

# Biological effects due to weak magnetic field on plants

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## Abstract

Throughout the evolution process, Earth's magnetic field (MF, about 50  $\mu\text{T}$ ) was a natural component of the environment for living organisms. Biological objects, flying on planned long-term interplanetary missions, would experience much weaker magnetic fields, since galactic MF is known to be 0.1–1 nT. However, the role of weak magnetic fields and their influence on functioning of biological organisms are still insufficiently understood, and is actively studied. Numerous experiments with seedlings of different plant species placed in weak magnetic field have shown that the growth of their primary roots is inhibited during early germination stages in comparison with control. The proliferative activity and cell reproduction in meristem of plant roots are reduced in weak magnetic field. Cell reproductive cycle slows down due to the expansion of  $G_1$  phase in many plant species (and of  $G_2$  phase in flax and lentil roots), while other phases of cell cycle remain relatively stable. In plant cells exposed to weak magnetic field, the functional activity of genome at early pre-replicate period is shown to decrease. Weak magnetic field causes intensification of protein synthesis and disintegration in plant roots. At ultrastructural level, changes in distribution of condensed chromatin and nucleolus compactization in nuclei, noticeable accumulation of lipid bodies, development of a lytic compartment (vacuoles, cytosomes and paramural bodies), and reduction of phytoferritin in plastids in meristem cells were observed in pea roots exposed to weak magnetic field. Mitochondria were found to be very sensitive to weak magnetic field: their size and relative volume in cells increase, matrix becomes electron-transparent, and cristae reduce. Cytochemical studies indicate that cells of plant roots exposed to weak magnetic field show  $\text{Ca}^{2+}$  over-saturation in all organelles and in cytoplasm unlike the control ones. The data presented suggest that prolonged exposures of plants to weak magnetic field may cause different biological effects at the cellular, tissue and organ levels. They may be functionally related to systems that regulate plant metabolism including the intracellular  $\text{Ca}^{2+}$  homeostasis. However, our understanding of very complex fundamental mechanisms and sites of interactions between weak magnetic fields and biological systems is still incomplete and still deserve strong research efforts.

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## 1. Introduction

During the evolution process, all living organisms experienced the action of the Earth's magnetic field (geomagnetic, GMF), which is a natural component of their environment. Previously many scientists believed that permanent magnetic fields are not biologically active. However, the results obtained have revealed the high

sensitivity of plants to permanent magnetic fields, in particular, in the intensity range from GMF level to very low ones. The term “weak (low) magnetic field” (WMF) is generally referred to the intensities from 100 nT to 0.5 mT, while that “superweak” or “conditionally zero” (“magnetic vacuum”) is related to magnetic fields below 100 nT.

It is known that a galactic MF induction does not exceed 0.1 nT, in the vicinity of the Sun—0.21 nT, and on the Venus surface—3 nT (Belov and Bochkarev, 1983). Investigations of WMF effects on biological systems

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have attracted attention of biologists due to planned long-term interplanetary flights. Interplanetary navigation will introduce man, animals and plants in magnetic environment where the magnetic field is near 1 nT. This brought a new wave of interest in WMF's role in regulating plant growth and development.

In laboratory, WMFs have been created by different methods, including shielding (surrounding the experimental zone by ferromagnetic metal plates with high magnetic permeability, which deviate MF and concentrate it in the metal) and compensating (using the system of the Helmholtz rings) (see Sytnik et al., 1984).

This article reviews our knowledge about the biological effects of WMF. It was demonstrated that the weak fields can cause or alter a wide range of phenomena, but the wide diversity of the reported effects remains the greatest problem for this research. Basic hypotheses concerning magnetosensing and consequent signal transduction (especially that involving calcium) are considered.

## 2. Germination, growth and development

Govoroon and co-workers (1992) have shown that germination of seeds of pea (*Pisum sativum* L.) lentil (*Lens culinaris* L.) and flax (*Linum usitatissimum* L.) is unaffected by WMF (1 nT) in a device "Magnetic Screen" (with 8 permalloy layers) designed in the Joint Institute for Nuclear Research, Dubna, Russia (Davidkov et al., 1981).

