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Effects of Electromagnetic Field Frequency on the Behavior and Mortalities of Living Organisms

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Abstract: The objective of this investigation is to assess the influence of electromagnetic fields on living organisms. The impact of electromagnetic radiation of varying intensities on alterations in behavioral responses and mortality rates of living organisms was examined under controlled laboratory conditions at the first Moscow state medical university, named after I.M. Sechenov. The subjects of the study encompassed 10 specimens of white rats (*Rattus norvegicus*), 100 individuals of honeybees (*Apis mellifera* L.), and 20 dung beetles (*Geotrupes stercorarius*). The study employed both correlation and regression analyses to objectively assess the relationship between the frequency of Electromagnetic Fields (EMFs) and mortality. It is worth noting that all necessary measures were taken to ensure the welfare and ethical treatment of living organisms throughout the research. It was observed that the subjects exposed to EMFs of different frequencies (50 Hz, 3 MHz, and 3 GHz) exhibited increased activity at the outset of the experiment. The highest percentage of fatalities (35 in rats, 49 in bees, and 100% in dung beetles) was recorded at an EMF frequency of 3 GHz. The research also confirms that the longer the exposure of organisms to EMFs, the stronger the impact on their behavior, and the correlation and regression analyses substantiated a significant increase in mortality with the escalation of EMF frequency for the studied organisms. This study is notable for its novelty as it is geared towards examining the impact of electromagnetic fields of different frequencies on the behavior and mortality of living organisms, thus expanding our understanding of the potential effects of these fields on biological systems. The practical significance of the results lies in their potential application in updating safety standards for practical EMF use and identifying patterns of interaction between EMFs and living organisms.

Keywords: Electromagnetic Radiation, *Rattus norvegicus*, *Apis mellifera L.*, *Geotrupes stercorarius*, Intensity, Behavior, Mortality

Introduction

Electromagnetic Fields (EMFs), specifically electric and magnetic fields, occur naturally when their sources are atmospheric electricity, solar radiation, cosmic rays, and extraterrestrial sources. Furthermore, EMF results from human activity, namely, technical equipment use. The earth continually produces a constant electric and magnetic field around it. All organisms that populate the earth are continually exposed to EMF and living organisms have adapted to the influence of evolution on natural sources of EMF. Dynamic development of technologies and systematic increase in the number of devices generating artificial EMFs with parameters exceeding the earth field intensity and induction values may disturb body homeostasis and harm health.

Artificial EMFs have been brought to the natural environment by humans. They are emitted by various technical devices used in electrical engineering, industrial, communications, radio navigation, radiolocation, medicine, science, and even at home (Safonov *et al*., 2021; Safonov, 2022). That is, each appliance supplied with electricity is its source. A major source of EMF radiation in our environment is high-voltage power lines, generating an electromagnetic field with a 50 Hz network frequency and emitting radiofrequency electromagnetic fields (Pophof *et al*., 2023).

At present, considerable attention is given to the issue of the interaction of EMF with living matter. Thus, in the course of the research, by Strašák *et al*. (2002); Öhman *et al*. (2007); Formicki *et al.* (2019); Thielens *et al*. (2020); Geffre *et al*. (2020); Lai and Levitt (2022) experimentally confirmed that small magnetic fields affect the motion direction of gill fish, including sharks and skates, kinetic movement of molluscs, migration behavior of birds, wagging "dance of bees," orientation and motion direction of magnetically sensitive bacteria. Studying the interaction between external EMFs and biosystems requires research into the effect of fields on the activity of living cells, their behavior, the body's structural changes, and the adaptation mechanisms.

Research Objective

This study aims to optimize the results achieved by scientists and obtain new experimental data on the effect of EMFs on animal organisms, thus making the subject relevant.

The findings obtained can be applied in developing patterns of the interaction of EMFs with living organisms. Further research will aim to adjust and update current sanitary and epidemiological standards and regulations.

Scientific Precision and Novelty

The novelty of this research resides in its focus on examining the impact of Electromagnetic Fields (EMFs) of various frequencies on the behavior and mortality of living organisms. This study complements existing studies that have explored the influence of EMFs on animals and expands our understanding of the potential effects of different EMF frequencies on living organisms.

