ELF-FIELD HEALTH EFFECTS: BIOLOGICAL, OR ILLOGICAL?

Robert O. Becker, in his response to a letter by Robert K. Adair (December 1991, page 103), rejects the "outmoded biological concept that living things are simply chemical machines all of whose functions result from chemical reactions in an aqueous medium." However, the evidence Becker gives does not support his position.

He says that the "primary events in detection of light by the retina and in photosynthesis" show that living things do not obey chemical laws. Those events, however, are readily explained as processes initiated by photons of energy many times thermal (kT).

Becker cites stimulation of healing of bone fractures by pulsed magnetic fields as being caused by processes far below kT, but the currents induced by those fields are much greater than those from noise.

He refers to the considerable number of reports of biological effects of weak extremely-low-frequency fields as evidence for events that "violate the kT concept." Adair has calculated that currents and voltages induced in normal mammalian cells by 60-Hz fields equal to that of the Earth, 50 microteslas, are less than those induced by thermal noise.[1] An unequivocal effect induced in such a cell by those fields would violate physical laws, but I have been unable to find even one such effect, clearly repeatable when irrelevant parameters are changed, in the confused and often contradictory reports in the literature. Adair also considers specialized structures in living creatures that can detect weak ELF fields, and finds none that violate physical laws:[1] Certain bacteria sense the Earth's magnetic field because of ferromagnetic inclusions; some sharks detect extremely weak ELF fields with organs that integrate fields over large distances and thus generate signals larger than noise; and so on.

Thus Becker's arguments do not "rip to shreds," to use Philip Anderson's arresting phrase (December 1990, page 9), the fabric woven by a half-century of molecular biology, and leave intact the paradigm that atoms in living cells obey the same laws as inanimate matter.

Becker's real concern is not that paradigm, but the conviction that stray fields from power lines, typically $1/1000$ to $1/100$ the strength of the Earth's field, cause effects in tissues *other than* organs specialized for detection of electromagnetic fields; an analogous case is the effects of sound on organs other than the ear. Although there are reports of such effects of ELF fields, they are too contradictory and the effects are too marginal to permit us to draw conclusions. However, such effects induced by processes that obey the laws of physics and chemistry cannot yet be ruled out.

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1. R. K. Adair, Phys. Rev. A **43**, 1039 (1991).

FRANKLIN HUTCHINSON
Yale University
New Haven, Connecticut

1/92

Robert O. Becker states that "the outmoded concept that kT must be exceeded for [biological] effects to occur" is shown to be false by the "primary events in detection of light by the retina and in photosynthesis."

I would like to point out that the minimum-energy photon detectable by the retina has about 1.6 eV of energy. This is 60 times kT. Photosynthesis is a two-photon process. The wavelength of the "red" photon is approximately 700 nm, with energy 1.75 eV—70 times kT. Becker's statement is false: Both detection of light by the retina and photosynthesis require photons of energy many times the thermal energy kT.

GEOFFREY A. LANDIS
NASA Lewis Research Center
Cleveland, Ohio

12/91

A letter from Robert K. Adair in the December 1991 issue criticizes books by Paul Brodeur and Robert Becker that discuss the possible effects on people of the man-made electromagnetic fields in our environment, and of

the power-line fields (60 Hz in the US, 50 Hz in Europe) in particular. Adair states that "good scientists hold these very weak 60-Hz fields harmless," and he repeatedly emphasizes the purported weakness of the fields. He further states that "such fields are considered harmless because their effects on the cellular level are very, very much smaller than kT and thermal noise. And over larger regions, the fields are very, very much smaller than other, indigenous noise fields in the body." These latter statements may or may not be true; readers should refer to Becker's reply following Adair's letter for a rebuttal.

Instead of following Adair's lead, I want to make a straightforward comparison of apples with apples: I will compare the amplitudes of the 60-Hz power-line fields that now surround us with the amplitudes of the 60-Hz fields that would exist if all the electric power in the world were to be turned off, that is, with the amplitudes of the natural electromagnetic background fields at 60 Hz. It is these latter fields in which we evolved, and they are the only 60-Hz fields to which we were exposed until the development of electrical power about a century ago.