The developmental studies of plants have been done at various WMF intensities. A two-layer permalloy magnetic screen designed at the Institute for Extremely Low Temperatures, Kharkov, Ukraine (Bogatina et al., 1978) was used to test the effects of a wide range of WMF (from 20 nT to 0.1 mT) on plant growth. In this device, 3–5 day old wheat (*Triticum aestivum* L.) seedlings grew slower than the artificial GMF control (Bogatina et al., 1978). The 3-day pea seedlings grown at 40  $\mu$ T exhibited a small increase in their length over the artificial GMF control as well as at 0.5  $\mu$ T or a reduction in 2  $\mu$ T-WMF (Bogatina et al., 1979). In these experiments no significant variations of dry weight of pea seedlings were observed. In other set of the experiments performed in the same device, WMF caused a statistically significant growth inhibition in sugar beet, pea and wheat seedlings (Sytnik et al., 1984). After the 4-day WMF exposure, growth of sugar beet (*Beta vulgaris* var. *saccarifera*) seedlings was reduced by 37% compared to the GMF control; the measured length of wheat and pea roots also displayed growth reduction by 26% and 17%, respectively. However, after the strong inhibition of root growth in wheat, pea and sugar beet seedlings during the first 4 days in WMF, later root elongation partially compensated the reduction and average root length reached

82%, 87% and 78% of those in GMF control (6-day experiments) (Sytnik et al., 1984).

Epicotyls of 3-day pea (cv. Alaska) seedlings exposed to WMF for 24 h in dark in two-layer permalloy magnetic screen were longer than in GMF controls because of their enhanced cellular elongation (Negishi et al., 1999). No significant difference in width of the epicotyls was observed between WMF and GMF samples.

The dominant response to WMF was a delay in seed germination observed in 67% experiments (Govoroon et al., 1992). However, the effect on pea seed germination was different: both inhibition and stimulation of the germination process were observed in different experimental sets. Tarakanova (1973) reported activation of germination of bean (*Vicia faba* L.) seedlings exposed to WMF (0.1 mT). In 50 nT WMF, inhibition of root growth of vetch (*Vicia villosa* L.), millet (*Panicum miliare* L.), barley (*Hordeum sativum* L.) and pea seedlings compared to GMF controls was observed at 48 and 72 h from germination (Kursevich and Travkin, 1973a). Shiyani (1978) observed germination delay of pea seeds in 10 nT WMF as well.

The longest experiment (3 weeks) was carried out on barley in Helmholtz rings with a 10 nT WMF by Lebedev et al. (1977). They showed a decrease in a fresh weight of shoots (by 12%) and roots (by 35%), as well as a dry weight of shoots (by 19%) and roots (by 48%) of barley seedlings exposed to WMF in comparison with GMF control. In addition, a slow seedling development in WMF-conditions was evident, since only 50% of these seedlings developed the third leaf, compared to 87% of GMF control seedlings. It was concluded that WMF was capable of delaying both organ formation and development.

In light conditions, WMF produced by Helmholtz rings (0.5 mT) could induce a stimulation of germination in radish (*Raphanus sativus* var. *sativus*) seeds more than 2-fold in comparison with the light controls. In darkness this effect was smaller, but significant (Novitskaya et al., 2001). By contrast, Kato (1990) documented the suppressed effect (near 20%) of a light on the root growth of 2-day maize (*Zea mays* L. cv. *Golden Cross Bantam 70*) seedlings exposed to WMF (50 nT) for 12 h, compared with the light controls in GMF, while he reported no significant difference between growth rates of treated and untreated maize roots. However, dark-grown roots, whether treated or not, were considerably longer than the corresponding seedling roots grown with light. In the same conditions, Kato et al. (1989) found that the growth rate of root hairs induced by the inoculation with *Agrobacterium rhizogenes* harboring Ri plasmid cultured in a magnetic field of 50 nT was greater than that of root hairs developed in GMF control. The authors suggested that the difference in the indices of growth between *Zea* primary roots and root hairs exposed to WMF could be induced

by physiological differences between intact and infected plants.

