An analytical survey of theoretical studies in the area of magnetoreception

V.N. Binhi

Electromagnetic Fields: Biological Effects and Hygienic Standardization
Eds.: M.H. Repacholi, N.B. Rubtsova and A.M. Muc
World Health Organization, Geneva, Switzerland, pages 155–170, 1999.

---

abridged version

There is no simple answer to the question of how a weak, about 1 *G* and less, low-frequency magnetic field (MF) causes a biological response. Processes of different hierarchic levels of a living organism, from molecular (bio)physical to complex adaptive biological processes, contribute essentially to the magnetobiological effect (Kholodov *et al*, 1992). In biophysics, separate magnetosensitive processes at the fundamental level of interaction of fields and substance are studied. It is exactly at this level that complex spectral or “window” modes of the relation between biophysical processes and biologically significant EMF parameters do originate.

There are different kinds of explanations of magnetobiological effects (MBE). This leads to a variety of conventional classifications of models in magnetobiology (Polk, 1991; Adey, 1993; Berg *et al*, 1993; Blank, 1993). The presence of the classifications, their ambiguity and rapid obsolescence reflects the difficulties in explaining the MBEs, their paradoxical character and the lack of knowledge of their physical nature.

List of mechanisms

Today, as the development of the indicated reviews, it is reasonable to pick out the following kinds of physical processes or ideas underlying hypothetically primary mechanisms of a biological magnetoreception.

— Biomagnetit in MF and ferromagnetic contamination
— Eddy electric currents, induced by alternating MF
— Classical and quantum oscillator models
— Cyclotron resonance in magnetobiology
— Interference of quantum states of bound ions and electrons
— Coherent quantum excitations
— Biologically active metastable states of liquid water that are susceptible to MF variations
— Magnetosensitive free-radical reactions and other “spin” mechanisms
— Parametric resonance in magnetobiology
— Stochastic resonance as an amplifier mechanism in magnetobiology and other random processes
— Phase transitions in biophysical systems displaying liquid crystal ordering
— Bifurcation behavior of solutions of non-linear chemical kinetics equations
— “Radio-technical” models, in which biological structures and tissues are portrayed as equivalent electric circuits
— Macroscopic charged vortices in cytoplasm

The depth of elaboration of the above-listed ideas in literature varies significantly. The predictive mathematical models only support several ideas.

Biogenic magnetite

Historically, one of the first ideas in the area of magnetobiology was an idea of the so-called biogenic magnetite. There are natural microscopic crystals, usually of magnetite, within the body of some animals and bacteria. They are capable of being magnetized. An external MF influences such crystals so that they tend to change their orientation. Consequently, the crystals exert pressure on the adjacent tissue and cause a biological response. In a number of cases, it is possible to explain by this manner the biological reception of a weak static MF (Kirshvink *et al*, 1992). Microscopic crystals of magnetite were found in the brain of some birds, which are known to navigate well in the geomagnetic field. Traces of magnetite are also found in some insects.

Magnetic contamination

An explanation of the ELF MF effect on cells in vitro based on the ferromagnetic contamination (Kobayashi *et al*, 1995) develops the biomagnetite idea. Small polluting magnetic particles are present not solely in the air dust. They are also deposited on the surface of laboratory devices, and penetrate into plastics and glass, into chemicals and purified water. Their mean size is about 10^{-5} *cm*. The particles consist of ferro- and ferrimagnetics, that is, possess spontaneous magnetization. The authors have shown that routine laboratory procedures like pouring or/and rinsing give rise to enrichment of the cell cultures by pollutants. The number of particles in cultures could be 10 times more than that of cells. The energy of such a particle is approximately three orders of magnitude greater than kT. In the author's opinion, the magnetic particle absorbed by a cell membrane can transfer its energy to the adjacent biophysical structures, for example, mechanically activated ion channels.

These mechanisms of MBE stand apart and do not solve the basic problem of magnetobiology. Indeed, many unicellular organisms, wherein magnetite is absent, are capable of reacting to the MF. The reaction in many cases is of a complex non-linear, depending on the MF parameters, character. The basic problem of magnetobiology is exactly in the explanation of this phenomenon, which is a paradoxical one from the viewpoint of orthodox physics.