This research, which gathers data on how various EMF frequencies affect living organisms and their behavior, has the potential to provide valuable insights into how external electromagnetic fields can influence living systems. This newly acquired knowledge may be instrumental in improving safety standards for EMF usage and could also have applications in ecological monitoring within the realms of biology, forestry, and agriculture.

Ethical Issues

Considering the involvement of animals in this study, ensuring their humane and ethical treatment is of paramount significance. Therefore, every possible effort has been made to minimize the suffering and discomfort experienced by the animals, providing proper care and creating optimal conditions for their well-being during the research. Adherence to these ethical principles is critical for establishing trust in the research outcomes and upholding its scientific reputation.

Beaubois *et al*. (2007) state that EMFs (shallow frequency) can benefit plants. The observed beneficial effect of the natural electric field may result from direct irritation of plant tissue or an increase in the level of chemicals beneficial to plants in the soil. The increase in the intensity of the natural EMF stimulates the rapid growth of vegetation seen in the latest spring, reaching 122 V/m and falling to 75 V/m in the summer (Beaubois *et al*., 2007).

Peter *et al.* (2006) stated that the electrical field positively affects plants, particularly the transport of electrically charged particles of organic compounds, including growth hormones auxins, which stimulate the active growth of plants. In turn, the magnetic field affects electrolyte transport in vegetable cells by modifying the permeability of potential-dependent ion channels (Peter *et al*., 2006).

The research of Krivov *et al*. (2020) confirms that seeds treated by constant and alternating electric fields germinate better and more quickly, giving more vigorous seedlings, from which plants with higher yields grow. Thus, exposure to an alternating electrical field with a mains frequency of 50-60 Hz and an exposure time of a few seconds to 30 min showed an increase in laboratory seed germination by 2-50%, field germination by 10-20%, and yield by 5-30% (Krivov *et al*., 2020). However, the study of (Vian *et al*., 2016), in which plants were irradiated with frequencies ranging from 450 MHz to 2.4 GHz, showed a very different reaction from plants. In particular, the author noted numerous disorders of cell metabolism, 6-fold higher genetic degradation, frequent abnormal cell division, inhibition of seed germination in half the cases, and a decrease in growth, height, and weight of plants and fruits ranging from 16-60% compared to uneradicated plants (Vian *et al*., 2016).

As for animals, studies by Vera and Muñoz (2020) on rodents demonstrated that mice become completely infertile in three generations under constant exposure to an EMF of 50 Hz. Furthermore, exposure to EMF of 50 Hz generates a high stress index in mice, provoking changes in their social behavior (Vera and Muñoz, 2020). Franczak *et al*. (2020) reported reproductive problems in pigs after installing a cellular telephone base station nearby. The number of litters and piglets has decreased considerably and the number of malformations has increased (Franczak *et al*., 2020). According to Wiltschko and Wiltschko (2005), if cows are exposed to 40 Hz electromagnetic fields, they produce less milk, their wool becomes soft and they may even have infertility.

Experimental data from Yamamoto (1998); Hyland (2000); Lahijani *et al*. (2009) confirm that when exposed to EMF frequency of 40-50 Hz, chickens suffer plumage loss and leukemia, horses suffer from heart disease, blindness, and rheumatism, rabbits show emotional agitation caused by stress and sheep have liver damage.

Detailed studies by Thielens *et al.* (2020); Geffre *et al.* (2020) have been carried out on honey bees, which were model organisms, to evaluate the radiation effects of cell phones. It was found that the electric field causes disturbances in the behavior of bees. In an electric field of 1.4 kV/m, they consume more oxygen and food; in a 4 kV/m, they produce less honey, and their mortality rate increases. At EMF strengths more significant than 7.4 kV/m, the swarm produces more heat and escapes from the hive more often. At 50 kV/m strength, the bees fight each other, stinging to death (Thielens *et al*., 2020; Geffre *et al*., 2020).

According to Cammaerts *et al*. (2012), radiation from cell phones and base stations can affect ants. Adverse effects included altered ant development and reproductive function and improper coordination of ants in the field. After a week of exposure, the ant colonies could not eat and died.