The 15-min treatment of wheat seeds by WMF (30 mT) followed by 17-h imbibition, when they initiated root growth, increased the root formation by nearly 25%; the same exposure of seeds to WMF after 24-h imbibition caused lesser effects. However, when the roots were already formed, 24-h WMF treatment after 24-h imbibition, showed no effect on the number of roots in the seedlings. The length of 6-day seedlings from the first set of experiments (WMF-treated + 17-h imbibition) displayed a 40% increase; in the second set this effect was much smaller (15%). Whereas in the third set (24-h WMF treatment after 24-h imbibition) wheat seedlings exhibited a 25% decrease in their length compared with GMF control (Aksonov et al., 2001). The results of these experiments show that treatment of wheat seeds by WMF for different terms of their imbibition causes different effects on a realization of genetic program for seed germination.

Growth of garden cress (*Lepidium sativum* L.) seedlings appeared to be unaffected by WMF (100  $\mu$ T) alone or when WMF applied after heat stress. However, if exposure to the magnetic field preceded the heat treatment, it alleviated the inhibitory effect of the heat shock (Ružič and Jerman, 2002).

Little is known why a different growth occurs in response to exposure of plants to magnetic north and south poles. Krylov and Tarakanova (1960) indicated that roots and shoots of maize (*Zea mays* L.) and wheat grew faster when their embryo micropyle were directed to the south pole of a magnet rather than to the north one. They suggested that different magnetic pole orientations could act differently on the enzyme activities of plants. Growth of barley, maize, radish, vetch and cucumber (*Cucumis sativus* L.) seedlings exposed to WMF (produced by the Helmholtz rings) increased when their roots were oriented to the magnetic south pole (Shultz et al., 1966). Moreover, even 240 h treatment of dry seeds of *Pisum arvense* L. in WMF with micropyle orientation directed to the south pole stimulated subsequent growth of their seedlings compared to those seeds that were placed antiparallely (i.e. micropyle to the magnetic north pole (Cerdonio et al., 1979)). Ružič and Jerman (1993) also showed that a south-pole orientation increased growth of a chestnut (*Castanea sativa* L.) more than a north pole. In contrast, Bogatina et al. (1978) found no effects of polar seed orientation on wheat seedling growth in WMF, although the control samples responded to the artificial GMF in the same pattern as other plants cited above.

There is some evidence that WMF may affect the development of cells and tissues cultivated in vitro. The first plant tissue cultures to be studied in the WMF conditions were of sugar beet (*B. vulgaris* var. *saccharifera*) and two strains derived from *Haplopappus*

*gracilis* that differed in their biomass production (Sytnik et al., 1984). The strain “K” had a lower biomass production than the strain “23”. Both strains of *H. gracilis* exhibited a 15% decrease in the callus production compared to the GMF control after their 5-day cultivation in WMF. Strains “K” and “23” exhibited 14% and 21% inhibition in biomass production during 10 days growth in WMF. Moreover, both strains displayed no significant difference in the cell number per 100 mg of callus fresh mass after 5 days in WMF, however, these indices were lower in the WMF-treated 10-day cultures than in corresponding GMF controls.

Only insignificant decrease in biomass production was observed during 21-day cultivation of 24-day sugar beet (*B. vulgaris* var. *saccharifera*) callus cultures in WMF compared to GMF control (Sytnik et al., 1984). At the 11th day of WMF-exposure, the cell index of cultures with the same initial callus developmental stages (the same initial cell numbers in both test and control) started to decrease. The biggest difference (47%) in the cell number between test and GMF control samples was observed in 13-day-old cultures (10 days of WMF-treatment). However, 24-day-old cultures had no changes in their cell numbers, even those after the 21 day long WMF-exposure.

Dijak et al. (1986) reported that application of very weak magnetic fields to suspension cultures of alfalfa (*Medicago sativa* L.) enhanced formation of somatic embryos from mesophyll protoplasts.

### 3. Proliferation and differentiation

Initial studies to determine whether the reduced growth of plants in WMF was due to the changes in the cell division have been carried out with pea, flax and lentil (Sytnik et al., 1984). The authors impulse labeled 1-day-old seedlings with  $^3\text{H}$ -thymidine for 1 h and followed their growth for up to 3 days, or 1-day-old seedlings grew with permanent  $^3\text{H}$ -thymidine-treatment for 2 days. They found that 2 mT WMF caused a remarkable decrease in the proliferative pool (general number of meristematic cells being in the reproduction cycle), compared to GMF control (68% and 95%, respectively). This is consistent with results of Nanushyan and Murashov (2001), who observed a significant decrease in the cell number with enhanced DNA content in *Allium cepa* L. root and shoot meristems after the artificial shielding of GMF. The general non-specific response of the root meristems of pea, flax and lentil to WMF conditions was an increase in the cell cycle duration. For example, WMF-treated (1 nT) seedlings of pea showed a 41% increase, flax – a 30% increase and lentil – a 33% increase in the cell cycle duration compared to GMF control (Fomicheva et al., 1992a). In addition, the cell system specificity in their responses to WMF