Eddy currents

Low-frequency MFs induce eddy electric currents in biological tissues. They can also cause biological effects. In general, the magnitude of the current follows the electric field strength, which is directly proportional to the product of the AC MF amplitude and frequency. If the hypothesis is true, there must be a correlation between MBE and that product. Indeed, there is experimental evidence that such a correlation appears with the growth of the MF amplitude (Lerchl *et al*, 1990; Schimmelpfeng *et al*, 1997). However, no correlation has been observed for relatively weak, like geomagnetic, MFs (Juutilainen, 1986; Liboff *et al*, 1987; Ross, 1990; Blackman *et al*, 1993; Jenrow *et al*, 1995; Prato *et al*, 1995). So, in (Ross, 1990) the MBE in a certain frequency window was invariant even with 40 fold change of the induced currents. This points to the existence of primary mechanisms irrespective of eddy currents.

Chemical kinetics

Informational character of the action of weak physical and chemical factors on biological systems is frequently discussed in literature. In this regard, a biosystem is assumed to be in the state of unstable equilibrium. Therefore, only a weak stimulus is required to put the system in a new state, at the expense of its intrinsic energy resources. In other words, the so-called biological amplification of a weak MF signal takes place. Chemical kinetic equations are used for the phenomenological description of this process. Under certain conditions, their solutions demonstrate a bifurcation behavior, the transition under weak disturbance into a qualitatively different dynamic mode (Kaiser, 1996).

Coherent excitations

Thermal fluctuations of the kT scale are ten orders greater than the quantum of the AC MF energy. In this case, the question is important — why do these random disturbances not destroy the MBE? A solution of the problem is suggested which is related to the idea of coherence of the external stimulus, against the background of incoherent thermal noise. Then a high quality molecular oscillator may be swung up (time coherence) to a condition, in which its energy will be sufficient for an initiating push. In addition, a system of oscillators may be swung up, in a time-space coherent manner, so that the quantum of a collective excitation will be released (Frohlich *et al*, 1983; Popp *et al*, 1979). Different microscopic objects were suggested as oscillators interacting with MF: charged molecular groups, plasmatic membranes, and whole organelles. It is significant that neither the idea of a biological oscillator, nor the idea of collective excitations have resulted in verifiable theoretical mechanisms in the ELF MF range yet. At best, time and amplitude threshold for the microwave exposure is predicted, which is necessary for a biological response to occur (Wu, 1996).

Stochastic resonance

One more idea to overcome the thermal factor appeals to the so-called stochastic resonance. The phenomenon consists in strengthening of a small signal against the background of a noise, at the expense of energy redistribution within the frequency spectrum of the signal-noise mix. It is crucial that the noise here is a useful feature of the system, not an embarrassment. In the case of a stochastic resonance, relatively weak physical or biological signals can cause essential dynamic changes, against the background of many disturbing factors. In (Wiesenfeld *et al*, 1995), the response of a crayfish mechanoreceptor cells to an acoustic stimulus, in the form of the mixture of a subthreshold signal and a Gaussian noise, satisfied attributes of a stochastic resonance. The phenomenon was made use of for solving *kT* problem in magnetobiology in (Makeev, 1993; Kruglikov *et al*, 1994). However, only about 100 fold strengthening were really achieved, with the loss of the quality of the signal, that is, its time coherence (McNamara *et al*, 1989). Such values are obviously not enough for the explanation of the biological efficacy of weak ELF MFs.

Radical pair reactions

The rate of some free radical reactions depends on the value of the static MF (Buchachenko *et al*, 1978). The probability of the product creation from a pair of radicals, which carry spin angular momentum, depends on their net spin momentum, that is, on the mutual orientation of their spins. A static MF influences the probability of a suitable orientation, thus shifting the biochemical balance. At the same time, this mechanism does not possess frequency selectivity. The lifetime of the radical pair until reaction or, on the contrary, until dissociation, that is, when the bound couple of radicals are susceptible to MF, is of the order of 10^{-7} sec. The pair perceives the ELF MF as a static field; no resonance does appear. Therefore, for explanation of frequency and amplitude windows in MBE, the magnetosensitive free radical reaction is assumed to be a link of the complex non-linear system described by chemical kinetic equations with bifurcation (Grundler *et al*, 1992; Kaiser, 1996). Difficulties of this group of models stem from the primary MF influence on the radical reaction rate. There is a set of physico-chemical reasons that restrict susceptibility of the rate to MFs by quantities of the order of 0.1% per G. It is not enough for MBE to be explained in reliable manner.

