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Review of Russian Literature on Biological Action of DC and Low-Frequency AC Magnetic Fields

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This review considers the Russian scientific literature on the influence of weak static and of low-frequency alternating magnetic fields on biological systems. The review covers the most interesting works and the main lines of investigation during the period 1900 to the present. Shown here are the historical roots, beginning with the ideas of V. Vernadsky and A. Chizhevsky, which led in the field of Russian biology to an increasing interest in magnetic fields, based on an intimate connection between solar activity and life on the Earth, and which determined the peculiar development of Russian magnetobiology. The variety of studies on the effects of magnetic storms and extremely low-frequency, periodic variations of the geomagnetic field on human beings and animals as well as on social phenomena are described. The diverse experiments involving artificial laboratory magnetic fields acting on different biological entities under different conditions are also considered. A series of theoretical advances are reviewed that have paved the way for a step-by-step understanding of the mechanisms of magnetic field effects on biological systems. The predominantly unfavorable influence of magnetic fields on living beings is shown, but the cases of favorable influence of magnetic fields on human beings and lower animals are demonstrated as well. The majority of Russian investigations in this area of science has been unknown among the non-Russian speaking audience for many reasons, primarily because of a language barrier. Therefore, it is hoped that this review may be of interest to the international scientific community. Bioelectromagnetics 22:27–45, 2001. © 2001 Wiley-Liss, Inc.

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INTRODUCTION

In Russia, interest in the biological action of magnetic fields has roots stretching back to the end of the 19th century. In 1881, in St. Petersburg, the book ‘‘Metalloscopy and Metallotherapy’’ by N. Grigor’jev was published, in which the author compiled the data on the therapeutic action of magnetic fields (MF) into one complete volume. In 1900–1901 in Kharkov, the two-volume monograph ‘‘Research in Physiological Action of Electricity over a Distance’’ by the Russian physiologist V. Danilevsky, was published. Most part of the monograph was devoted to the description of reactions of the central nervous system to electromagnetic fields (EMF). The author considered as his task not only ‘‘action of electricity over a distance,’’ but action of EMF and MF too. V. Danilevsky defined the following questions as a general problem: ‘‘... the influence of a magnetic flow, electric and electromagnetic field, the influence of electric rays in a variety of their forms, combinations, including action of currents of high voltage and high frequency over a distance, and so on. The objectives for investigation should not only be preparations of nerves and muscles, but of the whole organism as well, including the prokaryotes.’’

In the 1920s, a concept put forth by V. Vernadsky [1926, 1960] and A. Chizhevsky [1931, 1973] concerning the important role of cosmic processes in the rise of life and humanity on the Earth profoundly influenced those in the biological sciences. Vernadsky considered the Universe united with the motion of star systems, the organization of life and the development of human society. Chizhevsky found the common ties of relationship spreading all over the background of life in the Universe. Later, A. Pressman [1968, 1971, 1976], developing the ideas by Vernadsky and Chizhevsky further, considered EMFs as a bearer of general information in animate nature, the biosphere,

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and the cosmos. In light of this concept, Vernadsky, Chizhevsky, and Pressman found a unity of processes in the solar system, the controlling action of the Sun on the Earth's biosphere, the influence of bursts of the solar activity on disturbances in the geomagnetic field, and the action of these disturbances on the life processes on the Earth as quite natural things.

Of course, individual aspects of this concept may be accepted or rejected, but it exerted strong influence on the minds of many researchers, channeling them into investigation of the influence of solar activity on the terrestrial biosphere and the study of MF action on living objects. The concept launched investigations directed to revealing the influence of magnetic storms on human beings and animals, and it stimulated a variety of research projects that involved the action of laboratory MFs on biological systems.

These investigations into the biological actions of EMF and MF have been performed for long periods of time and on a large scale. Since 1964, various cities and institutions have been holding conferences and symposia devoted to the various aspects of this problem. The Academy of Science of the USSR has also given attention to this line of investigations. Since 1970, in Moscow, the permanent seminar "Biological Systems and Magnetic Fields" (Chairman Prof. Yu. Kholodov) of the Scientific Council on the complex problem of "Cybernetics" at the Academy of Science of the USSR (now the Russian Academy of Science) has been in progress. In 1992, the Problem Committee "Influence of Electromagnetic Irradiation on Biological Systems" (Chairman Prof. M. Zhadin) at the Scientific Council on the Problems of Biological Physics of the Russian Academy of Science was established. Working scientific groups and laboratories were formed not only in Moscow and Leningrad (now St. Petersburg), but also in other cities and towns such as Pushchino, Novosibirsk, Tomsk, Simferopol, Saratov, Samara, Rostov-on-Don, Troitsk, and Dubna. Every year, many interesting publications are being issued in various scientific journals and collections of scientific works. At the end of the 1960's and in the 1970's, the number of publications on the biological action of MFs coming out in the USSR was more than twice as large as in Western Europe and the USA combined [Kholodov, 1982]. This interest was created by the works by Vernadsky and Chizhevsky. The scientific and social activities of Prof. Kholodov also played an important role in this process.

However, the abundance of Russian scientific publications on biological and medical effects of DC and AC MFs resulted from Russian magnetobiology mainly taking the path of expanding the diversity of objects for MF action. Unfortunately, the mutual control of results obtained in one institution through attempts at reproduction in other institutions and the discussions connected with such sorts of control were of limited occurrence in Russian magnetobiology. Clearly, this could not help being reflected in the content of this review. The scientific level and degree of statistical validity of results greatly varied from article to article. We chose the most interesting and most reliable works for our review.

Over a period of decades, Russian magnetobiology was developed in conditions of relative isolation, primarily because of a language barrier and lack of contact with foreign scientists. But this situation changed in 1980's–1990's. The intercourse between Russian scientists and Western scientists, especially Americans, began strengthening. The visits of Profs. W. R. Adey, A. Guy, F. Barnes, R. Liburdy, A. Liboff, L. Anderson, H. Wachtel, B. Veyret and others to Russian laboratories and Profs. I. Akoev, M. Shandala. Yu. Kholodov, V. Lednev. E. Fesenko, M. Zhadin and others to the USA allowed for cross-fertilization of ideas between Russian and Western scientists and promoted gradual inclusion of the Russian magnetobiology into international science. At present this process is quickly developing. It should be noted that the majority of Russian investigations in biological action of DC and ELF MFs has been unknown among the non-Russian speaking audience. The recent general review [Zolin, 1995] that is mainly devoted to the high frequency EMF gave little information about influence of DC and ELF MFs. Solving this problem is a goal of the present review.

SOLAR ACTIVITY, THE GEOMAGNETIC FIELD, AND LIFE

The geomagnetic field (GMF) is a factor acting constantly over the entire surface of the Earth. Living beings can escape its action only under conditions of special laboratory shielding. The magnitude and direction of the GMF are different in different areas of the Earth. It varies from ~35 μT in the equatorial areas, where it is mainly parallel to the terrestrial surface, to ~70 μT in the vicinity of the magnetic poles of the Earth, where it is near-vertical. The GMF rather weakly varies with time. The variations of the GMF are very small compared with its own magnitude and are mainly caused by the Sun's influences. The magnetic storm (MS) is the most essential and prominent disturbance of the GMF.

The MS presents a sharp disturbance of the GMF that embraces the whole Earth and that lasts from several hours to several days [Yanovsky, 1964]. Its maximum magnitudes are up to 5 μT and are observed in the high latitudes; in the middle latitudes they reach values of about 1 μT. Four general phases of the MS are recognized: preliminary, initial, main, and recovery. In the preliminary phase, small changes in the GMF are observed. In the initial phase, a drastic change in the GMF takes place all over the Earth; and in the main phase, severe, quasi-periodical oscillations (mainly low frequency and ELF), and a drop in the horizontal component of the GMF also, occur all over the entire Earth. During the recovery phase, all these changes fade exponentially.