in root meristems of various plant species was characteristic for different phases of cell cycles. In meristem cells of pea seedling roots in WMF, changes in the cell cycle duration associated with a delay of the presynthetic ( $G_1$ ) phase and the invariability of the time indices for the remaining phases. Besides the delay in  $G_1$ -phase (by 51%), the post-synthetic ( $G_2$ ) phase also extended (by 33%) in flax root meristem exposed to WMF, compared to GMF control. In WMF-treated lentil roots  $G_1$  and  $G_2$ -phase were 60–70% longer than in controls. At the same time, the durations of the synthetic (S) phase and mitosis (M) remained nearly constant in all these plant species. The authors proposed that the proliferative activity might be the sensitive link in the complex chain of structural and metabolic alterations induced by WMF. Because of the appearance of blocks in  $G_1$  and, in part,  $G_2$ - phases under WMF conditions, the authors also studied the dynamics of the total contents of RNA and proteins.

In pea roots treated with 2 mT WMF, incorporation of  $^3\text{H}$ -leucine, associated with protein biosyntheses occurred 12 h earlier than in GMF control, and reached maximum after 24 h of development, while in GMF control pea roots it happened at 32 h (Sytnik et al., 1984). In GMF, following 32 h maximum the isotope outflow occurs until about 30% of maximum level is reached at 96 h. In WMF, only 10–12% of maximal radioactivity amount remained in the root tissue at the same time. Thus, the results presented by these authors for pea suggest that the processes of protein synthesis and break-up proceeded slower in GMF control than in WMF. Fomicheva et al. (1992b) used quantitative cytochemical methods to measure RNA content and the fluorescence microscopic method to measure protein content. They reported that a phase pattern of changes in total contents of RNA and proteins in root cells of pea and flax seedlings was observed in both sets of experimental samples, while such phases were nearly smoothed in lentil seedlings. However, in WMF conditions, these phases were shifted to later terms. These authors concluded that the decrease in the functional genome activities in root meristem of pea, flax and lentil seedlings occurred in the early prereplicative period under WMF conditions compared to GMF control.

#### 4. Cellular and subcellular changes

Artificial shielding of GMF caused several types of cell transformation in meristem cells of root and shoots in *Allium cepa* L. and wheat seedlings (Nanushyan and Murashov, 2001). The uncytokinetic mitosis with formation of binuclear and then tetranuclear cells as well as a fusion of normal nuclei resulting in appearance of giant cells with vast nuclei seems to dominate in the WMF samples. The in vitro experiments on isolated root tip

meristem allowed to exclude the possibility of centralized regulation of cell structure changes resulted in metabolite exchange between different tissues and organs in the whole plant.

Detailed analysis of the alterations in cellular structure of meristem cells of pea seedling roots exposed to WMF was performed by Belyavskaya (1981, 1992, 2001). Some changes in the ultrastructural organization of some organelles and cellular compartments were observed in comparison to the control roots (Fig. 1(a) and (b)). Alterations in condensed chromatin distribution became apparent in WMF conditions. It was associated with the nucleus envelope instead of being evenly distributed as in the control cells. The reduction in volume of granular nucleolus component and an appearance of nucleolus vacuoles in WMF-exposed cells might indicate a decrease in activities of rRNA synthesis in some nucleoli.

After 3-day growth, control cells were almost free of lipid bodies (Fig. 1(a)), while following WMF-exposure meristem cells exhibited a 9.6-fold increase in the volume of these inclusions that placed along plasmalemma (Fig. 1(f) and (g)). This phenomenon could be associated with slower lipolysis by means of lipolytic enzymes due to their inhibition or a decrease in enzyme synthesis. An interesting correlation with this structural data can be found in the paper by Novitskaya et al. (2001), where they showed elevated total content of neutral lipids in 5-day radish seedlings grown in the dark and exposed to WMF in comparison with GMF control.