Cyclotron resonance

In a number of cases, the effects of weak MFs are resonant in character, and the effective frequencies are close to cyclotron frequencies of ions Ca^{++}, Na^{+} and others. It has given the basis to assume that a cyclotron resonance underlies the observable phenomena. Many authors developed the theme of such resonance in magnetobiology. Nonetheless, it has not received recognition due to the lack of correct physical substantiation. At the same time, these experiments showed the essential role of ions, especially Ca^{++}, in magnetobiology.

To overcome weakness of the cyclotron resonance idea, macroscopic charged clusters or vortices formed by bunches of ions in biological plasma were postulated (Karnaukhov, 1994). These targets for MF effects were chosen because of their relatively large own energies, which may be comparable to *kT*. Then, even a weak MF can change significantly the energy of a vortex bearing, for example, a macroscopical electric charge. Yet, strictly determined conditions of the vortex movement are needed. In particular, the movement of the center of mass must be characterized by an angular momentum, otherwise MF can’t deliver energy to the moving object (Binhi, 1995). It is doubtful if such a motion is real for a macroscopic object like vortex in bioplasma. Moreover, the comparison between the energy of a vortex and *kT* makes sense only with existence of a conversion mechanism for that vortex energy to be transformed to the energy of a separate degree of freedom, that is, to the microscopic level. It is difficult to visualize such a mechanism. In addition, the physical nature of molecular forces, which could provide the existence and stability of the aforementioned clusters and vortices, is unclear.

Parametric resonance

Some biological effects of the MF modulated on its magnitude reveal windows of efficiency when scanning the frequency and the amplitude of the AC MF component. Frequency and amplitude spectra of MBEs are rather informative in terms of revealing the primary physical mechanisms of magnetoreception. For explanation of the MBE spectra, there were used different conversion mechanisms of the MF signal at the level of microscopic dynamics. Classical and quantum models of the ion binding by some proteins were studied in (Chiabrera *et al*, 1987; Chiabrera *et al*, 1991; Lednev, 1991). The biological activity of some proteins depends on whether or not the ion is bound with the protein. The value of MBE was assumed to vary approximately as the intensity of ionic quantum transitions. The MF was supposed to affect this intensity. However, collinear static and AC MFs affect only phases of wave functions, and do not really cause transitions in the Zeeman sublevels, or change intensity of such transitions induced by other factors. The population of each quantum state remains exactly constant regardless of the MF parameters. In spite of this, it was possible to demonstrate in (Lednev, 1991) the similarity of the amplitude spectra of some MBE and those of the effect of the parametric resonance in atomic spectroscopy. The last resonance deals with quantum transitions (for example, Alexandrov *et al*, 1991). This entailed a number of publications (Blanchard *et al*, 1994; Lednev, 1996), which did not clarify the relationship, though. The authors call the above-indicated controversial mechanisms "parametric resonance of bound ions."

Ion interference

In (Binhi, 1997; Binhi, 1997a), the known phenomenon of the interference of quantum states is involved for explanation of the physical nature of magnetoreception. MF, which is varied in its magnitude, not in direction, changes only the phases of ion wave functions. It is an interference that connects phase changes to physical observables in quantum mechanics. The interference of quantum states was observed in physical measurements either for free particles, including relatively heavy particles up to atoms, or for bound particles. In the latter case, the interference was observed only indirectly, through the characteristics of re-emitted electromagnetic fields. It reduced particles, suitable for the interference manifestations, to electrons in atoms. It has been suggested that the interference of bound heavy ions is also observable, by means of indirect biological measurements, with involvement of natural active biophysical structures (Binhi, 1997). This idea finds corroboration (Binhi, 1998a, 1999) in a good agreement with known experiments. The interference of bound ions may be regarded as a hitherto unknown physical effect detectable in principle only by means of biochemical or biological measurements. The interference of quantum states in atomic spectroscopy is related with coherent quantum transitions in atomic electron levels and is not related to the internal structure of electron wave functions. At the same time, it is the internal structure of ion wave functions that the ion interference is based on, even in the absence of any quantum transitions. As of today, the ion interference mechanism predicts multi-peak effects in the following cases:

— magnitude/direction modulated MF
— magnetic vacuum
— static MF with allowance for the own rotations of ion-protein complexes
— pulsed MF with an DC MF as the background
— MF of the NMR frequency subject to spin degrees of freedom of ionic isotopes
— the interference of states of a quantum rotator with distributed charge as the model of amino acid molecule
— weak AC electric fields
— the shift and splitting of MBE spectral peaks under the rotation of biological samples.