The MSs are induced by the solar plasma flows from the areas of bursts of the solar activity and reach the Earth 1.5–2.0 days after the Sun burst. The proton flows, rotating around the Earth under the action of the GMF, form an equatorial current ring, the MF of which weakens the GMF in the main phase of the MS. The MSs arise sporadically ten or more times a month. But their strength and the average frequency of their occurrence reveal extremely slow quasi-periodic oscillations with a period about 11 years, together with oscillations in the solar activity.

The Sun emits repetitive electromagnetic and corpuscular irradiation: the solar wind, as it is called, rotates with the Sun's rotation around its axis and fills the solar system's space [Vladimirsky, 1980]. The solar wind consists of four sectors, two with magnetic force-lines directed away from the Sun, marked as positive, and two with opposing force-lines, marked as negative.

Therefore, there are several periods of variation in the GMF, apart from the 11 year cycle: the 1 day cycle due to the Earth's rotation, the 6–7 day cycle corresponding to one sector, the 13–14 day cycle corresponding to the passage of two sectors, and the 27 day cycle that is the period of the Sun's rotation around its own axis. Besides these, there are other cycles: the 29.5 day (the synodic period of the Moon), 1 year (the period of the Earth's revolution), and some other cycles of the solar activity (not so prominent compared to the main 11 year cycle): 2, 3, 5, 8, 22, and 35 year cycles.

Apart from the above listed rhythms of an astronomic nature of the GMF, there is a continuous spectrum of quasi-periodic, low-frequency processes in the GMF, which are caused by oscillations in the plasmasphere and the magnetosphere of the solar wind and of the resonant oscillations in the ionosphere of the Earth, known as Schumann resonances [Vladimirsky, 1980; Sidjakin et al., 1985; Vladimirsky et al., 1995; Temur'jants et al., 1992b]. This spectrum has its maxima near the following frequencies: 100, 21, 8, 3, 1, 0.1, 0.01, and 0.001 Hz. These frequencies have been the focus of attention of researchers, especially the frequency 8 Hz, the most prominent among those just listed.

Plants and animals living constantly in the GMF have adapted to its action and have even learned to benefit from it. The orientation of birds (e.g., pigeons and sea gulls) to the GMF is long- and widely-known [Yeagley, 1947; Kholodov, 1975; Kirschvink et al., 1985; Barnes, 1996]. In the acoustico-lateral area of the skate's brain are two groups of neurons: one group excited by the MF with the South sense and the other group inhibited by the MF with the Northern sense [Broun et al., 1977]. Only the neurons connected with the respective electroreceptive system were responsive. As for plants, it was shown that the GMF participates in the orientation of the branches of the root system [Bogatina et al., 1986] and that it plays a role in the metabolism in root meristem cells [Beljavskaja et al., 1992], in the proliferative activity of these cells [Fomichjova et al., 1992a], in protein synthesis in plants [Fomichjova et al., 1992b], and in branching of plants [Govorun et al., 1992].

For the purpose of revealing the role of the GMF in the life of animals and plants, a number of experiments were performed in which the GMF was shielded in special chambers with a shielding index of several tens up to 100. These experiments were rather difficult to perform, due to the necessity of generating all ecological and environmental parameters (the level of ionizing irradiation, concentration of all air ions, the level of acoustic noise etc.) within the shielded chamber. Unfortunately, there is always an uncertainty as to whether sufficiently complete precautionary measures were taken in these experiments. So there lingers some doubt when considering the results of these experiments. These experiments are described in detail in some monographs [Pavlovich, 1985; Temur'jants et al., 1992b] and in reviews [Kopanev et al., 1979; Grigor'jev, 1995].

Depression of vital functions of bacteria was found [Achkasova, 1973; Alfjorov and Kuznetsova, 1981] in the weakened GMF. The disturbance in rhythms of cell division of fibroblasts of the human embryo [Kaznacheev and Mikhajliva, 1985] and some cytopathic effects, for example an increase in sensitivity of the cell culture to poisons [Kaznacheev et al., 1989], were observed. The decrease in the erythrocyte sedimentation rate was marked in the weakened GMF [Sosunov et al., 1972; Golubchak and Vasilik-Parkula, 1973]. As a result of housing rats in shielded chambers for several days, it fell by 50% [Panasjuk et al., 1991]. Learning processes were investigated in rats whose conception, and embryonic and postnatal development occurred in hypogeomagnetic conditions [Grigor'jev, 1995]. Effect on these rats was manifested in an increase in the rate of learning. The concentration of catecholamines increased in their brain (in the hippocampus). However, the lag of imprinting in chickens hatched out in the shielded chamber was doubled.

In the shielded chamber, Podkovkin [1995] subjected guinea-pigs to a DC MF ten times weaker than the natural GMF for 30 min. An increase of epinephrine and histamine levels and a decrease of serotonin level in blood were observed. Another group of animals was previously exposed to a 2 Gy X-radiation. After 30 days, when all biochemical parameters caused by the X-radiation became normal, the animals were enclosed in the shielded chamber for 30 min. In this case the action of the weakened GMF did not influence the epinephrine and serotonin levels, and the effect on the histamine level was essentially weaker compared to that for guinea-pigs that were not exposed to the preliminary X-radiation.

A weakened GMF also influenced plants. A set of specific features of cells in the meristem of seedling roots of pea, flax and lentil under conditions of GMF shielding was revealed by electron microscopy. Changes in different subcellular structures, especially in mitochondria, were found [Beljavskaja et al., 1992]. A 68–75% reduction in proliferation of meristem of these seedling roots was observed [Fomichjova et al., 1992a]. The dynamics of RNA and protein synthesis in cells of this root meristem was also investigated [Fomichjova et al., 1992b]. A fall was shown in functional genome activity in all the plants examined under GMF shielding during the early prereplicative period.

The most spectacular manifestation of the influence of the solar activity on GMF disturbances are the Sun bursts. The influence of solar activity on the GMF, the biosphere and social processes was noted as early as in the beginning of the century [Anuchin, 1908; Bogolepov, 1912]. However, this idea arose in its entirety in the works of Chizhevsky [1928, 1931, 1973] as the first great interdisciplinary problem in the history of science: "Solar Activity—Biosphere—Society" [Vladimirsky, 1995]. He formulated the following important empirical regularities:

1) Solar activity is of a broad nature, and it influences all living beings from bacteria to human beings;
2) The 11 year cycle is prominent in many phenomena of the organic world, but different phenomena have different phases regarding the solar cycle and are affected by either a maximum or a minimum of the solar activity;
3) The degree of prominence of the 11 year cycle for a given biological parameter and its phase can be different in different geographic areas, and over a large territory these changes tend toward "compensation";
4) The physical factor mediating the action of solar activity on living beings and the biosphere is mainly the EMF.

Chizhevsky's belief that revolutions and social catastrophes are influenced by solar activity led him to prison. His books were withdrawn from libraries. In 1942 he was arrested. He was released as late as 1958 and a few years later, in 1964, he passed away [Yagodinsky, 1987]. It was only as late as 1973 that his remarkable monograph, "The Terrestrial Echo of Solar Storms," was republished, becoming available once again to scientific society.

Magnetic storms correlate with anxiety and irritability in people, lower attention and accuracy in their work, which raises the probability of transport accidents [Ashikaliev et al., 1995] and of mistakes by airmen in piloting planes [Derjapa et al., 1986; Usenko et al., 1989]. In the course of magnetic storms, the number of ambulance calls increases [Sergeenko and Kuleshova, 1995; Oraevsky et al., 1995] and glaucoma attacks rise [Zhokhov and Indejkin, 1970; Kachevanskaja, 1989]. The information about acute attacks of cardiovascular diseases is especially abundant [Klimov et al., 1980; Novikova et al., 1989; Rozhdestvenskaja et al., 1989; Gurfinkel' et al., 1995; Tyvin et al., 1995; Villoresi et al., 1995; and others]. An essential increase in the number of cases of instantaneous death from cardiovascular disease takes place on these days [Gnevyshev et al., 1982]. Most of the cited data were obtained by correlation of the known days with MSs with many years of records from the proper institutions. All the data were statistically significant.