In WMF conditions, different components of the lytic compartment such as vacuoles, cytosomes and myelin-like bodies were found to form (Fig. 1(b) and (g)). As a rule, vacuoles had a round form and electron-dense deposits with loose structure were seen along the tonoplast. Such deposits may be interpreted as the remains of protein bodies that are in part lysed in vacuoles. Lysis of cellular components can be realized by means of cytosomes. The significant role in their genesis is attributed to enzymes of the endoplasmic reticulum whose cisternae, when they separate, isolate cytoplasm zones and hydrolytic enzymes in their cavities pass into such closed sack. In some cases, partial degradation of cytosome content leads to formation of myelin-like body. The latter is a structure consisting of concentric or coaxial membranes with homogenous material between them. Although the possibility of formation of myelin-like bodies as a result of intense plasmalemma growth is not ruled out, the more preferable point of view is the resistance of cellular membranous components to breaking action of hydrolases. The presence of different components of a lytic compartment that were absent, as a rule, in cells of GMF control could indicate advanced pathological processes in meristem cells of seedling in WMF.



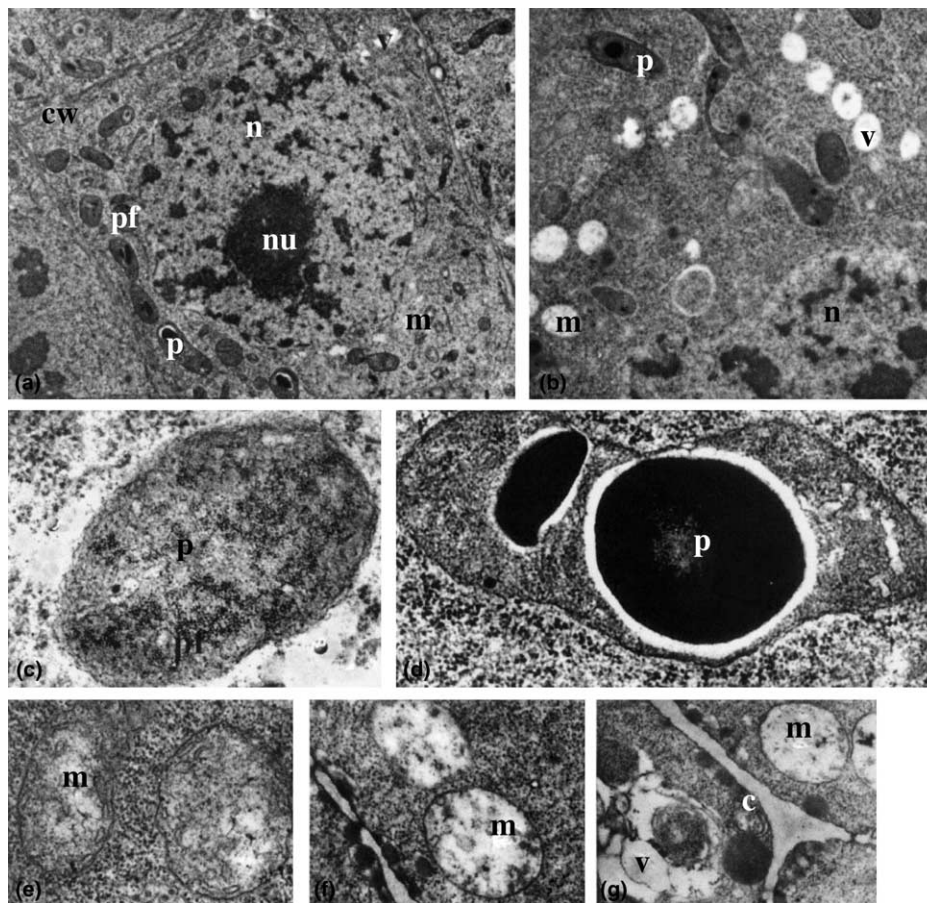


Fig. 1. Meristem cells of pea roots. (a), (c), (e) Stationary control (a) 5000 $\times$ , (c) 17 000 $\times$ , (e) 10 000 $\times$  (b) Effect of WMF. (b) 10 000 $\times$ , (d) 11 200 $\times$ , (f) 5200 $\times$ , (g) 8000 $\times$ . Abbreviations: c, cytosomes; cw, cell wall; lb, lipid body; n, nucleus; nu, nucleolus; m, mitochondria; p, plastid; pf, phytoferritin; v, vacuole.