Appropriate biological effects, except for the last, were really observed in experiments. The formulas provide the dependence of the ion-protein dissociation probability from the MF parameters, the frequency of the AC component, the amplitudes and mutual orientation of the AC and DC components. Significant features of the MBE spectra calculated after the mechanism depend on masses, charges, and magnetic momenta of the involved ions. In most of the cases under study, ions of calcium, magnesium, zinc, and hydrogen and sometimes potassium appeared to be relevant.

Metastable water states

One of the primary MBE mechanisms associates MF effects with altered states of liquid water in biological media (Fesenko *et al*, 1995; Binhi, 1992; Konyukhov *et al*, 1995). The changes in water are a consequence of the external field influence; they are transmitted further to the biological level at the expense of water taking part in a variety of the metabolic biochemical reactions. It is unclear today, what is it exactly in liquid water that could be the target for MF action? In (Fesenko *et al*, 1995a), the stable water-molecular clusters were discussed based on observed low-frequency spectra of the water electric conductivity. The clusters were assumed to memorize an electromagnetic activation. The stable changes in structure properties of water were observed in (Lobyshev *et al*, 1995) using the UV luminescence spectrophotometer. They have been attributed to different water structure defects that include specific centers of luminescence. Alterations in the biological activity of liquid water were found in (Rai *et al*, 1994) with the static MF influence, in (Akimov *et al*, 1998) after the influence of a domestic TV. In (Binhi, 1992), the nuclear proton spins were considered as primary targets of MF. The metastability of water states was associated with microscopic orbital currents of protons in water-molecular hexagons, and the deviation from the right stochiometric composition of water. Existence of these states is verifiable in relatively easy experiments (Binhi, 1998b). The effects of memory of water, interacting with EMF, were observed in

(Sinitsyn *et al*, 1998) in radio-frequency spectra. The effect was supposed to originate from the oscillations of water-molecular hexagons.

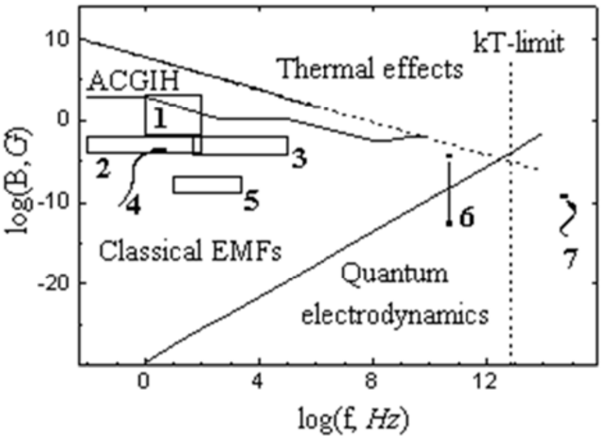
An increasing number of investigations demonstrate that very weak MFs, at the level 0.1 G and less, can also affect biological systems. These data, schematically depicted in the Figure, are of significant concern because they are hardly consistent with any of the proposed mechanisms. It poses the question of physical constraints defining the possible fundamental nature of the biological effects of hyperweak MFs. Figure shows several theoretical limits of different mechanisms and descriptions of EMF bioeffects. The *kT* and thermal limits are well known. The last was derived repeatedly in many scientific researches and works on EMF standardization. The quantum electrodynamics limit needs further comment.

Theoretical limits

Interaction between EMF and a substance is classified within the different types of description, classical or quantum, both of EMF and field of matter. The most of supposed primary mechanisms applies classical material particles interacting with classical EMF, a wave field. Recent predictive mechanisms, which use the quantum description of ions in classical EMFs, are based on the so-called semiclassical approximation. QED sets conditions for a classical EMF description to be valid: populations of states of EMF oscillators must be sufficiently large compared to unit. It follows the relation that links the frequency and the classical amplitude of the magnetic EMF component: $H > (hc)^{1/2}(2p/c)^2f^2$. This limit, the lower inclined line, is shown in Figure. As is seen, all "low frequency" effects but the hyperweak MM radiation effects do require only classical EMF description. However, this does not set the minimal intensity of EMFs detectable by biological systems. The natural constraint on the electromagnetic susceptibility of the biological reception, as well as that of any receiver of the physical nature, relates to general QM lows.