Studies by Hutchison *et al*. (2020); Levitt *et al*. (2022) have proven that there are many mechanisms by which electromagnetic radiation can harm living organisms. In animals, these may be electromagnetic senses (such as those possessed by bees, birds, whales, and dolphins) that directly perceive technical radiation, causing animals to lose their orientation (Hutchison *et al*., 2020; Levitt *et al*., 2022). Moreover, the behavior of flying insects changes under the influence of EMF at 50 Hz. Thus, small insects hardly fly and large insects fly prudently, avoiding places with increased field strength (Balmori and Hallberg, 2007).

Nevertheless, at the same time, scientific research shows that isolating plants and animals from natural electromagnetic fields also causes undesirable symptoms. The plants are no longer in growth and their tropisms are disturbed. The animals, in turn, lose appetite, molt and exhibit signs of autonomic nervous system instability and neuroses. Histological changes in tissues were also observed (Wiaderkiewicz, 2008; Bogatina and Sheikina, 2010).

Statement of Objectives

Therefore, it is worth noting that more research is needed to examine the influence of electromagnetic fields on living organisms. Numerous publications indicate the interest of the scientific community in the subject. However, the influence of specifically low, high, and ultra-high frequencies on the behavior and mortality of living organisms has not yet been sufficiently studied, which makes research relevant.

Describing the existing problems of the subject under investigation, this study aims to analyze the effect of electromagnetic fields on living organisms.

As a result, the following tasks were defined in the study evaluating the effect of EMF on different species of living organisms, such as white rat (*Rattus norvegicus*), honeybee (*Apis mellifera* L.) and common dung bee (*Geotrupes stercorarius*); studying the impact of electromagnetic radiation of different intensities on changes in animal behavioral reactions: Motor activity, orientation activity, aggressiveness, and mortality.

The practical significance of the findings is their application to the development of models describing the interaction between EMFs and living organisms. Other research may aim to adapt and update current sanitary and epidemiological rules and regulations and monitor the environment in biology, forestry, and agriculture.

Materials and Methods

The study was conducted in May-July 2022 under laboratory conditions at the I.M. Sechenov first Moscow state medical university. The effect of electromagnetic fields of different frequencies on changes in the behavioral responses of living organisms given in the research objectives was studied. During the experiment, the "open field" method was used to evaluate the effect of EMFs on rats by observing their behavioral responses: Motor activity, orientation activity, and aggression.

Bee flight activity has been assessed using a device developed by the ministry of human and animal physiology and biochemistry. The sensor was a sequence of photocells placed on a control panel. The sensor was connected to an amplifier and an electrical meter, which recorded bees flying past the photocell. Sensor readings were logged for 2 min in total.

The apparatus for assessing bee flight activity consists of several fundamental components:

1. Photoelements: The sensor comprises a sequence of photoelements. Photoelements are specialized sensors that respond to light and convert it into an electrical signal. In this context, photoelements are arranged sequentially adjacent to one another on the control panel
2. Amplifier: The signal from the photo elements requires amplification for subsequent analysis. An amplifier is employed to increase the signal's amplitude, preserve details, and reduce noise, facilitating the acquisition of more precise results
3. Coulomb counter: The coulomb counter is a device designed for measuring the quantity of electrical charge passing through it. In this case, it records the passage of bees over the photo elements and measures the amount of signal generated by each photo element during a bee's transit

The procedure for assessing bee flight activity unfolds as follows.

Bees fly past a sequence of photo elements. Each photo element registers the passage of a bee and generates a corresponding electrical signal. These signals from the photo elements are then amplified to enhance their quality and preserve fine details. The coulomb counter records the quantity of signal passing through it over a 2 min interval. This system enables the precise measurement of bee flight activity and the retention of data for subsequent analysis.

The measurement of locomotor activity in *Rattus norvegicus* was defined as the number of steps taken by them within a specific time frame (1 h). To measure the locomotor activity of white rats in their cages, counters were installed, which recorded the number of steps taken by the rats within a designated period. These counters enabled the precise quantification of rat activity under the influence of electromagnetic fields.

The motor activity of the beetles was determined by counting the number of animals in motion. The animals' orientation activity was determined by observing their ability to find food and their aggression by their aggressive behavior toward each other. Only active animals were selected for testing. Object mortality was also determined as a percentage of fatalities compared to the total number of individuals in the group.

For all three animal species (bees, white rats, and beetles), aggression was measured by observing their interactions during the experiment. Parameters such as attacks, collisions, or other aggressive behaviors between the animals were documented.

