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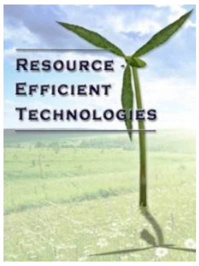

Review Article

RESOURCE-EFFECTIVE SOLUTIONS TO ADDRESS HYPOMAGNETIC INFLUENCE ON HUMAN BODY

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Abstract

Relevance: Hypomagnetic conditions have undesirable effects concerning various fields of science and technology. In biology, they cause adverse circumstances, which affect the functioning of living organisms. However, humans experience hypomagnetic fields (HMF) during space exploration, through some branches of production, military objects, and community transport. On the other hand, various high-precision technologies must have or operate under a hypomagnetic field. **Aims:** We aimed to provide a critical analysis of several ways of preparing hypomagnetic field, differences between hypomagnetic chambers and Helmholtz coils, and review of thematic patents and articles available in the Russian Federation. **Methods:** We structured and analyzed modern achievements in HMF. Experimental studies on living organisms were evaluated because they show different technical conditions connected to the theme of the hypomagnetic field. **Results:** Based on this analysis, a new resource-effective technology, which reveals several concerns on the hypomagnetic field, was offered. This technology is essential to be used during preparations for space missions, which require products with special necessities in terms of effectiveness and reliability. **Conclusion:** We summarized and correlated the results of experiments with possible magnetic conditions, which can occur during space missions and in some military and civil applications. Protection strategies from hypomagnetic conditions were considered. Novel experiments regarding realistic conditions were suggested.

Keywords: Hypomagnetic field, magnetic safety, the Helmholtz coils, hypomagnetic chamber, magnetic screens.

1. Introduction

In the Russian Federation, for the first time in the world (2009), sanitary rules (SanPiN 2.1.8/2.2.4.2489-09), including the hypomagnetic field (Earth's low magnetic field, HMF), were accepted in manufactures, residential and public houses and buildings. According to SanPiN, a person can remain no longer than 2 hours a day under low geomagnetic reference field (GRF). Excess of norms also results in additional compensation of staff under these conditions. Magnetic field strength in human spaceflight missions to the Moon or Mars can vary. On the Moon surface, the magnetic field is 1000 times lower compared to the Earth's magnetic field. Cosmonauts and astronauts suffer due to the exposure to the hypomagnetic field for extended periods. Moreover, adverse space effects such as zero gravity and space radiation add to the hypomagnetic influence [1]. The combined effects of space effects

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during human spaceflight missions to the Moon have been investigated. [2, 3]. The changes in psycho-emotional states were detected. Experimental data on the stimulations of HMF on animals have shown physiological changes. For example, the conductivity of skin was strongly differentiated [4]. In addition, the strength of the hypomagnetic field on the orbit of International Space Station decreases by 20–30 % from the Earth's field [1].

Terrestrial experiments were performed for modelling HMC in a compartment of a spaceship under the conditions of distant human spaceflight missions. The simulation of magnetic surroundings in some departments of the space shuttle was presented [RU2344485C1]. The magnetic field volume was compared to the volume of a manned spacecraft. However, a detailed analysis of these studies has shown that all communications and electro equipment act as extremely strong hypomagnetic field sources. Therefore, conducting experiments on isolated volunteers in hypomagnetic conditions is hardly possible and highly costly. On the other hand, cosmonaut's protection from hypomagnetic influence is urgently required.

Recently, a compensating device consisting of a dielectric frame with a multilayer coating and volume comparable to the torso, head, and limbs of an astronaut was invented [RU 2592736]. The coating is formed by alternating conductive and dielectric layers of foil and polyethylene. The coating is provided with pins for connection to a current source. Inside the volume bounded by the frame, when an electric current passes through the coating, an artificial magnetic field that simulates the Earth's magnetic field is created, protecting it from the effects of hypomagnetic conditions. We estimate that the minimum weight of such a unit is at least 30 kg, and the consumption is up to 100 W. These figures should be multiplied by the number of crew members. Weight and energy consumption are critical in spaceflight conditions. Alternatively, a magnetic field that will be created in the living space of a spacecraft due to the analogs of Helmholtz coils made of aluminum wire is proposed. The weight of the magnetic field generator will be about 200 kg, and the power consumption will be about 160–180 W [1]. In the conditions of an acute shortage of energy and payload, it is necessary to justify the need for such installations on the spacecraft. Currently, research on the effects of HMF on living objects and humans is ongoing, but there is still a lack of clear understanding of the acting mechanisms. The proposed mechanism of action of a weak magnetic field on the animal body was considered [3–5], but it has not been experimentally confirmed. The influence of magnetic field on water has been studied [6] since water is considered as one of the conductors of magnetic field. However, the magnetic permeability of water is close to one, which is inconsistent with the changes that occur in the complex biochemical system of a living cell. There is still no clear understanding of the effect of magnetic field and especially its absence or noticeable weakening on living objects. This paper is devoted to a critical analysis of these studies. An emphasis on the analysis of the rationality of resource expenditures on the requirements of the SanPiN 2.1.8/2.2.4.2489-09 is also provided. Risk assessments regarding the HMF factor that must be considered during the planning of space missions are highlighted.