There is the relation $et > h$ between the minimal energy change e and the time t required for its registration. Consequently, for example, an ELF EMF photon of the frequency f to be registered by any system, including biological one, the time $t=1/f$ is to be spent, at least. At the same time, this relation also does not set a lower limit of the susceptibility to EMFs.

The figure illustrates various limits and areas of EMF biological effects as functions of two variables, EMF frequency f and amplitude B. The large scale of both the variables is chosen to show qualitatively different cases of the effects and theoretical approaches. A quantum of EMF energy is less than kT to the left of the dashed vertical line. This line defines a paradoxical area, wherein the biological effects are not possible from the orthodox viewpoint. The top downward line separates very approximately areas of thermal and nonthermal EMF bioeffects. The lower upward line is the QED limit. EMFs are to be described as a quantum object below this line. The step-inclined line is the ACGIH limit for the safe levels of the EMF exposure.



Seven areas marked by digits mean ranges of parameters of: **1** – ELF EMFs used in most of magnetobiological experiments; **2** – EMFs produced by magnetic storms that are known to correlate in time with peaking of cardiac-vascular diseases; **3** – background EMFs produced by the variety of home appliances, video display terminals such as TV and computer monitors; **4** – MFs that affect some amino-acid solutions (Fesenko *et al*, 1997); **5** – MFs calculated at 0.5 m from the TecnoAO protective device, Tecnosphere, France, patent No.93/00546 (Youbicier-Simo *et al*, 1996, 1998), which protects against harmful VDT irradiation; **6** – EMFs below a quantum electrodynamics limit, used in (Belyaev *et al*, 1996), that significantly affect cell culture; **7** – susceptibility threshold of the human eye. As is seen, almost all the magnetobiology falls into the paradoxical area, to the left of *kT* limit.

kT problem

The most important and equally paradoxical problems concerning MFs of the geomagnetic level, are as follows. 1) A mechanism or process of conversion of the MF signal to the biochemical response, whose energy scale *kT* is ten orders greater than the quantum of ELF MF energy. 2) Why thermal fluctuations of the same order *kT* do not destroy the indicated weak signal conversion. At first sight, the paradox of the second problem is much more drastic, because an "obvious" solution of the first one is in the signal energy storage or in the signal amplification. Therefore, the main attention was paid to the solving of the second problem, with the almost arbitrary choice of the conversion mechanism. However, it is the conversion mechanism that the description of "window" multi-peak spectra depends on. This mechanism defines the predictive force of the model. Thus, as of today, there are no *predictive* models solving both the problems simultaneously. At the same time, predictive models (Binhi, 1997, 1998a, 1999) have appeared; and they solve the first problem. This characterizes the current state of theoretical studies in the field of magnetobiology. The predictive force of such models means that the biological effects of weak MFs, as an important ecological factor, are becoming predictable as well.