The following statistical tests were employed for data analysis:

- Analysis of Variance (ANOVA) was used to compare the means between groups
- The student's t-test for independent samples was applied to assess the significance of differences between groups

In addition, statistical analysis was conducted to determine the reliability of the effect of EMF on the study subjects, and a 3-month comparative analysis of the data. The resulting data are presented as the mean and standard deviation of the mean (M ± SD). P values at <0.05 were considered significant.

The determination of the duration of electromagnetic field exposure is rooted in practical and scientific justifications. In this study, a three-month exposure duration was selected. Such a timeframe allows for the observation of long-term changes in the behavior and morphology of living organisms under the influence of different frequencies. This temporal interval also permits the detection of potential cumulative effects and adaptive changes in response to prolonged exposure.

The choice of a specific electromagnetic field frequency can be justified by previous research findings, theoretical predictions, or specific practical circumstances. In this case, frequencies of 50 Hz (low frequency), 3.0 MHz (high frequency), and 3 GHz (ultra-high frequency) were selected. These frequencies may correspond to various sources of electromagnetic fields commonly encountered in the environment (e.g., 50 Hz from high-voltage power lines or household appliances, 3.0 MHz and 3 GHz from wireless communication, and other sources).

In the past, living organisms were prepared in three laboratories with the necessary temperature and moisture. For example, white rats were kept in plastic cages of 60×40×20 cm, which did not limit freedom of movement. Rodents were given standard feed and access to potable water. Throughout the experience, the ambient temperature was maintained at 22°C and the humidity content of the air was 65%. Bees were kept indoors at 21-24°C in small hives in a mesh chamber and supplied with food, water, and free flight. Adults were kept in plastic boxes measuring 40×40×20 cm, fed, and watered at a constant temperature of 25°C.

All living organisms were divided into 3 experimental groups (with variable EMF) and 1 control (without EMF exposure), so the number of rodents in each group was 10 pcs, bees 100 pcs, and beetles 20 pcs. The experiments were carried out by modern laboratory practice requirements for experimental (pre-clinical) research in the Russian Federation (GOST 351000.3-96 and GOST 51000.4-96).

The selection of specific organism quantities in each experimental group was justified with consideration of the variation in the sensitivity of different species to EMFs, their suitability for observation and experimentation, and adherence to standards and recommendations for similar research studies:

1. Rats (10 individuals per group): The selection of 10 rats in each experimental group was based on the established standard group size for laboratory rat studies. This group size is considered sufficiently representative for assessing the impact of EMFs on behavior and mortality
2. Bees (100 individuals per group): Due to the smaller size of bees compared to rats and the potential for less individualized behavior, a higher number of bees was included in each group as a deliberate choice. This extensive volume of observations allowed for more precise data and enhanced result reliability
3. Beetles (20 individuals per group): The choice of 20 beetles in each group was made because they are smaller than rats but larger than bees. This quantity facilitated the observation of their behavior and maintained statistical significance in the results

The organisms in the control group were not subjected to the influence of electromagnetic fields. They were maintained under conditions identical to those of the experimental groups. Locomotor activity, orientation activity, and aggression in beetles were recorded using the same principles as in the other groups. The control group was crucial in establishing a baseline level of behavioral responses in animals unaffected by electromagnetic fields. This allowed for a proper comparison of the results obtained in the experimental groups and determined whether significant differences arose due to the influence of different electromagnetic field frequencies.

In each laboratory, an EMF generator of variable frequency was used as the source of electromagnetic radiation. It emitted frequencies of 50 Hz (low frequency), 3.0 MHz (high frequency), and 3 GHz (ultrahigh frequency) for the first, second, and third experimental groups, respectively. Magnetic field induction was 10 mTl with an electromagnetic field strength of 0.2 µT for all groups. Treatment was carried out over three months, with a daily EMF exposure of 4 h. Throughout the test period, the resistance of the EMF electrical component was determined with a Narda NBM-550 meter (Narda safety test solutions GmbH, Germany). The frequency was monitored using an AKS-1201 spectrum analyzer (GS instruments Co., Ltd., Korea).

For the documentation and subsequent analysis during observations, a Sony HDR-CX240E camera (Sony, Japan) was utilized. This video camera enabled the recording of object movements and their interactions with the precision required for the observations.