The correlation between medical parameters as well as social events and different data sets from typical cycles (7 day, 27 day, 29.5 day, 2, 3, 5, 8, 11, 22, 35 year cycles) of variations in the solar activity were revealed by spectral Fourier analysis in investigations of records for deterioration of functional state of the human nervous system [Belisheva et al., 1995], psychopathic attacks [Rudakov et al., 1984], cases of hospitalization of schizophrenia, alcoholic psychosis, and epilepsy patients [Samokhvalov, 1989], risk of breast cancer in women [Rjabykh and Bodrova, 1992], rates of mortality and birth [Zajtseva and Pudovkin, 1995], the number of registered crimes [Chibrikin et al., 1995a], the size of money issued [Chibrikin et al., 1995b], and main events in European history such as wars, economic cycles, social crises, and intellectual creative works [Vladimirsky and Kislovsky, 1995].

Here is a series of works that was performed under laboratory conditions on animals on the days of GMF disturbances. Changes in conditioning activity of rats, pigeons and dogs were investigated by Sidjakin et al. [1989a]. There was a remarkable decrease in the number of correct conditioned reactions at the stage of conditioning when the number of conditioned reactions was less than 100%. Reactions of single neurons were registered in the motor neocortex in cats [Sidjakin et al., 1989b]. They were evoked by electrical stimulation of the hind limb nerve or of the caudate nucleus. Seventy percent of neurons responded with initial excitation and 30% with initial inhibition. During days with GMF disturbances, the duration of initially excitatory reactions was reduced and the duration of initially inhibitory reactions was extended. Six physiological parameters of the cardiovascular system and ultrastructure of cardiomyocytes were investigated in rabbits during the strong double planetary MS of September 21–23, 1984 [Chibisov et al., 1995]. At the initial and main phase of the MS, the normal circadian structure in each cardiovascular parameter was lost. Desynchronization increased with the MS, and an abrupt drop of cardiac activity was observed during the main phase of the MS. The main phase of the MS was followed by destruction and degradation of mitochondria in cardiomyocytes. Parameters of cardiac activity became substantially synchronous, and the circadian rhythmic structure became more prominent, while the amplitude of deviations was still significant at the recovery stage of the MS.

The ultrastructure of the rabbit's intact heart tissue was also studied by electron microscopy with simultaneous estimate of its contractive function during the MS [Frolov and Pukhljanko, 1986]. The authors investigated the maximum intraventricular pressure, mitochondrion size, and iron concentration in the serum of arterial blood. The experiments were performed for three days of an intensive MS. A disturbance in the energy supply for the contractive function of heart provided by mitochondria was observed. Cell cultures of mouse, hamster, and trout were used in other experiments [Belisheva and Popov, 1995]. Morphological parameters, including the percentage of polynuclear cells, were estimated. It was shown that the dynamics of morphological and functional states of cell culture was associated with the GMF variations. The disturbance of the GMF was followed by stepwise changes in the state of cell cultures, i.e., properties of the cell surface, the appearance of heterokaryons, and the strengthening of cellular adhesion and aggregation.

The effect of GMF disturbances on the bioluminescent activity of bacteria were investigated by Berzhanskaja et al. [1995]. Bioluminescent intensity changed depending on the amplitude and duration of the MSs. The authors proposed that the synchronization of luminous radiation in different cells takes place as the frequency of GMF disturbances increasingly approaches the intrinsic oscillation of a bioluminescent system. A high sensitivity of bioluminescence to the MSs was detected. Pavlova and Sorokina [1986] even noted that the oxidation-reduction potential of water depended on the heliophysical situation.

Of course, the results of one or another—or even a set of experiments—mentioned in this section can be doubted. Certainly, a rhythm revealed to coincide with some typical GMF rhythm can alternatively be caused by the rhythmic processes of other forces found in nature (geophysical, meteorological, social) or of their harmonics. But the totality of the matter described here strongly supports the hypothesis that the GMF disturbances correlate with the general human condition.

LABORATORY INVESTIGATIONS OF THE BIOLOGICAL EFFECTS OF DC MAGNETIC FIELDS

In the works described in the previous section, the biological effects correlated with occurrence of the disturbances of natural MFs. In these investigations, as a rule, the parameters of the MFs were not measured; only the days and hours during which the disturbances arose were noted. In contrast to these investigations, in a variety of laboratory experiments described in this and following sections, MFs with simpler waveforms and preassigned parameters (amplitude, frequency, and duration of exposure) were used. This allowed researchers to investigate the effects of MFs on lower animals and human beings in more detail and to more closely approach establishing cause-and-effect relationships and an understanding of the mechanisms of MF action. In almost all the works discussed below, except as otherwise noted, uniform MFs were used.

From the outset, the nervous system was considered the most sensitive to EMF action among all the systems of an organism [Bawin et al., 1975; Kholodov, 1966, 1975]. So subsequently, most investigations of the biological effects of MFs were directed toward the nervous system. Prolonged and systematic exposure (for months and even years) to DC MFs of some tens of mT on human beings in industrial conditions is reported [Vjalov, 1971] to cause fatigue, dizziness, sleeplessness, headache, and heart pain.

It was shown that DC MFs with a magnitude measured in tens of mT produced an increase in motional activity in insects, birds, and mammals [Kholodov, 1966, 1975, 1982]. It is interesting that a

MF with a magnitude of 50 mT increased motional activity of mice, while the strengthening of the MF to 100–200 mT caused depression of this activity [Andrianova and Smirnova, 1977]. Later, Ryskanov [1980] also found an increase in the motional activity of mice in the MF of 2.2 mT. In a series of experiments, Kholodov [1966, 1975] was able to condition fish and rabbits to MFs with a magnitude measured in tens of mT. An MF of 40 mT disrupted the learning process in mice in a maze especially if the exposure was given immediately after the learning [Ryskanov, 1980], that is, the DC MF disrupted the process of formation of the memory trace.

A DC MF (20–100 mT) applied to the head of a rabbit induced the rise of slow waves and high-amplitude spindles in the EEG [Kholodov, 1966]. These were the signs of inhibitory processes in the rabbit's brain. An objective computer analysis of the rabbit's EEG [Zhadin et al., 1966] under the influence of MF (10 and 60 mT), where the dispersion and coefficient of asymmetry of EEG waves were calculated on-line, confirmed these results. Subsequently, on-line computer analysis [Kholodov and Shishlo, 1979] showed synchronous time progression of these slow waves and spindles in different areas of the cerebral cortex under MF greater than 20 mT. In the EEG of human beings subjected to prolonged and systematic exposure to the DC MF of some tens of mT in industrial conditions, similar effects were observed: slow waves and spindles of the alpha-rhythm arose in the quiet state and during the rhythmic light test [Shpil'berg and Vjalov, 1972].

In a series of experiments, human sensory sensitivity to a DC MF was investigated [Kholodov, 1982]. The right hand of a patient was located inside solenoid where an MF of 1–90 mT was created with exposure duration of 1 min. The MF was turned on randomly. The patient confirmed whether he felt the MF action or not. Different patients felt the MF application in different ways: as pricking, weak itch, heating, or cooling. The threshold value for the MF causing the reaction varied in the range of 1–5 mT among different patients. With regard to the sensitivity to MF, the work of Volobuev et al. [1985] is of interest. They discovered a fall in the threshold of excitation and a slowing down in propagation of the action potentials in the sciatic nerve under the influence of MF (5.5 mT).