In 14% of plastids of pea meristem cells of the stationary control, the electron-dense inclusions of phytoferritin with a diameter near 7 nm were observed (Fig. 1(c)). Phytoferritin is an iron-storage protein, consisting of a hollow sphere made of 24 subunits and capable to accommodate up to 4500 iron atoms per molecule inside its internal cavity (Harrison and Arosio, 1996). The inclusions are freely distributed in plastid stroma and can occupy nearly all of the sectional area of the plastid. In WMF-exposed cells, only 1.5% of the plastids had phytoferritin and a number of its granules did not exceed 10–20 per plastid section (Fig. 1(d)). The observed very low levels of phytoferritin suggest that WMF conditions result in either suppression of phytoferritin synthesis or in an increase of its utilization for synthesis of iron-containing proteins (Belyavskaya, 1981). In addition, iron as a transition metal can react with oxygen to produce reactive oxygen intermediates that can generate oxidative stress (Briat and Lebrun, 1999).

The most significant changes in WMF-exposed pea root meristem cells were observed in mitochondria. Their population density (number of the organelles per cellular section) increased by 12% and the mitochondria

were 1.5–2 times bigger in diameter than those in control cells. Mitochondria that had typical elongated shape in stationary control (Fig. 1(e)) became roundish after WMF exposure (Fig. 1(f)). Their cristae were transformed into narrow short tubes located on the organelle periphery. The amount of cristae decreased significantly (up to several per the mitochondria section) and they were absent in some organelles. The mitochondria matrix was prominent and it often contained electron-dense inclusions whose structure was not specific. No filaments of mitochondria nucleoids were found in the matrix. Mitochondria ribosomes were rarely found in the organelles. According to the conventional classification, such type of mitochondria alterations is considered as organelle swelling that is associated with disturbances in water-saline exchange, which can indicate depression of the functional activities. Moreover, mitochondria are known as the  $\text{Ca}^{2+}$  buffer that can pump out excess  $\text{Ca}^{2+}$  from cytoplasm. Furthermore, the specific feature of such activity is mitochondria swelling.

Cytochemical experiments were conducted to discover  $\text{Ca}^{2+}$  localization using the pyroantimonate method in meristematic root cells of 3-day pea, flax

and lentil seedlings grown in 1 nT WMF and in control (Belyavskaya, 2001; Belyavskaya et al., 1992). “Diffuse” pyroantimonate precipitate in the cytoplasm and intensification of the pyroantimonate reaction in mitochondria were observed in WMF-treated cells. In GMF controls,  $\text{Ca}^{2+}$  pyroantimonate granules were observed in the apoplast and in  $\text{Ca}^{2+}$ -sequestering stores. Thus, the cytochemical studies have demonstrated a disruption in  $\text{Ca}^{2+}$  balance in WMF.

## 5. Physiological and biochemical changes

Osmotic pressure of cell sap at the middle part of pea epicotyls measured by the vapor pressure method using an osmometer was significantly higher in 0.5  $\mu\text{T}$  WMF than in GMF control (Negishi et al., 1999). An experimental study on water absorption by lettuce (*Lactuca sativa* L.) seeds previously treated in stationary magnetic field of 0–10  $\mu\text{T}$  showed a significant increase in the rate of water absorption (Reina et al., 2001). The authors concluded that the experimental data provide strong evidence that the WMF alter the water relations in seeds, and this effect may explain the reported alterations in germination rate of seeds treated with magnetic fields.

Peculiarities of respiration of barley seedlings in 10  $\mu\text{T}$  WMF were studied by Kursevich and Travkin (1973a,b). They demonstrated that the respiration intensity and  $\text{CO}_2$  emission increased by 70–100% in WMF compared to GMF control (Kursevich and Travkin, 1973b). Further studies have shown that after 24 h the catalase activity enhanced only slightly, while after 48 and 72 h it increased nearly by 30% and 100%, respectively, compared to GMF controls. At the same time, measurements of polyphenoloxidase activity exhibited a gradual reduction, reaching a 50% level after 72 h, whereas peroxidase activity decreased insignificantly (Kursevich and Travkin, 1973a).