References

- W.R. Adey. Biological effects of electromagnetic fields. J. Cell Biochem., 51:410–416, 1993.
- A.E. Akimov, V.N. Binhi, N. Yu. Lasareva. Alterations of the biological activity of liquid water under the influence of the domestic TV irradiation. Consciousness and Physical Reality, 3(1):72–74, 1998. In Russian.
- Ye.B. Alexandrov, G.I. Khvostenko, M.P. Chaika. Interference of the atomic states. Nauka, Moscow, 1991, pp.256. In Russian.
- I.Ya. Belyaev, V.S. Shcheglov, Ye.D. Alipov, and V.A. Polunin. Resonance effect of millimeter waves in the power range from 10^{-19} to 3.10^{-3} W/cm^2 on Escherichia coli cells at different concentrations. Bioelectromagnetics, 17:312–321, 1996.
- H. Berg and L. Zhang. Electrostimulation in cell biology by low-frequency electromagnetic fields. Electro- and Magnetobiology, 12(2):147–163, 1993.
- V.N. Binhi. Biomagnetic correlations and the hypothesis of current states of a proton in water. Biophysics, 37(3):502–505, 1992.
- V.N. Binhi. Nuclear spins in primary mechanisms of biomagnetic effects. Biophysics, 40(3):671–685, 1995.
- V.N. Binhi. Interference of ion quantum states within a protein explains weak magnetic field's effect on biosystems. Electro- Magnetobiology, 16(3):203–214, 1997.
- V.N. Binhi. The mechanism of magnetosensitive binding of ions by some proteins. Biophysics, 42(2):317–322, 1997a.
- V.N. Binhi. Interference mechanism for some biological effects of pulsed magnetic fields. Bioelectrochemistry and Bioenergetics, 45:73–81, 1998a.
- V.N. Binhi. Structural defects of liquid water in magnetic and electric fields. Biomedical Radioelectronics, (2):7–16, 1998b. In Russian.
- V.N. Binhi. A formula for frequency and amplitude windows of some ELF and null MF bioeffects follows from the Schroedinger equation. In F. Bersani, editor, Electricity and Magnetism in Biology and Medicine. Kluwer Academic, Plenum Publishing Corporation, 1999, NY, pages 417–421.
- C.F. Blackman, S.G. Benane, and D.E. House. Evidence for direct effect of magnetic fields on neurite outgrowth. FASEB Journal, 7:801–806, 1993.
- J.P. Blanchard and C.F. Blackman. Clarification and application of an ion parametric resonance model for magnetic field interactions with biological systems. Bioelectromagnetics, 15:217–238, 1994.
- M. Blank, editor. Electricity and Magnetism in Biology and Medicine. San Francisco Press, San Francisco, 1993.
- A.L. Buchachenko, R.Z. Sagdeev, and K.M. Salikhov. Magnetic and Spin Effects in Chemical Reactions. Nauka, Novosibirsk, 1978, pp.294.