An investigation [Luk'janova, 1969] of pulse unit activity of neurons in different brain structures (neocortex, hippocampus, thalamus, hypothalamus, and reticular formation) in rabbit showed that the action of an MF (90 mT) predominantly manifested an inhibitory influence. The mainly inhibitory action of a DC MF (50 mT) on the electrical activity of the receptor neuron of a crayfish was also obtained in the experiments of Kogan et al. [1971]. In the work of Bravarenko et al. [1988] the isolated nervous system of an edible snail, where all the large neurons are mapped, was subjected to the action of DC MFs (23, 120, and 200 mT; 20 min). Some neurons inhibited earlier were activated, or, conversely, some spontaneously active ones became inhibited under the influence of the DC MF. The reactions usually were the more prominent, the stronger the applied MF. Then the nervous tissue was treated by a proteolytic enzyme that removed the perineuronal glia cells. In doing so, the spontaneous activity of the neurons did not change, but the reactions of most of the neurons to the MF disappeared. The authors concluded that glial cells mediate neuronal reactions to the DC MF.

The idea that glial cells participate in reactions of neurons to the MF arose earlier on the basis of histological investigations of Aleksandrovskaja and Kholodov [1966], who employed light microscopy. They observed an increase in the number of stained astrocytes, microglia and oligodendroglia cells in the sensomotor area of a rabbit's neocortex after exposure of the head of an animal to DC MFs (20–30 mT, 1 h). An increase in size of the glial cells and their branches was also observed. The neurons were intact. But after a very prolonged, many-hour exposure, swelling of the neuronal bodies also appeared. Kholodov [1975, 1982] considered these results as evidence of the influence of DC MFs on hematoencephalic barrier ("blood-brain" barrier) functioning and for primacy of the glial cells in forming neuronal reactions to the MFs. A stronger MF (60 mT) influenced neuronal ultrastructure [Lazariev and Kiknadze, 1977]. The neurons and synapses in the cat's neocortex were investigated with an electron microscope. The cisterns and channels of the endoplasmic reticulum were enlarged, the number of ribosomes was decreased, mitochondria swelled, the Golgi complex hypertrophied, and the number of synaptic vesicles fell.

A detailed, combined investigation of the influence of MF on glial cells, vessels, and intercellular contacts in the rat's brain was performed by Artjukhina [1988]. The MF (10–50 mT; 2 h daily for 1, 3, 6, 14, and 21 days) acted on neurons, glial cells, synapses, and blood vessels in the brain. Both light and electron microscopy were used. The walls of capillary and great vessels collapsed, the lumens were narrowed and widened, and they formed aneurisms directly, depending on the number of exposure days. After three days of exposure, an active proliferation of glial cells and a strengthening of impregnation features of the synapses were observed. The many-day exposure led to the vacuolization of cytoplasm of the neurons and glial cells, to an increase in the number of interneuronal contacts of nonsynaptic nature, and to a fall in density of synapses.

Some interesting data were obtained by Bukharin et al. [1988] by exposing rats to a DC MF. Three sets of experiments were performed: the first set (10 mT, 8 h/day), the second set (20 mT, 4 h/day), and the third set (30 mT, 4 h/day). Each set lasted for 5 days. In the first set there were not any remarkable changes. In the second and third sets, the dilation of microvessels with accumulation of erythrocytes was revealed in the cerebral cortex of the brain and in the medulla. In the brain, the destruction of 5–7% of neurocytes in the neocortex and of 4% of Purkinje cells in the cerebellum was observed. In the third set, a three- to fivefold increase of eosinocytes and a remarkable increase of numbers of megakaryocytes and promegakaryocytes with changed nuclei were found in the medulla. Thus the influence of the DC MF on glial cells and brain vessels can be demonstrated, and this provides good support for the hypothesis that the hematoencephalic barrier is a mechanism in the brain quite sensitive to the effects of MFs.

The experiments of Bresler et al. [1978], who discovered changes in the microvascular plexus due to changes in permeability of biomembranes in the brain under the action of the DC MF, also favored the hypothesis about a field-sensitive hematoencephalic barrier. In these experiments, DC MFs (0.8–2.0 T) influenced active transport of fluorescein in the nerve tissue. This effect depended on strophantin (a specific inhibitor of Na,K-ATPase) and on the concentration of K and Na ions. Bresler's data was not supported by Savich et al. [1982] who worked in vitro on Na,K-ATPases in suspensions of lipoprotein vesicles at different temperatures and over a wide range of concentrations of Na and K ions and strophantin. The influence of the MFs on the enzymatic activity of the preparation was not observed in a wide range of MFs of up to 10 T. The differences in preparations probably could be a reason for this discrepancy.

A set of experiments on effects of strong DC MF on membrane processes in vitro was performed by Piruzjan and Kuznetsov [1983]. Among their experiments were those that tested 1) effects of MFs (up to 10 T) on activity of Na,K-ATPases; 2) effects of MFs (up to 650 mT) on activity of catalase and degrading hydrogen peroxide by Fe-EDTA; 3) effects of MFs (up to 350 mT) on aqueous systems saturated and unsaturated with oxygen; 4) effects of MFs (up to 1.0 T) on respiration in mitochondria; and 5) effects of MFs (up to 600 mT) on photoaggregation of rhodopsin. In all these experiments, no effects of MFs were observed. However, it was observed that MFs (up to 850 mT) parallel to the surface of lipid membrane increased the electrical conductivity of the membrane. The influence of weak MFs (0.27 mT) on the processes in the neuronal membrane was examined by Sagijan et al. [1996]. The MF effect on the pH-dependence of Ca uptake in *Helix pomatia* neurons in vitro was investigated. Under conditions of both high (8.3) and low (6.0) pH, the Ca uptake decreased in comparison with the control pH (7.7). The authors suggested that this effect was due to the Na-K pump blockade by the MF exposure. The differing interpretations about the cell membrane role in all the above experiments could be due to differences in processes in the membrane, in the objects studied, and in experimental conditions.

Apart from the works devoted to investigation of the MF influence on the nervous system, which made up the great bulk of investigations, a set of interesting works investigated other aspects. Podkolzin and Dontsov [1994], for example, studied the immunomodulating action of the weak DC MF. Previous immunization of mice was performed by a intraperitoneal injection of rat's erythrocytes. After 3, 4, and 5 days of sensitization, suspension of extracted spleen cells in vitro was exposed to a MF (20–200 μT; 2–4 min.) Next the erythrocytes were added, and a day later the number of cells forming antibodies was determined. A depression of secretion of antibodies by immune spleen cells forming the antibodies was revealed. The maximal effect was observed at an MF magnitude of 50 μT. The effect was enhanced as the exposure duration increased. Anisimov et al. [1996] pointed to the promoting effect of the DC MF (300 μT; 3 h/day for two weeks) on mammary carcinogenesis in outbred female rats. Lighting of the animals for 24 h/day during the MF exposure enhanced the carcinogenesis process, and 24 h darkness depressed it. Simonov et al. [1986] revealed the effect of a strong DC MF (1.1 T) on formation of artificial bilayer lipid membrane (BLM) from egg lecithin. The rate of the BLM formation decreased if the MF was parallel to the BLM surface, and increased if the MF was perpendicular to this surface. Pavlovich [1971], Kogan et al. [1971], and Vasiljev et al. [1971] gave a series of examples of the depressing action of DC MFs of tens or hundreds of mT on the vital functions (growth and reproduction, activity of some enzymatic systems, and so on) of different microorganisms.

As to depression of functioning microorganisms, the space-structured DC MF produced by the magnetic domain ferrite-garnet films (MDFGFs) with domain size measured in tens of micrometers and magnetic saturation of about several mT [Alipov et al., 1998] were effective. A culture of *Treponema pallidum* (agent of syphilis) was placed on the MDFGF where it remained for 5–7 days. These bacteria lost their mobility and pathogenicity, and died [Milich et al., 1989].