The effects of WMF on photosynthesis in plants have not been studied in detail, but there is evidence that screening of magnetic fields results in decline in contents of photosynthetic pigments, chlorophyll a and b, in kidney bean (*Phaseolus vulgaris* L.) leaves (Kazimov, 1984).

Novitskaya et al. (2001) studied the effects of 0.5  $\mu\text{T}$  WMF produced by Helmholtz rings (with or without light) on neutral lipids and proteins in radish seedlings. Protein content in WMF-treated light-grown plants increased compared with the GMF control light-grown seedlings, whereas it remained almost unchanged in dark-grown plants. In GMF control, biochemical studies of neutral lipids reported a 5-fold increase in neutral lipid content in light-grown seedlings in comparison with dark-grown ones. Among these lipids the triacylglyceride content in light was 25-fold higher than the sum of free sterols and sterol esters, while in the dark, the difference was only 2-fold. The combination of

WMF and light lowered total neutral lipid content, however, the level of free sterols simultaneously increased. In the dark, WMF elevated total content both of neutral lipids and of free sterols and sterol esters. These results were interpreted as a WMF stimulation of neutral lipids' synthesis in the dark as well as its suppression in the light (Novitskaya et al., 2001).

Nechiporenko et al. (2001) indicated a disruption of mineral balance in onion and radish seedlings under WMF conditions (0.5  $\mu\text{M}$ ). This was manifested by a significant increase in iron level found only in WMF-treated onion plants. Calcium accumulated mainly in onion roots as well as in both leaves and storage organs of radish seedlings while in onion seedlings, magnesium level decreased in the 4th leaf and enhanced in their roots. Sodium content decreased by 25–30% in radish roots. According to the authors, it is still unclear, whether these changes in cations' levels in WMF resulted from their redistribution between organs, or from selective inhibition, or activation of the cation absorption and extrusion by root systems in soil (Nechiporenko et al., 2001).

Interestingly, magnetization of  $\text{CaCl}_2$  solution that washed leaves of *Elodea canadensis* resulted in reduction of the resting potential of the leaf cells that correlated with the decrease in  $\text{Ca}^{2+}$  activity (Evdokimov et al., 1975; Kartashev et al., 1978).

In experiments with 2-day maize (*Zea mays* L. cv. Golden Cross Bantam 70) seedlings, there was weak and near equal gravitropic response in a darkness, whether exposed to WMF (50 nT) or not, however, they became bent when were illuminated (Kato, 1990). Furthermore, the roots of seedlings grown in WMF exhibited higher levels of curvature (by 37%), compared to the light controls in GMF.

In the Helmholtz rings, where the magnetic flux density could vary from 0.5 to 350  $\mu\text{T}$ , a gravitropic response of flax (*Linum bienne* L.) apical shoot segments (without leaves) was studied (Belova and Lednev, 2001). At 2  $\mu\text{T}$ , a significant gravitropism activation was found in comparison with GMF control. The increase in magnetic flux density to 100  $\mu\text{T}$  resulted in inhibition of the gravitropic response of shoot segments. The authors proposed that the effects of the activation and the inhibition of the gravitropic response in flax shoot segments, which occurred under increasing the magnetic flux density, might be initiated by effects of permanent magnetic fields on the rates of some  $\text{Ca}^{2+}$ -dependent biochemical reactions in gravisensitive cells, statocytes.

## 6. Possible mechanisms

For a number of years laboratory studies on the biological effects of WMF have demonstrated that the fields

can produce or alter a wide range of phenomena. Explaining the diversity of the reported effects is a central problem.

In recent years, the following types of physical processes or models underlying hypothetically primary mechanisms of the interaction of WMF with biological systems have been proposed (Binhi, 2001):

- Classical and quantum oscillator models.
- Cyclotron resonance model.
- Interference of quantum states of bound ions and electrons.
- Coherent quantum excitations.
- Biological effects of torsion fields accompanying WMF.
- Biologically active metastable states of liquid water.
- Free-radical reactions and other “spin” mechanisms.
- Parametric resonance model.
- 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.