- Chiabrera and B. Bianco. The role of the magnetic field in the em interaction with ligand binding. In M. Blank and E. Findl, editors, Mechanistic Approaches to Interactions of Electric and Electromagnetic Fields with Living Systems, pages 79–95. Plenum, New York, 1987.
- Chiabrera, B. Bianco, J.J. Caufman, and A.A. Pilla. 1. Quantum dynamics of ions in molecular crevices under electromagnetic exposure. 2. Quantum analysis of ion binding kinetics in electromagnetic bioeffects. In C.T. Brighton and S.R. Pollack, editors, Electromagnetics in Medicine and Biology, pages 21–26; 21–31. San Francisco Press, San Francisco, 1991.
- E.E Fesenko, V.I. Geletyuk, V.N. Kazachenko, and N.K. Chemeris. Preliminary microwave irradiation of water solutions changes their channel- modifying activity. FEBS Letters, 366:49, 1995.
- E.E Fesenko and A.Ya. Gluvstein. Changes in the state of water, induced by radio-frequency electromagnetic fields. FEBS Letters, 367:53, 1995a.
- E.E. Fesenko, V.V. Novikov, and Yu.P. Shvetsov. Molecular mechanisms of the biological effects of weak magnetic fields. Biofizika, 42(3):742–745, 1997. In Russian.
- H. Frohlich and F. Kremer, editors. Coherent Excitations in Biological Systems. Springer-Verlag, New York, 1983.
- W. Grundler, F. Kaiser, F. Keilmann and J. Walleczek. Mechanisms of electromagnetic interaction with cellular systems. Naturwissenschaften, 79:551–559, 1992.
- K.A. Jenrow, C.H. Smith, and A.R. Liboff. Weak extremely-low-frequency magnetic fields and regeneration in the planarian Dugesia tigrina. Bioelectromagnetics, 16:106–112, 1995.
- J.P. Juutilainen. Effects of low frequency magnetic fields on chick embryos. Dependence on incubation temperature and storage of the eggs. Z. Naturforsch., 41C:1111–1115, 1986.
- F. Kaiser. External signals and internal oscillation dynamics: biophysical aspects and modeling approaches for interactions of weak electromagnetic fields at the cellular level. Bioelectrochemistry and Bioenergetics, 41:3–18, 1996.
- A.V. Karnaukhov. Dissipative structures in weak magnetic fields. Biofizika, 39(6):1009–1014, 1994. In Russian.
- J.L. Kirshvink, A. Kobayashi-Kirshvink, J.C. Diaz-Ricci, and S.J. Kirshvink. Bioelectromagnetics S, 1:101, 1992.
- Yu.A. Kholodov and N.N. Lebedeva. Reactions of the Human Nerve System on the Electromagnetic Fields. Nauka, Moscow, 1992. In Russian.
- A.K. Kobayashi, J.L. Kirschvink, and M.H. Nesson. Ferromagnetism and EMFs. Nature, 374:123, 1995.
- V.K. Konyukhov, V.P. Logvinenko, and V.I. Tikhonov. Separation of the spin-modifications of water and determination of the spin-conversion time in water molecules. Brief Reports on Physics of P.N. Lebedev’s Physical Institute RAS, (5–6):83–86, 1995. In Russian.
- I.L. Kruglikov and H. Dertinger. Stochastic resonance as a possible mechanism of amplification of weak electric signals in living cells. Bioelectromagnetics, 15:539–547, 1994.
- V.V. Lednev. Possible mechanism for the influence of weak magnetic fields on biological systems. Bioelectromagnetics, 12:71–75, 1991.
- V.V. Lednev. Bioeffects of weak combined, static, and alternating magnetic fields. Biofizika, 41(1):224–232, 1996. In Russian.
- Lerchl, K.O. Nonaka, and R.J. Reiter. Pineal gland “magnetosensitivity” is a consequence of induced electric eddy currents. J. Pineal Res., 10:109–116, 1990.
- A.R. Liboff. Geomagnetic cyclotron resonance in living cells, J. Biol. Phys., 13:99–102, 1985.
- A.R. Liboff, S.D. Smith, and B.R. McLeod. Experimental evidence for ion cyclotron resonance mediation of membrane transport. In M. Blank and E. Findl, editors, Mechanistic Approaches to Interactions of Electric and Electromagnetic Fields with Living Systems, pages 109–132. Plenum, New York, 1987.
- V.I. Lobyshev, B.D. Ryzhikov, R.E. Shikhlinskaya. The peculiarities of water luminescence stipulated by the polymorphism of its structure. Vestnik MSU, series Physics and Astronomy, 36(2):48, 1995. In Russian.
- V.M. Makeev. Stochastic resonance and its possible role in living nature. Biofizika, 38(1):194–201, 1993. In Russian.
- Polk. Biological effects of low-level low-frequency electric and magnetic fields. IEEE Transactions on Educat., 34(3):243–249, 1991.
- F.S. Prato, J.J.L. Carson, K.P. Ossenkopp, and M. Kavaliers. Possible mechanism by which extremely low frequency magnetic fields affect opioid function. The FASEB Journal, 9:807–814, 1995.
- S. Rai, U.P. Singh, K.P. Singh, and A. Singh. Germination responses of fungal spores to magnetically restructured water. Electro- and Magnetobiology, 13(3):237–246, 1994.

- S.M. Ross. Combined dc and ELF magnetic fields can alter cell proliferation. Bioelectromagnetics, 11:27–36, 1990.
- J. Schimmelpfeng and H. Dertinger. Action of a 50 Hz magnetic field on proliferation of cells in culture. Bioelectromagnetics, 18:177–183, 1997.
- N.I. Sinitsyn, V.I. Petrosyan, V.A. Yolkin, N.D. Devyatkov, Yu.V. Gulyaev, O.V. Betskii. Particular role of a “MM wave — water medium” system in the nature. Biomedical Radioelectronics, (1):5–23, 1998. In Russian.
- K. Wiesenfeld and F. Moss. Stochastic resonance and the benefits of noise: from ice ages to crayfish and squids. Nature, 373:33–36, 1995.
- T.M. Wu. Quantum mechanical concepts of coherent states in biological systems. Bioelectrochemistry and Bioenergetics, 41:19–26, 1996.
- B.J. Youbicier-Simo, F. Boudard, and M. Bastide. Bioeffects of continuous exposure of embryos and young chickens to ELF displayed by desk computers: protective effect of Tecno AO antenna. In Abstract Book of 3 Intern. Congress of the EBEA, Nancy, France, 1996.
- B.J. Youbicier-Simo, J.C. Lebecq, and M. Bastide. Damage of chicken embryos by EMFs from mobile phones: Protection by a compensation antenna. In Abstract Book of the 20-th Annual BEMS Meeting for Electricity and Magnetism in Biology and Medicine. St. Petersburg, Florida, USA, June 7–11, 1998.