The camera was used with the aim of impartially and thoroughly documenting the movements and interactions of entities (animals) exposed to electromagnetic fields. This objectivity is crucial for precise data analysis and interpretation. The obtained video recordings allowed for a more detailed analysis of the animals' responses, aiding in the identification of specific changes in their behavior and interactions that might have been overlooked with other measurement methods. The Sony HDR-CX240E video camera provided the necessary level of detail and accuracy to capture even the slightest movements of animals and their interactions, which is essential for providing objective evidence and analyzing the research results.

Hence, the utilization of the video camera played a crucial role in ensuring data accuracy and reliability, as well as in conducting a meticulous analysis of animal responses to electromagnetic fields in this study.

To ensure measurement accuracy and reliability, particularly when employing sensors and counters, several measures were taken:

1. Calibration of equipment: Sensors and counters underwent calibration procedures before usage, confirming their accuracy and proper functioning
2. Standardized procedures: Standardized methods were employed for measuring locomotor activity and orientation activity to obtain comparable results
3. Error control and recording: Throughout the experiment, records, and documentation of all actions and parameters that could impact measurement accuracy were maintained
4. Multiple measurements: Several measurements were conducted for each parameter to obtain average values and assess variance
5. Object preparation: Living organisms were systematically prepared before measurements, ensuring uniform conditions for control and experimental groups
6. Equipment functionality verification: The operation of sensors and counters was regularly verified during the experiment to identify potential malfunctions or impediments to accurate measurements

Results

The study showed that regardless of the frequency of EMFs, all exposed animals had difficulties and an inability to focus on foraging, aggressiveness, and poor coordination of their movements over time. At that time, the higher the radiation intensity, the greater the difference in the behavior compared to the non-exposed subjects (Tables 1-3).

Table 1: Behavioral changes among white rats exposed to electromagnetic radiation

	Intensity of electromagnetic radiation				
Behavior Indicator	Month	Control	50 Hz	3 MHz	3 GHz
Motion activity, count	May	10±0.91	9±0.32	8±0.71	8±0.82
	June	10±0.35	7±0.64	6±0.46	6±0.36
	July	10±0.96	6±0.35	4±0.32	4±0.42
Indicative activity, count	May	10±0.56	9±0.85	8±0.71	8±0.64
	June	10±0.41	8±0.25	6±0.26	7±0.33
	July	10±0.52	6±0.14	5±0.47	6±0.21
Aggressiveness, count	May	-	1±0.12	2±0.64	4±0.32
	June	-	2±0.45	4±0.52	6±0.54
	July	-	2±0.93	4±0.34	6±0.27
R and $D_{0,05}$		1.26	1.39	1.16	1.31

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Table 2: Behavioral changes in reactions of honeybees exposed to electromagnetic radiation

Behavior Indicator	Month	Control	50 Hz	3 MHz	3 GHz
		Intensity of electromagnetic radiation			
Flight activity imp./min	May	100±0.26	89±0.63	85±0.19	79±0.31
	June	100±0.36	75±0.52	72±0.85	69±0.47
	July	100±0.47	68±0.47	65±0.96	61±0.25
Indicative activity, count	May	100±0.24	86±0.26	81±0.26	81±0.83
	June	100±0.36	76±0.36	69±0.85	64±0.27
	July	100±0.95	70±0.84	65±0.36	61±0.36
Aggressiveness, count	May	2±0.21	10±0.36	16±0.31	19±0.64
	June	2±0.15	21±0.65	26±0.32	31±0.25
	July	2±0.85	26±0.46	33±0.21	34±0.63
R and $D_{0,05}$		1.16	1.28	1.34	1.21

Table 3: The behavioral changes in reactions of common dung beetle exposed to electromagnetic radiation

Behavior Indicator	Month	Control	50 Hz	3 MHz	3 GHz
		Intensity of electromagnetic radiation			
motion activity, count	May	20±0.57	18±0.32	17±0.69	17±0.76
	June	20±0.63	16±0.96	13±0.57	13±0.16
	July	20±0.85	15±0.84	11±0.63	12±0.28
Indicative activity, count	May	20±0.56	18±0.24	17±0.36	17±0.21
	June	20±0.62	15±0.45	15±0.74	14±0.96
	July	19±0.74	13±0.74	13±0.95	14±0.26
Aggressiveness, count	May	-	3±0.26	3±0.54	4±0.42
	June	-	5±0.29	6±0.49	7±0.74
	July	-	7±0.74	7±0.47	7±0.63
R and $D_{0,05}$		1.21	1.42	1.32	1.18