LABORATORY INVESTIGATIONS OF THE BIOLOGICAL EFFECTS OF AC MAGNETIC FIELDS

Investigations into the biological effects of AC MFs developed in parallel with the investigations into the DC MF effects. In these two types of studies, similar problems were posed and the results of these studies were often published in the same articles. The effects of the AC MFs on the nervous system were also the focus of attention.

The clinical and hygienic manifestations of prolonged and systematic work of human beings under the effects of AC MFs of tens of mT were basically the same as under the DC MFs' effects [Vjalov, 1971]. The unfavorable effects of EMFs with industrial frequency were pointed out [Kozjarin and Shvajko, 1988]. The sensitivity of rats to the MFs with intensities typical of regions near power transmission lines was investigated in old, pubescent, and preadolescent rats, as well as in rat embryos. The authors studied changes in body mass, internal organ mass, rectal temperature, oxygen consumption, thyroid gland function, and biochemical indicators of blood, liver, brain, and kidney tissues. The highest sensitivity to the MFs was revealed in preadolescent and old rats. The MFs generated by power transmission lines and by sources in industry are considered by hygienists as a potential danger for people living in residential homes and working offices [Grigor'jev, 1997]. However, favorable influences of the AC MFs were also noted [Kopylov and Troitsky, 1982]: an exposure to MFs (4 μT; 0.02 Hz and 8.0 Hz; 3 h) which preceded total exposure to a lethal dose of X-rays (7.5 Gy on the same day as the MF exposure day) essentially increased the survivability of mice that would otherwise have died from such an intense level of X-rays.

Attempts were made [Kholodov, 1966, 1975, 1982], with good results, to enhance the conditioning of fish, birds, and rabbits to AC MFs (tens of mT). Ataev [1972] was able to condition cats to MFs with frequencies of 20–100 Hz. Similar to DC MFs, the low frequency MFs acted unfavorably on the learning processes in animals, especially if they were exposed immediately after a session of learning. This led to the belief that the AC MFs negatively influence consolidation of the memory trace [Kholodov, 1966, 1975]. The increase in the latent period of conditioned reactions and the disinhibition of differentiation in conditioning were revealed under the influences of MFs (20 mT; 50 Hz) [Venger, 1968]. Concerning aversive learning patterns of mice in a Y-maze [Aminev, 1966], exposure to MFs (30–47 mT, 100 Hz) did not influence learning to choose one turn from two turns in the maze, but hastened relearning to choose the other turn, thus pointing to reducing stability of the conditioned reflex by the MF exposure. Also noted was the influence of MFs on memory in human beings [Aminev, 1966; Vjalov and Shpil'berg, 1969]. MFs (5 μT; 5 or 8 Hz; 3 h/day for 10 days) caused a decrease in the number of correct conditioned reactions and an increase in the latent periods of conditioned reactions in rats [Sidjakin, 1986; Sidjakin and Yanova, 1988]. In experiments of Norekjan et al. [1987], an MF (3 mT; 10 Hz; 2 h/day daily before conditioning) exerted 1) an inhibitory influence on conditioning; 2) reduced stability in the conditioning process; and 3) increased latent periods of avoidance in rats. However, upon lowering the amplitude of the MF to 1 mT, the inhibitory influence of the MFs on conditioning was not observed [Norekjan and Matjukhina, 1988].

Lebedeva [Lebedeva et al., 1988; Lebedeva, 1998] employed a method similar to that used earlier by Kholodov [1982] and described in the previous section. AC MFs (1 mT, 1–10 Hz and 30 or 75 mT, 50 Hz; duration of 0.5–1.0 min) affected the patient's hand. The patients felt touching, pricking, cooling, or heating, as in the above experiments with DC MFs. The EEG register showed changes as a result of the MF action. In most cases, weakening of delta-activity and strengthening of alpha-activity were observed. The exposure consisted of 20 trials, each trial lasting 1 min; the time interval between trials was 1 min. The sensations described by the patients pointed to the participation of skin receptors in perceiving the MFs.

The electrophysiological data on the effects of AC MFs on electrical activity of the nervous system are rather scarce, because of electrical interference, caused by the MFs themselves, with the measurement of biopotentials. Only the measurement of electrical activity after the exposure or in experiments performed with extremely weak MFs was possible. Among these experiments, the following merit attention: Medvedev et al. [1992] investigated the influence of an MF (10 mT; 45 Hz; 1 h) on the spectrum of the human EEG. Ten volunteers received exposure to a continuous MF and another ten received intermittent exposure (1 sec on/1 sec off). The EEGs before and after each exposure were analyzed. Intermittent exposure was more effective. It caused an increase in alpha-activity (8.5–12 Hz) and a decrease in sigma-activity (12.5–14.5 Hz). Vlasova at al. [1988] investigated the effects of MFs (100 nT; 0.05, 0.1, 0.25, or 5.0 Hz) on neurons of the cerebellum in mice. They showed that MFs with the above parameters mainly exerted a "triggering" activating influence. But in individual cases, an inhibitory influence was observed. Agadzhanjan and Vlasova [1992] studied the effects of MFs on rhythms in neuronal electrical activity and on neuronal resistance to hypoxia. MFs (100 nT; 0.05, 0.1, 0.25, or 5.0 Hz) were applied to the surviving slices of the mouse cerebellum. The MF was also a trigger for the nervous cells. A 5 Hz MF caused a two-phase response: inhibition and excitation in neuronal pulse activity. In some cases, it activated previously inactive neurons. In addition, a convulsive effect of the MF was registered. In the experiments with simultaneous exposure to hypoxia and to MF, the prohypoxic effect of the MF was revealed after reoxygenation, especially when the oxygen concentration was very low. These data revealed an influence opposite that of the DC MF on the nerve cells [Luk'janova, 1969; Kogan et al., 1971]. Zolin's review [1995] noted that a strong DC MF (400 mT) increases the resistivity to hypoxia due to activation of the sympathetic-adrenalic system and development of adaptative responses [Kazakova, 1991]. Orlova et al. [1995] studied the effects of an MF (20 μT; 8 Hz) on movement-related activity of neocortical neurons and on spontaneous firing of neurons in the substantia nigra in awake cats. The MF produced a modulation of the neuronal activity in the parietal cortex that preceded self-initiated front paw movements, and an increase in the cell firing rate in the substantia nigra.

As described below, many experiments were devoted to a morphological, histological, and biochemical analysis of the effects of AC MFs on different systems of an organism. Exposure of guinea-pigs to an MF (20 mT; 50 Hz; 6.5 h) caused disorder in hemodynamics in blood vessels, hemorrhage, and emphysema in the lungs and swelling of the testicles [Toroptsev et al., 1971]. But the application of a low frequency MF (20 mT; 10 min every second day; frequency not given; device "Poljus ('Pole')") accelerated recovery after insult, lowered the high blood pressure, decreased swelling in the optic nerve, and resolved hemorrhages in human beings [Gilinskaja and Zobina, 1988]. Anisimov et al. [1996] showed that an MF at an industrial frequency (160 μT; 50 Hz; 3 h daily) can be an additional promoting factor that strengthens the action of chemical carcinogens. In this work, the mammary carcinogenesis in female rats induced by nitrosomethylurea (NMU) intravenously was investigated. The incidence of adenocarcinoma in the conditions of usual light regime (12 h light, 12 h dark) was 31%. Further exposure to the AC MF shortened the latent period of development of adenocarcinoma as compared to the group without the MF exposure. The regime of round-the-clock illumination stimulated carcinogenesis. The frequencies of adenocarcinoma in the groups exposed only to NMU and to combined action of NMU and MF were 57 and 81%, respectively, with halving of the latent period of their development compared to the usual light regime. Each group included 50 animals. The experiment was completed within 15 months when all the surviving rats were killed.