Of course, it is no longer a simple matter to measure the natural background fields at 60 Hz directly. Even at the far extremes of the world, in the Antarctic and northern Greenland, two locations where I make measurements of natural low-frequency electromagnetic noise,[1] it is impossible to avoid 60-Hz power-line fields. However, by making measurements at frequencies other than the two power-line frequencies or any of their harmonics and interpolating, it is possible to estimate the natural amplitudes at 60 Hz. The range I obtain,[2] from measurements at six locations around the world, is 150–600 femtoteslas for a 1-Hz frequency band centered on 60 Hz. These measurements are in good agreement with the results of two earlier surveys of natural low-frequency radio noise.[3]

Now let us look at the amplitudes of the 60-Hz power-line magnetic fields that we are exposed to every day.[4] As one might expect, the fields near electrical appliances vary widely, but typical amplitudes lie in the range 1–100 microteslas, or up to 10^9 times the natural background fields. Typical 60-Hz magnetic field amplitudes measured inside homes but away from appliances lie in the range 0.1–1 μT, or up to 10^7 times the natural fields. Finally, measurements of the "ambient background" outside the home cover a very wide range, but typically vary from the picotesla level up to the microtesla level.

Weak fields? I don't believe so. Their effect on mankind? Well, we are clearly in the middle of a great experiment to see what a century of exposure to these power-line fields will do to us, and the evidence is not all in. And there is another issue. Just as a rising tide lifts all the boats (to borrow a phrase from President Kennedy), so the rising tide of 60-Hz (and 50-Hz) fields has increased our susceptibility to the possible effects of electromagnetic fields at higher frequencies. There is no need for me to explain to readers of PHYSICS TODAY how the peak amplitudes of the higher-frequency fields can be increased by the presence of the lower-frequency fields. And increases of the order of 10^9 in these peak amplitudes, as might occur near an electrical appliance, cannot be described as trivial.

I am mindful of the controversy aroused by Rachel Carson and her book *Silent Spring* when it was first published. Ultimately, it was facts that proved her right. To be able to judge the books by Brodeur and Becker, many more facts are needed, but the issues they raise concerning power-line fields cannot be glibly dismissed on the grounds that the fields are small. Fortunately, the Electric Power Research Institute has an extensive program of studies of the possible biological effects of power-line fields, and there is a possibility the Federal government, which dropped the ball on the issue, will reinstate its active support of research in the area. Physicists have contributed much to these studies and will undoubtedly contribute much more.

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ANTONY C. FRASER-SMITH
Stanford University
Stanford, California

1/92

The letter from Robert Adair and the reply by Robert Becker started me to rethinking the question of possible adverse effects of extremely-low-frequency fields, and especially their magnetic component.

The references to such effects that I had previously seen usually concerned the danger of fields from high tension lines. I had therefore been skeptical because of the inability of electric fields to enter the body. The same, however, does not apply to magnetic fields. In fact, even very small varying magnetic fields can affect some organisms. R. W. Murray found that the electric organs of certain fish could respond to electrical fields of less than 1 μV/cm, which he induced by moving a small magnet that he held in his hand at a distance from the aquarium.[1] Similar responses have been observed by others in a variety of aquatic species; it is evident that the response results from a stimulus far below the Boltzmann kT/e "limit." (Alan L. Hodgkin and Andrew F. Huxley[2] encountered a similar but less severe problem in their analysis of the sensitivity of squid axons.[2]) I resolved these apparent anomalies by a statistical analysis of the stochastic processes involved,[3] in which Ca^{2+} may play an essential role.[4]

The fact that low-level 60-Hz magnetic fields *could* cause problems is not, however, evidence that in fact they do so!

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FRANKLIN F. OFFNER
Northwestern University
Evanston, Illinois

1/92

ADAIR REPLIES: The comments by Geoffrey Landis and by Franklin Hutchinson are illuminating—and correct.

