Annual BEMS Meeting, Copenhagen, Denmark, p 141.

Lai H, Singh NP (1995): Acute low-intensity microwave exposure increases DNA single-strand breaks in rat brain cells. Bioelectromagnetics 16:207–210.

Liburdy RP (1992): The influence of oscillating electromagnetic fields on membrane structure and function: Synthetic liposomes and the lymphocyte cell membrane with direct application to the controlled delivery of chemical agents. In Norden B, Ramel C (eds): "Interaction Mechanisms of Low-Level Electromagnetic Fields in Living Systems." Oxford, UK: Oxford University Press, pp 259–279.

Liburdy RP, Magin RL (1985): Microwave-stimulated drug release from Liposomes. Radiat Res 103:266–275.

Liburdy RP, Tenforde TS (1986): Magnetic field-induced drug permeability in liposome vesicles. Radiat Res 108:102–111.

Liburdy RP, Rowe AW, Vanek PF Jr (1988): Microwaves and the cell membrane. IV. Protein shedding in the human erythrocyte: Quantitative analysis by high-performance liquid chromatography. Radiat Res 114:500–514.

Litovitz TA, Krause D, Penafiel M, Elson EC, Mullins JM (1993): The role of coherence time in the effect of microwaves on ornithine decarboxylase activity. Bioelectromagnetics 14:395–403.

Lowenstam HA (1962): Magnetite in denticle capping in recent chitons (*polyplacophora*). Geol Soc Am Bull 73:435–438.

Mann S (1985): Structure, morphology, and crystal growth of bacterial magnetite. In Kirschvink JL, Jones DS, MacFadden BJ (eds): "Magnetite Biomineralization and Magnetoreception in Organisms: A New Biomagnetism." New York: Plenum Press, pp 311–332.

Mann S, Sparks NHC, Walker MM, Kirschvink JL (1988): Ultrastructure, morphology and organization of biogenic magnetite from sockeye salmon, *Oncorhynchus nerka*: Implications for magnetoreception. J Exp Biol 140:35–49.

Maranie E, Feirabend HK (1993): A nonthermal microwave effect does not exist (editorial). Eur J Morphol 31:141–144.

Michaelson SM (1991): Biological effects of radiofrequency radiation: Concepts and criteria. Health Phys 61:3–14.

Nesson MH, Lowenstam HA (1985): Biomineralization processes of the radula teeth of chitons. In Kirschvink JL, Jones DS, MacFadden BJ (eds): "Magnetite Biomineralization and Magnetoreception in Organisms: A New Biomagnetism." New York: Plenum Press, pp 333–363.

Rafferty CN, Knutson JR (1987): Effects of pulsed microwave fields on soluble proteins and liposomes. Proceedings of the 9th Annual Conference of the IEEE Engineering in Medicine and Biology Society, pp 701–702.

Robertson EC (1988): Thermal properties of rocks. US Geological Survey, Open File Report 88-441. Reston, VA: US Government Printing Office.

Romanov DA, Rudashevsky EG, Nikolaev EI (1993): Magnetooptical detection of standing longitudinal hypersound waves excited by uniform FMR mode. IEEE Trans Magnet 29:3405–3407.

Schulman RG, Walsh WM, Williams HJ, Wright JP (1961): Ferromagnetic resonance in DNA samples. Biochem Biophys Res Comm 5:52–56.

Smit J, Wijn HPJ (1959): Ferrites: Physical properties of ferromagnetic oxides in relation to their technical applications. New York: John Wiley and Sons, 369 pp.

Spring S, Amann R, Ludwig W, Schleifer K-H, vanGemerden H, Petersen H (1993): Dominating role of an unusual magnetotactic bacterium in the microaerobic zone of a freshwater sediment. Appl Environ Microbiol 59:2397–2403.

Stuchly MA, Stuchly SS, Liburdy RP, Rousseau DA (1988): Dielectric properties of liposome vesicles at the phase transition. Phys Med Biol 33:1039–1324.

Svistov LE, Safonov VL, Low J, Benner H (1994): Detection of UHF sound in the antiferromagnet $FeBO_3$ by a SQUID magnetometer. J Phys Condens Matter 6:8051–8063.

Tenforde TS, Liburdy, RP (1988): Magnetic deformation of phospholipid bilayers: Effects on liposome shape and solute permeability at prephase transition temperatures. J Theor Biol 133:385–396.

Towe KM, Moench TT (1981): Electron-optical characterization of bacterial magnetite. Earth Planetary Sci Lett 52:213–220.

Vali H, Kirschvink JL (1990): Observations of magnetosome organization, surface structure, and iron biomineralization of undescribed magnetic bacteria: Evolutionary speculations. In Frankel RP, Blakemore RP (eds): "Iron Biomineralization." New York: Plenum Press, pp 97–115.

Walker MM, Kirschvink JL, Perry AS, Dizon AE (1985): Methods and techniques for the detection, extraction, and characterization of biogenic magnetite. In Kirschvink JL, Jones DS, MacFadden BJ (eds): "Magnetite Biomineralization and Magnetoreception in Organisms: A New Biomagnetism." New York: Plenum Press, pp 154–166.

Walkiewicz JW, Kazonich G, McGill SL (1988): Microwave heating characteristics of selected minerals and compounds. Minerals and Metallurgical Processing, February 1988, p 39–42.

Walkiewicz JW, Clark AE, McGill SK (1991): Microwave-assisted grinding. IEEE Trans Indus Appl 27:239–243.