In experiments on rats, Garkavi et al. [1990] studied tissue respiration, oxidative phosphorylation, and anaerobic and aerobic glycolysis in the hypothalamus under the influence of an MF (0.1–50 mT; 10–100 Hz; one minute to tens of minutes). The MF caused activation of tissue respiration, strengthening of phosphorylation in the hypothalamus, and an increase in glycolysis in the brain. A rise in the cholinesterase level in the blood was also observed. The same group of authors [Garkavi et al., 1996] reasoned that the reaction of an organism to a MF is a general nonspecific adaptive reaction according to the whole complex of biochemical data and that it could be favorable or unfavorable for the living organism, depending on the parameters of the MF and the locus of its application. For example, MFs > 10 mT applied to the head of rats with frequency > 50 Hz were unfavorable, and MFs < 10 mT applied to peripheral parts of body with frequency < 50 Hz could cause favorable effects. The character of changes in the body and its subsystems was determined by the type of reaction developing under the MF action: the stress or antistress reactions, low activation or enhanced activation. Under stress, the homeostatic parameters went beyond the norm and the protective effects interwove with the damaging ones. The antistressor adaptive reactions, especially the activation reactions at higher levels of reactivity, enhanced nonspecific resistance, in contrast to the stress, without any damage or waste of energy. They produced antitumor, protective (in reference to toxic agents and X-radiation) and rejuvenating effects, and promoted self-organization. The antitumor and rejuvenating effect of the AC MF on old rats was demonstrated earlier by these authors [Ukolova and Kvakina, 1971; Garkavi et al. 1990]. For example, exposure to the MF (50 mT; 0.03 Hz; 20 min daily) of experimental inoculated sarcoma for 1–2 weeks caused disappearance of the tumor in 60% of the rats. Similar results were obtained by Kholodov [1975] who applied the MF with parameters close to those described above, not only to the tumor, but to the rat's head as well.

Ir'janov [1971] showed with electron microscopy that exposure to an MF (100 mT; 50 Hz; 5 h/day for 1–2 weeks) caused changes in the mitochondria and endoplasmic reticulum of neurons in the mouse brain. Electron microscopic investigation [Akimova and Novikova, 1988] of the neocortex in rabbits and rats after exposure to a weak MF (500 μT; 3.12 Hz) revealed ultrastructural changes, the degree of which in different nerve-tissue elements was dependent on the duration of exposure. A single exposure (4 h) only caused changes in glial elements, while multiple exposures (5 days, 4 h/day) caused changes both in glial cells and in neuronal bodies. Within three days after a single exposure to the MF and within 15 days after multiple exposure, complete repair of nervous tissue was observed: no destructive or pathological alterations were found that pointed to the functional character of the reactions induced. The neuromorphological alterations were of the same character, whether induced by the weak MF or by other biophysical factors, for example, a weak DC electric current. This finding (see [Garkavi et al., 1996]) was evidence also for the common mechanisms of the nonspecific adaptive reactions. The stress-factor (hypokinesia through a restraint) was able to modify the reaction of the adaptation to the MF (8 Hz; 5 μT) [Temur'jants et al., 1995]. This finding was corroborated by the depression of nonspecific resistance during the initial adaptation period, by the increase in excitability of the central nervous system, and by the absence of accumulation of catecholamines in the hypothalamus and in the adrenal glands.

In the work of Podkolzin and Donzov [1994], which was described in the previous section, the influence of MFs (20–100 mT; 10–50 Hz; 4 min) on mice antibodies formed by the immune spleen cells after previous immunization with rat's erithrocytes was studied. The depression of antibody secretion by the MFs was frequency-dependent. A prominent narrow (0.1 Hz width) resonant peak at the MF frequency of 21.1 Hz was revealed. It is interesting that this frequency is close to one of Schumann resonances. An MF (20 mT; 50 Hz; 6 h) caused a fall in antibody formation in guinea-pigs [Vasil'jev et al., 1971].

In works by Temur'jants et al., an attempt was made to understand and to reproduce in the laboratory the effects observed under the influence of the MS. Here the frequency 8 Hz—typical of the MSs—was the focus of attention. The amplitude of the AC MF was made as small as possible, but of course it was still larger than that of the MSs. The MF (5 μT; 8 Hz; 3 h daily for 9–45 days) caused changes in indices of lipid and cholesterin exchange in rats [Temur'jants et al., 1989]. Changes in hemocoagulation and in nonspecific resistance were also observed. The authors suggested that the applied MF promoted more effective adaptation of animals to hypokinesia. In other experiments, the influence of an MF (5 μT; 8 Hz) on the functional state of blood neutrophils, on the sympathoadrenal system and on the brain integrative activity in rats was investigated [Temur'jants and Grabovskaja, 1992]. Animals with low, moderate, and high levels of mobility determined by an "open field" test were used. It was discovered that the MF provoked a stress-reaction in rats with low mobile activity. The adaptation that developed in the rats with high and moderate mobile activity came 5–7 days later. Two subsequent experiments studied the influence of MFs on the superslow (many-day periods) or so-called "infradian rhythms". An MF (5 μT; 8 Hz; 3 h daily for 45 days) shifted the phases of the infradian rhythms in diuresis, as well as in excretion of epinephrine and norepinephrine by rats with a moderate level of mobile activity in the "open field" test [Temur'jants et al., 1992a]. The MFs restored the synchrony of processes studied in rats with desynchrosis provoked by hypokinesia. It was also demonstrated [Temur'jants et al., 1996] that an MF (5 μT; 8 Hz; 3 h daily for 40 days) changed the infradian rhythms of functional state parameters of lymphocytes (succinic- and glycerophosphate dehydrogenase activity) and neutrophils (peroxidase activity) in the blood of rats. These changes consisted in rearrangements of integral rhythms and their amplitudes and phase.

It is worth noting that AC MFs exerted effects on microorganisms and even on plants. Like the DC MFs, the AC MFs (20–30 mT; frequency not given) depressed the vital functions (growth and reproduction, activity of some enzymatic systems, and so on) in different microorganisms, but in a lesser degree as compared to the DC MFs [Pavlovich, 1971]. MF treatment (30 mT; 30–33 Hz; 7–10 min) markedly increased the germinating power and accelerated the germination process in old wheat seeds [Aksjonov et al., 1996].

BIOLOGICAL EFFECTS OF COMBINED ACTION OF DC AND AC MAGNETIC FIELDS

The pioneer works by Liboff [1985] and Blackman et al. [1985] devoted to analysis of mechanisms of action of combined DC and ELF MFs on biological objects opened a new page in bioelectromagnetics. These and later works [Thomas et al., 1986; Chiabrera and Bianco, 1987; Chiabrera et al., 1991; Blackman et al., 1989, 1994; Lovely et al., 1992; Jenrow et al., 1995] found their reflection and development in works of Russian scientists.

In the work of Shuvalova et al. [1991] the parallel DC (20.9 μT) and AC (20.9 μT; 8–20 Hz; 10 min) MFs acted on a solution of calmodulin, myosin, and kinase in light chains of myosin. The rate of calmodulin-dependent phosphorylation of myosin by kinase of light chains of myosin was studied. Three peaks of inhibitory influence of the MFs: 16.0, 14.0, and 13.0 Hz were revealed. The half-widths of these peaks were about 1 Hz. The frequency of 16.0 Hz was equal to the cyclotron frequency for calcium ions at the DC MF applied. Chemeris and Safronova [1993] studied the influence of the parallel DC (21 μT) and AC (140 μT; 16 Hz; 15–20 min) MFs on the period of *Daphnia magna* heartbeats. The fluctuations in the period of heartbeats were analyzed by using fast Fourier transforms. It was shown that the AC MF combined with DC MF caused maxima in the power spectra of the heartbeat fluctuations at the 16 Hz frequency of the AC MF, which was the cyclotron frequency for calcium ions at the DC MF applied.