It is important to note that exposure to 50 Hz EMF (industrial frequency field) did not result in sudden changes in animal behavior. However, studying the dynamics of their motor activity has shown that reliable changes in the behavior of rats and bees have already occurred in the second month of exposure to the magnetic field. For the common dung beetle, these changes took place on about days 50-55. But at the same time, the magnetic field with a frequency of 50 Hz under the studied conditions of its influence caused non-specific reactions in the animal's body, which manifested in unconditioned reflex behavior.

Under the influence of the 3.0 GHz EMF, more significant changes in the behavior of the experimental organisms were already noted on days 14-15th. Thus, reduced motor activity in rats has been established and already on day 20-25th, more pronounced disorientation, slow movement, and aggression have been manifested. Agitation, increased aggression, and chaotic flight were observed in bees at that time. Behavioral changes were also observed in dung beetles. Their movements were too stiff or, conversely, more mobile; they were unable to find food as quickly as the control group.

The study of the electromagnetic field exposure of 3.0 GHz showed that during the first week of the experiment, the behavior of white rats and beetles was characterized by a substantial disturbance of movement coordination and aggressiveness. Honeybees have even noticed a drop in height. Moreover, given the behavior of living organisms under the influence of the electromagnetic field, the lack of coordination of their movements progressively increased with the duration of exposure and the frequency of the EMF itself.

Behavioral Changes in Organisms Under the Influence of EMF

As a result of the study, noticeable changes in the behaviour of various organisms subjected to Electromagnetic radiation (EMF) exposure were observed. Specifically, the following changes were observed.

White Rats

- Locomotor activity: In groups of rats exposed to 50 Hz, 3 MHz, and 3 GHz EMF, a decrease in locomotor activity over time was observed. Higher EMF intensities resulted in greater differences in mobility compared to control rats. They became less active and exhibited impaired motor coordination
- Aggression: Aggression increased with higher EMF intensity and duration of exposure. Elevated instances of aggression were observed among rats exposed to EMF

Table 4: Mortalities in living organisms exposed to electromagnetic fields, %

	Intensity of electromagnetic radiation			
Animal	Month	50 Hz	3MHz	3 GHz
White rats	May	-	-	-
	June	5±0.21	21±0.47	24±0.34
	July	11±0.35	25±0.26	35±0.67
Honeybees	May	-	-	-
	June	10±0.65	26±0.36	31±0.82
	July	15±0.24	29±0.81	49±0.16
Common dung beetle	May	-	-	-
	June	14±0.29	26±0.59	45±0.37
	July	18±0.74	30±0.64	100±0.34

Bees

- Flight activity: Decreased flight activity was observed among bees exposed to 50 Hz, 3 MHz, and 3 GHz EMF. Higher EMF intensities resulted in reduced flight activity
- Aggression: Bee aggression also increased with higher EMF intensity and exposure duration. Bees exhibited greater aggression towards each other

Beetles

- Locomotor Activity: Under the influence of 50 Hz, 3 MHz, and 3 GHz EMF, a significant decrease in the coordination of beetle movements was observed. They became less active and experienced difficulties in finding food
- Aggression: Aggression increased with higher EMF intensity and exposure duration. Roadside beetles exhibited greater aggression towards each other

Timeframes

The timing of behavioral changes varied depending on the organism's species and the frequency of the EMF. Behavioral changes in white rats became noticeable after the second month of exposure to the magnetic field. In the case of bees, these changes occurred by the second month of exposure, while beetles exhibited behavioral changes towards the end of the second month.

Consequently, as the experiment continued, apparent aggressiveness and loss of orientation activity manifested in the study's object exposed to different EMF frequencies. For instance, it was found that the more prolonged EMF exposure lasts, the greater the effect on behavioral changes in living organisms.

In reviewing mortality rates, it is essential to note that no lethal results were observed in animals in the control groups. The highest percentage of lethal scores (35 in rats, 49 in bees, and 100% in dung beetles) were reported under the influence of 3 GHz of EMF frequency. However, the other two studied frequencies also influenced the number of dead animals. For example, three months of daily exposure to 50 Hz industrial standard EMFs resulted in the deaths of 11% of rats, 15% of bees, and 18% of dung beetles (Table 4).