Franklin Offner refers to the detection of very-low-frequency fields of 1 μV/cm by fish and to the results of the beautiful Hodgkin–Huxley experiments as demonstrating responses "below the Boltzmann kT/e" limit. Actually, large sharks detect electric fields of 1 μV/m, 100 times smaller, by integrating responses over large distances and large numbers of detectors (the ampullae of Lorenzini) in a manner that does not violate kT constraints.

Offner's "Boltzmann limit" on electric fields is better written as kT/q, where q, the charge carried by the ion, is known to be sometimes as large as $7e$ or $8e$. Moreover, the characteristic transmembrane potential differences that Alan L. Hodgkin and Andrew F. Huxley found to elicit significant current changes were of the order of 25–50 mV, while $kT/e \approx 25$ mV; hence there is no contradiction between their results and the kT limit.

Antony Fraser-Smith appears to argue that any artifact not found in precisely the same form in nature is, *per se*, highly suspect. I disagree.

Then, in the course of a remarkable statement to the effect that 60-Hz fields increase our susceptibility to fields at higher frequencies, he says that 60-Hz fields "near an electrical applicance" might generate "increases of the order of 10^9 in these peak amplitudes [of higher-frequency fields]." He supports that unusual conclusion by the remark that "there is no need for me to explain [this] to readers of PHYSICS TODAY." But this reader, who lives in the Earth's field, which is much larger than most environmental fields, is puzzled—and incredulous.

Fraser-Smith then says the Federal government has "dropped the ball" on the issue of research on the biological effects of electromagnetic fields. The government has supported, and is supporting, appreciable research on the effects of electromagnetic fields on biological systems. Whether the support is too much or too little must follow from comparisons with other research priorities.

However, I would argue that much of the research support, including that provided by the Electric Power Research Institute, is badly directed.

ROBERT K. ADAIR
Yale University
New Haven, Connecticut

7/92

To Aid Teachers, Fix the Bureaucracy

We are very impressed by the work Leon Lederman described in his Reference Frame column "Of Scientists and School Systems" (May, page 9). His enthusiasm and the depth and scope of the Teachers' Academy of Mathematics and Science will undoubtedly have a positive impact on the teaching of math and science in the Chicago schools. Lederman speaks highly about the contributions of many of his colleagues in higher education; however, he mentions only in passing the work of master teachers at his academy. We hope that he will make full use of the expertise of teachers in the Chicago system. The lack of appreciation of the work of fine teachers is one of the shortcomings of many otherwise noble efforts by the university community.

Lederman says rightly in his article that the educational bureaucracy must ultimately be fixed. We believe that this cannot wait and must be done simultaneously with the training and support of teachers. A major part of the current problem is the conditions under which teachers teach. They have too many students, excessive nonteaching duties, few dollars for materials, little or no support for laboratory work, and pressures resulting from inappropriate curriculum guidelines and testing methods. If these conditions do not change, Lederman's efforts may not have the long-term impact that they should.

Finally, it is most important that the academic community not overlook one of the primary causes of the poor preparation of teachers: Many of the science and mathematics courses that prospective teachers take in college transmit only factual knowledge and are lecture based. These courses do not provide the necessary depth of understanding of what science and math are, nor do they engage students in the process of scientific inquiry. The heavy emphasis on research for promotion and tenure and the few rewards for excellence in teaching discourage necessary innovations. We believe it is the responsibility of the academic community to look to its own problems as well as those of the schools.

VICTOR F. WEISSKOPF
Massachusetts Institute of Technology
Cambridge, Massachusetts
KAREN WORTH
Education Development Center
and Wheelock College
Boston, Massachusetts

6/92

LEDERMAN REPLIES: The comments of Viki Weisskopf and Karen Worth, reasonable and wise, are so typical of attitudes we have often met that they are worthy of reaction. There are so many experts, so many initiatives and so many strongly held opinions, for example: "Why bother with teachers if you can't fix families?" or "But the streets are unsafe" or, as Weisskopf and Worth say, "this [fixing the educational bureaucracy] cannot wait and must be done simultaneously."

What are we to do? Wait? Why