Lyskov et al. [1996] exposed (30 min) rats to parallel MFs in two combinations: Exposure I (AC: 46 μT, 50 Hz; DC: 65 μT) and Exposure II (AC: 46 μT, 50 Hz; DC: 14–17 μT). Exposure I led to the increase in the number of errors in a Y-maze, to a shortening of the time of adaptation to a new unfamiliar situation, to a decrease of aggression and sociability levels, and to a rise in the level of defensive reactions. During Exposure II there was a fall in levels of aggressive and defensive reactions. The results obtained showed that the influence of the 50 Hz MF depended on the presence of the DC MF. The combined MFs with the frequency of the AC MF equal to the cyclotron frequency of calcium ions at the DC MF applied (Exposure I) were more effective. In the other work [Derjugina et al., 1996], the influence of the parallel DC (500 μT) and AC (250 μT; 20 min) MFs on rat behavior in the ‘‘open field’’ test was studied. The action of the cyclotron and Larmor frequencies for calcium, sodium, potassium, chlorine, magnesium, lithium, and zinc ions were investigated. A significant influence of cyclotron frequencies for calcium and magnesium ions at the DC MF applied was revealed. The calcium frequency (380 Hz) caused a depression in the exploratory activity of the animals, and the magnesium frequency (630 Hz) enhanced the moving and investigating activities. Exposure at other frequencies did not significantly affect the animal's behavior.

Tiras et al. [1996] investigated the influence of combined MFs on the rate of regeneration in the planarian, *Dugesia tigrina*. It is known that amputation of the head of a planarian is accompanied by the release of neurotransmitters from severed nervous fibers to the extracellular space located near the wound (postblastema), which induces the pool of undifferentiated cells (neoblasts) to divide. The activated proliferation of the neoblasts, which may be quantitatively estimated by measurements of the mitotic index in the postblastema, provides cells for the regeneration of the blastema. After 2–3 days of regeneration, morphological parameters (length and area of the blastema and of the whole regenerant) were measured by using a computer image-analysis technique. The DC (20.9 μT) and AC (38.6 μT; 16 Hz; 4–240 h) MFs, tuned to the cyclotron frequency for calcium ions at the applied DC MF, substantially changed the rate of regeneration in the planarians, which manifested itself as an increase in the rate of mitosis in the postblastema and as an acceleration of the rate of blastema growth. Given the above methods, and varying the amplitude of the AC MF (5–200 μT) at the constant DC MF (20.9 μT), the existence of amplitude windows (that is, alternate strengthening and weakening of the effect as the amplitude of the AC MF increased) [Blackman et al. 1994; Lednev 1996] were confirmed.

To conclude the above sections, it is clear that the whole complex of the works listed in them provided a great diversity of data on the effects of DC and AC MFs—even very weak ones—on living organisms, and reliably supported the views of Bawin and Adey [1976], Liboff [Liboff, 1985; Liboff et al., 1987], and Blackman et al., [1985] about important role of free calcium ions in biological action of an ELF EMF.

MECHANISMS OF BIOLOGICAL EFFECTS OF MAGNETIC FIELDS

In Russian biophysics much attention has been given, not only to experimental works, but also to the theoretical analysis of mechanisms of the biological effects of MFs.

An important step forward was the work of Dorfman [1971]. He considered the mechanism of a rise of a ponderomotive force in the living tissue from the nonuniform DC MF interacting with the magnetic susceptibility of the tissue. The paramagnetic tissue was described as being forced towards the point of maximum field, and the diamagnetic tissue, which would be the majority of biological tissues, in the opposite direction. This force each point depends on the value and sign of the MF gradient. These forces tend to turn all the diamagnetic cells in the same direction in the DC MF and could be the reason for the magnetotropism of plants, when all the parts of the plant change the direction of their growth in the nonuniform DC MF. The author also considered a rise of a pulsing force acting across the myelinated nerve in the saltatory propagation of an action potential and in the braking action of the DC MF on the blood's motion along a vessel due to the magnetohydrodynamic forces. According to Dorfman's estimates, all the above effects could be noticeable at DC MFs in the order of 100–1000 mT.

The problem of interaction of ionic channels in the neuromembrane with a spreading action potential was investigated by Volobuev et al. [1991, 1993]. A possible role of inductance of the membrane of a nerve fiber in the propagating action potential was considered. The nonlinear differential equation for the action potentials which has soliton solutions, was derived. An attempt to explain the effects of DC MFs and laser irradiation on an organism was made on the basis of a mathematical electrodynamic model of the neurofiber membrane. The authors proposed that the external MF interacts with the hypothetical internal MFs created by the ionic channels and nodes of Ranvier. The proposed mechanism could explain the effect of the decrease in propagation velocity of the action potentials in the DC MF observed by these authors [Volobuev et al., 1985]. This model was criticized by Binhi [1995a] who considered it as not sufficiently physically sound.

A different set of models and conceptual considerations has been directed toward an understanding of the nature of influence of the GMF disturbances on biosystems: Agulova and coworkers [Opalinskaja and Agulova, 1984; Agulova et al., 1989] considered the behavior of complicated nonequilibrium systems, especially unsteady states, in weak AC MFs. Two modes of MF influence on the state of the body were considered: 1) the direct perception of the MF by biomolecular structures and 2) the signal role of the MF through the central nervous system. The authors considered which of these two modes best characterizes the interaction between the environment and the organism. The authors pointed to the possible influence of GMF pulsation on hypertensive individuals and to the effects of general magnetic disturbances on healthy and sick human beings. The authors noted the influence of the GMF disturbances on comparatively simpler systems, such as the Piccardi test (a standard chemical reaction, the test is a rather complicated multiple-stage process including hydrolysis of bismuth chloride and production of bismuth oxychloride [Piccardi, 1962]) and precipitation and agglutination reactions in aqueous solutions.

Kislovsky [1982] considered the biosphere as a complicated, hierarchically organized system working in auto-oscillation mode. He believed that the flexible feedbacks uninterruptedly optimize the mode of their functioning on all levels for preserving the whole system. The sharpening of sensitivity to signals that is significant for the intact system and the depression of sensitivity to not-so-important stimuli are the features typical of such a super-complicated system. In his other work, Kislovsky [1989] showed the possibility of dissipative clathrate structure formation in the aqueous medium and on its borders in nonequilibrium conditions. The duration of conservation of such structures was considered as an example of near-critical phenomena that are close to the temperature of phase transitions of the second kind: liquid–liquid. In this case the phase transitions would be at the lower critical temperatures of stratification of the aqueous solutions, at which the elements of short-range order inherent in clathrate structures were abolished. The suggestions were demonstrated by the attempted explanation of mechanisms of fluctuation phenomena connected with the GMF disturbances. Zhvirblis [1989] was interested in the problem of reproducibility of heliobiological experiments. The results of the experiments, the purpose of which was to reveal fluctuations in the state of the human autonomic nervous system, were presented as a phase histogram. The coordinates included results of some medico-biological tests and the index of GMF disturbance, where sector boundaries of the interplanetary magnetic field associated with the solar wind (Vladimirsky, 1980), were taken as day zero. The following specific regularity was revealed: The direction of moving along the phase trajectory contour changed at the moment the Earth crossed the sector boundary. A general consideration of the nature of the influence of solar activity on the biosphere was undertaken.