The table shows that mortality in the animals examined tends to increase with increasing frequency of EMF and over time. Consequently, as a statistical confirmation of the study, a correlation and regression analysis was carried out according to the influence of the different EMF frequencies. The meaning value for a white rat is R = 0.9585, for a bee R = 0.9984 and for a dung beetle R = 0.9758. This means that the model provides an accurate description of the available data.

The above suggests that electromagnetic radiation has an adverse effect on animals. Long-term organisms exposed to electromagnetic fields can undergo significant changes in their behavior. Moreover, electromagnetic radiation eventually leads to their death.

Discussion

All living creatures live in a static, magnetic, electrical and sometimes natural EMF; they have to adapt and even learn to use it. However, the rapid development of scientific and technological advances depends on the presence of artificial sources which can affect living organisms.

Different organisms may respond differently to various EMF frequencies. For instance, some studies suggest that specific EMF frequencies may impact bees, reducing their ability to orient and collect nectar, while other organisms may not exhibit such changes (Pophof *et al*., 2023).

Several potential mechanisms can explain the impact of EMF frequency on living organisms. One such mechanism is the influence of EMF on biochemical processes within cells, such as alterations in ion levels and enzyme reactions. Additionally, changes in the behavior of organisms may be associated with modifications in their neurophysiology or receptor sensitivity.

Furthermore, some studies suggest that EMF may affect living organisms through bioelectromagnetism. This means that EMF can interact with the bioelectrical processes in an organism, such as nervous activity and muscle function. This mechanism may explain the changes in the behavior and physiology of organisms under the influence of EMF (Vian *et al*., 2016; Krivov *et al*., 2020).

In general, the impact of EMF frequency on living organisms is a complex and actively researched issue. Many prominent organizations, such as the World Health Organization (WHO) and the International Agency for Research on Cancer (IARC), are conducting studies to determine potential risks associated with the influence of EMF on humans and the environment. However, at this time, there is no definitive conclusion regarding the impact of EMF frequency on living organisms and researchers continue to work on this topic.

The experimental results published so far show that animals' exposure to electromagnetic fields can significantly impact their behavioral reactions (Yamamoto, 1998; Zhang *et al*., 2017; Bartos *et al*., 2019). Thus, the study by Elferchichi *et al*. (2011) showed that rats exposed to a 50 Hz magnetic field with an induction of 5 μT for 32 weeks demonstrated no deviations in morphological and histological parameters of the liver, heart, and lymph nodes or deviations in the blood picture and behavior. However, the exposure to a frequency of 100 Hz with induction of 7 mT for 30 min/day and two consecutive weeks caused a significant deviation of these indicators in rats from the control and a slight reduction in brain size (Elferchichi *et al*., 2011).

Similar findings were obtained in another study where a group of rats exposed to 150 Hz EMF demonstrated increased motor activity, sniffing, and defecation over time (Peter *et al*., 2006). According to Zosangzuali *et al*. (2021), mice under the influence of 30 Hz EMF show different behavioral patterns, such as apparent stress, aggression, and eye irritation. Moreover, mice avoid proximity (Zosangzuali *et al*., 2021).

This study is consistent with the works of (Thielens *et al*., 2020). He noted that under the influence of 1.2 MHz EMF, honeybees show poor direction and flight coordination and begin to fly more actively than unexposed bees (Thielens *et al*., 2020).

Furthermore, Cammaerts *et al*. (2012) noted sequential reactions of various insects (beetles, ants, etc.,) as a function of the duration of exposure to EMF. They first attempted to escape and then there were motor disturbances and coordination problems, such as stiffness, immobility, and even death, which was confirmed in the study (Cammaerts *et al*., 2012). A study of the effects of EMF on birds, (Wiltschko and Wiltschko, 2005; Schwarze *et al*., 2016) shows that EMF seriously affects the ability of birds to use magnetoreception. Migrating birds lost their sense of direction, eventually leading to massive mortality.