2. Methods of modeling the hypomagnetic conditions

There are two main ways of modeling HMF: the first one is by using Helmholtz coils (HC) [7, 8], which can stop electromagnetic radiation in experimental volumes. The intensity of the natural magnetic field of the Earth can be shielded with specified accuracy and generated besides the artificial magnetic field.

The second way is by using hypomagnetic chambers, which consist of closed research volumes that shield not only the magnetic field of the Earth but the electromagnetic field (EMF) [9]. One of the hypomagnetic chambers is magnetic screens. To increase the remaining magnetic field inside the magnetic screen (own magnetic noise) was invented additional magnetic screen [RU 1762430] made from the woven grid, which was formed from formless metallic lines/tapes. The ending of tapes was closed, by that the power lines of the magnetic field in the material of the screen was locked so that the voltage magnetic field was decreased. Close to the construction of the magnetic screen [RU 2274914] made from tapes of amorphous metallic alloy had initial magnetic permeability no lower than 10–1000. The tapes overlapped the cover, which was not less than the thickness of the tape and were fixed relative to each other with the help of an elastic cover. Besides the magnetic screen (type), there are electromagnetic screens [RU 2442174] made in the shape of a closed membrane, which covers the screened cavity. The membrane consists of two layers, where the inner layer was made of a ferromagnetic material and the exterior layer from a conductive material closed in a sheet perpendicular to the exterior magnetic field. Most of the magnetic screens are formed from rolls of magnetic soft tape, the axis of which is perpendicular to the facing surface; the inner surface of the magnetic screen was formed of flat parts of rolls and pressed in an axial direction by the loops of the tape [RU 2627928 и RU 2572059]. The same principle was for an organized magnetic superconducting screen [RU 2271582]. It is considered that superconducting screens are the most effective but the most expensive variant to create HMF.

An important difference between the two variants of protection (magnetic screens and HCs) from exterior magnetic fields is the ability of shielding EMF by hypomagnetic chambers compared to HCs. Hypomagnetic chambers have been collectively assessed for their influence on live objects. Thus, the results with hypomagnetic chambers were wrongly associated with hypomagnetic conditions, and the shielding of electromagnetic radiation (EMR) was disregarded. This factor must be evaluated while planning experiments.

The rate of the shielding geomagnetic field mostly depends on form conditions, which were essential for modeling in the experiment. As a general rule, modeling magnetic conditions at the surface of the Moon (nearly in 1000 times lower than that of the Earth)) or recreating this connection is performed on various technical objects or bunkers, where wearing of the geomagnetic field does not exceed 90% of its strength. Time spent under hypomagnetic conditions depends on the choice of biological objects. For humans, it is not over two hours; for cell colonies, it is around several days, and for animals and birds, it can take several months.

The difficulty of simulating HMF for humans is due to the complexity in the design of life support systems because it is necessary to use systems that are not themselves sources of a magnetic field. Due to this reason, all devices that operate from electric amperage, including metals, are not suitable. As a result, very few long-term experiments involving humans have been conducted. Below, we examine various schemes for conducting experiments involving biological objects and humans.

3. Hypomagnetic influence on biological objects

The effects of hypomagnetic conditions on biological objects and humans have been presented [10]. Let us take a closer look at the conditions and results of experiments involving humans and various biological objects in recent experimental works.

3.1. Human cells

Studies have shown the weakening of human cognitive activity under conditions of an exposure-HC, magnetic shielding (MSh) of 0.1 ± 0.4 μT, exposure time (eT) of -1 hour and 17 minutes. The number of errors increases against the general background of increasing task fulfillment time. Tests for determining the time of simple motor activity, letter identification, and short-term memory of color were considered [11]. Under hypomagnetic conditions, there was a slight improvement in color short-term memory in women and, conversely, in men [12]. Under the conditions of natural changes in the geomagnetic field, the deterioration of the cardiovascular and autonomic nervous systems and a decrease in performance were shown. Natural changes associated with magnetic storms were considered. As a statement, the value of GMF before a magnetic storm was reduced by several tens of percent and then sharply increased. Sometimes the increase reached half of the GMF values. The duration of these processes ranged from several hours to several days [13].