Vladimirsky [1989] found that Piccardi test was sensitive to the polarity of a radial component of the interplanetary MF. The rate of the test reaction was regularly lowered in the sectors of negative polarity. The effect was small ($\approx 1.5\%$), but was statistically highly significant. It depended on the time of day and on the border type, but did not reveal any association with a season or with a phase of the solar activity cycle. The author supposed that the effect was caused by amplitude and spectral variations of the natural GMF within the range of geomagnetic micropulsations (0.007–0.1 Hz). Vladimirsky and Temur'jants [1996] presented a list of the most important general regularities in the action of weak ("non-thermal") and ultraweak ("natural") AC MFs on biosystems and inorganic matter. The basic sources of empirical information were considered: the laboratory research on effects of the AC MFs within prescribed parameters, the influence of natural GMF disturbances, the experiments with shielding of the external GMF, and the influence of technogenic EMFs. The results of several independent research programs were taken into account. The empirical regularities formulated by the authors pointed to a possible role of nuclear magnetic resonance in the GMF variations. It should be noted that Binhi [1995b] considered the nuclear magnetic resonance as impossible in biological magnetoreception.

The attention of Russian biophysicists has been attracted to phenomena of resonance at the cyclotron frequency under the combined influence of DC and AC MFs. Remarkable works by Liboff [1985], Arber [1985], McLeod and Liboff [1987], Chiabrera and Bianco [1987], Chiabrera et al. [1991], and Edmonds [1993] initiated these investigations.

Lednev [1989] has advanced a physical approach for the resonance. The molecules of calcium-binding protein were suggested as a place of primary action of combined MFs. The combined MFs cause the splitting of energetic levels of calcium-ion oscillation in the molecule (the Zeeman effect). The width of this splitting is equivalent to the cyclotron frequency of this ion and the applied DC MF. Parametric resonance was proposed by Lednev as a mechanism for increasing ionic energy. The maximal effect was expected for the AC MF at the cyclotron frequency or its harmonics in this case. The effects of different harmonics and subharmonics of the cyclotron frequency were discussed. The phenomenon of so-called "amplitude windows," that is, the alternate strengthening and weakening of the effect as the amplitude of the AC MF increased, was already known from experimental practice and was explained on this basis. This theory was later developed by Blanchard and Blackman [1994] in what they called it an ion parametric resonance model.

Lednev [1996] further studied the oscillation of the calcium ion in the molecule of calcium-binding protein. As in his previous work, he took the damping coefficient to be equal to zero for the above oscillation, that is, he considered the phenomenon to take place in the absolute vacuum. The expression for the degree of polarization of these oscillations of the calcium ion under the influence of the MFs was derived. It was shown that the DC, AC, and combined DC+AC MFs can change the polarization degree. This expression showed amplitude and frequency windows as applied to the polarization effect. The most prominent change occurred for the combined parallel DC+AC MFs with the frequency of the AC MF equal to the cyclotron frequency for the calcium ion. The author supposed (unfortunately, without sufficient evidence) that the biological effects of the MFs are determined by the polarization degree of the calcium-ion oscillation.

The mechanism of magnetosensitive ion binding by some proteins, including the calcium-binding protein, was considered by Binhi [1997]. The probability density of the wave function of an ion in a protein molecule was approximately considered. The changes in this probability density under the influence of external AC MFs were studied in the framework of an idealized quantum model. The dissociation probability of an ion-protein complex was shown to depend to some extent on the magnetic field parameters (frequency and amplitude). This is a consequence of the interference of angular modes of the ion wave function. The attempt was made to explain effects of MFs with different parameters (DC MFs, parallel and inclined DC+AC MFs, magnetic vacuum, pulsed MFs).

In the work of Zhadin and Fesenko [1990], the thermal oscillations of the calcium ion in a molecule of calcium-binding protein under the influence of the combined DC+AC MFs were considered. The DC MF causes the Larmor precession of ion oscillation. Since the cyclotron frequency is twice as large as the Larmor frequency, the authors suggested that this process could serve as the basis for increasing the ion kinetic energy due to parametric resonance. In the framework of this suggestion, the AC electric field perpendicular to the DC MF (or the AC MF parallel to the DC MF) is expected to increase the ionic energy. The maximal effect was expected at the cyclotron frequency of the AC MF.

Later, Zhadin [1996] carried out a general analysis of the physical foundations for the effects of the DC MFs as well as of the combined parallel DC and AC MFs or the ELF modulated high frequency EMF on biosystems. The main goal was solving the energetic problem of primary detection of the MFs. The equations of motion of the ion in a macromolecule under the influence of the MFs were derived and approximately solved, taking into account the damping effects and the influence of particles surrounding the ion. The regularities of the MF influence on thermal motion of the ion in a macromolecule were investigated. The conditions for the rise of parametric resonance were analyzed. Some features of magnetic fields' actions favorable for parametric resonance development were revealed. However, contrary to Lednev [Lednev, 1989; Lednev et al., 1996] and to Blanchard and Blackman [1994], it was shown that the possibility of the parametric resonance is quite incredible for the AC MF frequencies many orders of magnitude less than the natural frequency of the ion in the macromolecule. The pronounced, resonance-like phenomena were revealed to be caused by the action of the DC field alone and by the combined DC and AC (ELF or modulated high frequency) MFs without any parametric resonance. It was estimated [Zhadin, 1998] that under certain conditions the MFs may cause changes in energy of the ionic thermal motion, which can be several percent or even 10% of initial thermal energy of the ion, equivalent to temperature shifts by as much as tens of degrees Celcius. This would be quite sufficient to trigger changes in the conformational state of the macromolecule. The numerical solution of the above equations of ionic motion in the macromolecule under the influence of the MFs [Zhadin et al., 1998] in general terms supported the results of the analytical solution [Zhadin, 1996] of these equations.

Of course, the overall situation in magnetobiology, just as in the development of the general theory of the biological effects of MFs, is still far from complete. However, the theoretical advances described in this section have revealed the nature of different biomagnetic phenomena and could serve as important structural material in developing a comprehensive general theory of MF influences on biological systems.

CONCLUSION

As we noted in the Introduction, the Russian literature on the biological effects of the MFs is both abundant and diverse. Of course, it was impossible to cover all of it in our review. We were able only to survey the basic lines of the investigations and to familiarize the reader with the most interesting works. In this review, we tried to show the main avenues in the development of Russian research in the magnetobiology of DC and ELF MFs, as described below:

1. The historical roots of increased interest in Russian biology in the DC and ELF MFs arising from the ideas of V. Vernadsky and A. Chizhevsky, based on an intimate connection between solar activity and life on the Earth.
2. A variety of studies on the effects of magnetic storms and ELF periodic variations of the GMF on human beings and lesser animals, as well as on social phenomena.
3. Attempts to reveal a correlation between the artificial weakening of the GMF itself and the living activity of organisms.
4. The variety of experiments involving artificial laboratory DC and AC MFs acting on different biological objects under diverse conditions.
5. Revealing the predominantly unfavorable influence of MFs on living beings; of still greater importance, however, is the demonstration of the cases of favorable influence of the MFs on human beings and animals, opening the prospects for their wide use in future medical applications.
6. Attempts at revealing which MF parameters may be favorable; but unfortunately, such cases are still so few in number and so little explored that they do not provide reason enough to say definitely what these parameters are. However, these cases give some hope that the MFs could be used in future medical applications.
7. Investigations of the combined action of DC and AC MFs that provides possibilities of specifically directed action on the biologically active ions in an organism.
8. Diverse theoretical advances opening up the way for a step-by-step understanding of the mechanisms of MF effects on biosystems. Only a deep insight into these mechanisms can prevent the harmful influences of the MF action and can enable MFs to serve as a medical tool in the struggle for human health and for the health of the environment.

During the time that these Russian researches on the biological effects of MFs were being carried out, they were practically unknown among the non-Russian speaking audience. This hiatus was mainly due to the language barrier, as well as some other reasons. Subsequently, by writing this review, we are attempting to apprise the international community of the diversity of results of the many Russian studies on the effects of MF actions and to show the historical logic of the investigations. If we have accomplished this, even in part, then we can consider that our objectives have been achieved and rest assured that our work is of value.

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