A study examining the effects of electromagnetic fields on fish by Öhman *et al*. (2007) shows that EMFs prevent marine animals from navigating and identifying their prey. As a result, they begin to eat less food, and their life expectancy is reduced. In addition, they experience problems with reproduction (Öhman *et al*., 2007). The research conducted by Levitt and colleagues in 2022, which focused on mammals and reptiles, revealed that the animals exposed to radiation exhibited reduced behavioral activity after six months of the experiment. After 12 months, they began to absorb less oxygen and produce less carbon dioxide than the controls. Additionally, changes in the immune system of irradiated animals compared to controls were observed during this period (Levitt *et al*., 2022).

Conducting studies on nematode worms at a frequency of 50 Hz EMF with intensities of 0.5, 1.2, and 3.0 GHz. Shi *et al*. (2015) found that although there was no significant difference in lifespan, worms affected by EMFs differed in hatching and reproductive rates. Studies on the effect of very low-frequency EMFs (7-75 Hz) on monkeys showed no change in their behavior. Sometimes minor differences in activity and response rates were observed, but no sustained effects were achieved (Kazemi *et al*., 2022). This experience, therefore, proves that electromagnetic radiation has a negative impact on animals. Furthermore, its long-term exposure leads to the fact that living organisms can succumb to essential changes in their behavior, which even leads to their death.

Based on these results, the prospect of further research may be the effect of fields of varying intensity on several other living organisms, such as domestic and farm animals. Specifically, it is crucial to determine which ranges of EMF frequencies are safe for various types of living organisms and the thresholds at which EMF does not pose health risks to them. These research questions can contribute to a better understanding of the impact of EMF frequency on living organisms and the development of effective safety measures in this field.

Conclusion

The environment has a constant presence of electromagnetic fields of different frequencies (Ventsova and Safonov, 2021). Its direct or indirect influence can cause discomfort in animals' habitats, especially for those sensitive to changes in the strength of EMFs. It is proved by the behavior of living organisms under study: White rat *(Rattus norvegicus)*, honeybee *(Apis mellifera* L.*)*, and common dung bee (*Geotrupes stercorarius*).

The study confirms that the longer the exposure to EMF, the more significant the effect on the behavior of living organisms. It manifests in excitation, inhibition, loss of coordination of movements, aggression, and inability to find food.

As a result of the study, it was found that white rats, bees, and beetles exposed to different frequencies and intensities of electromagnetic radiation exhibited increased aggression and reduced locomotor activity over time. For instance, in the case of white rats exposed to 3 GHz EMF, decreased locomotor activity was observed, with the number of movements decreasing from 10-4 over two months, along with increased aggression, which increased from 0-4 aggressive acts. Bees exposed to 3 GHz EMF exhibited reduced flight activity, where the number of flights decreased from 100-61 over two months, and increased aggression, with the number of aggressive acts rising from 2-34. In the case of beetles, exposure to 3 GHz EMF led to a significant reduction in locomotor activity, with the number of movements decreasing from 20-11 over two months and increased aggression, with the number of aggressive acts increasing from 0-7.

The highest percentage of lethal outcomes, 35% in rats, 49% in bees, and 100% in dung beetles, were observed under the 3 GHz EMF frequency and three months of daily exposure to industrial-normalized 50 Hz EMFs resulted in the deaths of 11% of rats, 15% of bees and 18% of dung beetles. The correlation and regression analysis of the mortality indices of the living organisms studied determined the upward trend of this index as a function of the frequency of EMFs. The significance value for white rats was $R = 0.9585$, for honeybee $R = 0.9984$ and for dung beetle $R = 0.9758$, which means that the model adequately describes the available data.

The practical and scientific importance of the results is considerable, given their potential for enhancing the refinement of models concerning the interaction of Electromagnetic Fields (EMF) with living organisms. Furthermore, these findings may contribute to the development of safety standards for the practical use of EMF and environmental monitoring across various sectors, including biology, forestry, and agriculture. These programs hold vital importance for safeguarding the well-being of living organisms and for the responsible utilization of EMF in diverse industrial and ecological contexts. The limitation of this study lies in its restriction to specific frequencies and intensities of electromagnetic radiation. Other frequencies and intensities may have varying effects on organisms.

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Author’s Contributions

Tatyana Degtyarevskaya: Participated in all experiments, coordinated the data-analysis and contributed to the written of the manuscript.

Andrei Vokhmintsev: Designed the research planed and organized the study.

Ethics

This article is original and contains unpublished material. The corresponding author confirms that all of the other authors have read and approved the manuscript and that no ethical issues are involved.

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