There is considerable evidence for each of these mechanisms. Although there are clear instances in which some models seem unlikely, there may also be situations in which such a mechanism can become significant. Finally, we cannot rule out mechanisms combining these concepts and models.

Another basic hypothesis is that WMF effects are generally indirect, and arise as a consequence of sensory transduction of the fields (Creanga et al., 2002). In this view, WMF detection and its biological responses occur in different types of cells and tissues. Experimental verification of the hypothesis will ultimately require data showing that the interaction of WMF with tissue results in biological changes, which are the same as or similar to changes that occur during sensory transduction. The goal is to identify the specific phenomena, which can be expected to occur if the hypothesis is true. Many kinds of processes were identified in connection with transduction of different stimuli, but it was found that a change in the conductance of a membrane ion channel in animal cells (neuron or a neuroepithelial cell) was the primary process occurring in all forms of sensory transduction (Creanga et al., 2002). Evidence from an appropriate model excitable cell or tissue that WMFs affect membrane currents or membrane potential would therefore support the hypothesis that WMF transduction is a type of sensory transduction.

By analyzing the changes in  $\text{Ca}^{2+}$  distribution and contents in cells of pea, flax, lentil, onion and radish seedlings exposed to WMF we can conclude that such a stress has resulted in serious disturbances at the cellular level, particularly in the  $\text{Ca}^{2+}$  balance. In our opinion, the potential sensing component could be  $\text{Ca}^{2+}$  ions. The increase of  $\text{Ca}^{2+}$  level is fully consistent with the assumption of the parametrical resonance model (Lednev, 1996) that the primary link in the chain of events triggered by WMF action in a biological system is the  $\text{Ca}^{2+}$  ions connected with  $\text{Ca}^{2+}$ -binding sites of the proteins.

## 7. Conclusions and perspectives

There is a large body of experimental data demonstrating various effects of WMF on plants. In most cases WMF suppress the growth processes, cell division and differentiation, induce significant changes at the cellular and subcellular level, alter the  $\text{Ca}^{2+}$  balance, enzymes' activities and various metabolic processes. However, in some experimental sets, the dynamics of these processes indicated an adaptation to WMF conditions.

The analysis of the results presented here provides evidence that plants can perceive WMF. However, we still know very little about the molecular nature and function of the putative WMF receptors and how receptor activation leads to formation of a physiological signal. The nature of the physiological signal has not been elucidated, although some phytohormones can be such components. Their patterns of action and involvement in the coordination of the overall response in different plant organs have yet to be determined.

WMF is only one of several factors that affect plant growth and development aboard space ships. For example, microgravity and radiation also regulate growth patterns. Simultaneous exposure to multiple and competing environmental factors may result in complex growth patterns. For instance, growth of garden cress seedlings was unaffected by WMF alone, however, if the magnetic field's exposure preceded the heat treatment, it alleviated the inhibitory effect of the heat shock (Ružič and Jerman, 2002). Therefore, the molecular mechanisms responsible for the integration of these complex regulatory processes have yet to be determined.

In recent years, much research has focused on the mechanisms with which plants sense and respond to WMF. The physicists and biophysicists have proposed several hypotheses and models concerning physical aspects of interaction between biomolecules/cellular components and WMF. However, there is also convincing body of evidence indicating that such mechanisms cannot account for some biological effects in all cases. Other possibilities include changes in intracellular  $\text{Ca}^{2+}$  levels that control numerous processes in plants.  $\text{Ca}^{2+}$



signaling has been implicated in plant responses to a number of abiotic stresses including low temperature, osmotic stress, heat, oxidative stress, anoxia, and mechanical perturbation, which has been reviewed by Knight (2000). Our observations of the increase in the  $[Ca^{2+}]_{\text{cyt}}$  level after exposure to WMF allow us to suggest that  $Ca^{2+}$  entry into the cytosol can constitute the primary WMF sensing mechanism in plants (Belyavskaya et al., 1992; Belyavskaya, 2001). Clearly, much research still remains to be done in order for us to sort out these hypotheses and better understand WMF sensing by plants and their responses to the environmental stimulus. It is obvious that revealing the relationships between WMF parameters and response of plants becomes urgent question in light of planned long-term flights to other planets. The studies can provide the fundamental background, necessary to develop scientific recommendations for design of life-support systems and their plant components for future space flights.

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