The effect of HMF on the cardiovascular system and microcirculation was revealed when exposed to HC, MSh of ±10 nT, eT of 1 hour. Under HMF conditions, the rate of capillary blood flow increased and later returned to normal when the surroundings returned to normal conditions. Diastolic pressure in GMF decreased, as well as significantly decreased heart rate during the experiment [14, 15]. At the same time, in hypomagnetic conditions (HC, MSh: 0.1±0.4 μT, eT: 1 hour and 17 minutes), human cognitive functions were suppressed, which is expressed in terms of increased number of errors and time required to complete tasks [16]. Blood parameters also changed with a slight change in the magnetic field during the experiment (HC, MSh: ±0.1 μT, eT: 48 hours). The concentration of cuprum was sensitive to the magnetic field. The concentration of zinc in human blood plasma under HMF conditions did not have a significant effect. The loss of cuprum ions in plasma was higher in HMF than under normal conditions. This result indicates the sensitivity of cuprum ions bound to serum proteins and/or transport through cell membranes in the absence of the standard geomagnetic field [17]. Two types of micro-organisms isolated from humans were found:

sensitive and insensitive strains to geomagnetic field compensation. It was found that magnetosensitive strains represent about one-third of the analyzed samples. Statistical analysis shows a general trend of decreasing antibiotic resistance [18]. In the study [19], a hypomagnetic chamber consisting of permalloy was used. Due to the construction of the camera, it was possible to achieve the shielding of the Earth's permanent magnetic field to values of 22±1 nT. However, the impact of a technogenic alternating (50 Hz) magnetic field was successfully shielded to the values of 2.74 ± 0.07 μT, which this is the best result that the researchers have been able to obtain to date. Exposure to HMF led to a decrease in the concentration of reactive oxygen species in human neuroblastoma cells. Restoring the initial reactive oxygen species level with an additional amount of H_2O_2 preserved enhanced HMF cell proliferation. Studies have shown that HMF can affect the development of the embryo due to cell proliferation, as well as the formation of tubulin in vitro (HCh, MSh: 12 nT, eT: 6 hours). 2464 differentially expressed genes were identified, 216 of which were amplified, and 2248 were attenuated after HMF exposure [20]. Similar results have been found elsewhere [21].

It is proved that the activity of enzymes (aminotransferase and alanine aminotransferase) decreases by 24–31% in human blood serum, resulting in stronger hemolysis. This is likely due to the processes of denaturation and degradation, which occurred faster under HMF conditions (HC, MSh: <1 μT, eT: 72 hours) [22]. It was found that with increasing shielding of the Earth's magnetic field (HCh, MSh: <0.5 μT, eT: 1 hour), the osmotic resistance of red blood cells increases, which actively influenced the regulation of cell energy metabolism and water-salt metabolism [23].

3.2. Rodent cells

GMF (HCh, MSh: <300 nT, eT: 28 days) can exacerbate the loss of bone mineral component and change the biomechanical characteristics of the hip in rats if it is not loaded on the hind limbs [2]. The experiment on rats was conducted in combination with hanging (modeling the safety of the hind limbs of rats—a physiological model of weightlessness used by NASA). The control group of rats was also exposed to hanging. Hanging was performed by the tail of the rat so that the angle between the surface and the body of the rat was 30 degrees from the horizon. When exposed (HC, MSh: <10 μT, eT: 10 days), 19 hours a day, depressive behavior is detected, which is diagnosed by reducing the duration of active swimming in the Porsolt's test (Animal models of depression), and an increase in intraspecific aggressiveness [24]. The depressing effect of HMF (HC, MSh: <10 μT, eT: 5, 10, and 21 days) on the central nervous system tone was also found, which is expressed as a decrease in motor activity, absolute power of electroencephalogram rhythms, and the level of neuronal activation, as well as decrease in the antinociceptive response and aggressiveness [25].

Exposure to HMF (<200 nT) generated by the magnetic field screening chamber (HC, MSh: <200 nT, eT: 7 days) promotes the proliferation of neural progenitor cells/stem cells (NPC/ SC) from C57BL/6 mice. After seven days of exposure to HMF, primary neurospheres (NS) were significantly larger, and twice as many NPC/SC were collected from neonatal NS compared to HMF controls. The ability to self-renew and multipotency of NS was preserved since HMF-exposed NS were positive for NC markers and could differentiate into neurons and astrocyte/glial cells. In addition, adult mice exposed to HMF for one month were found to have a greater number of proliferated cells in the subventricular zone. These data show that continuous exposure to GMF increases the proliferation of NPC/SC in vitro and in vivo [26, 27]. There was a pronounced neurotropic effect of long-term (for 25 and 10 days) exposure to HMF (HC, MSh: <50 nT, eT: 21 days). Immunohistochemical analysis showed no significant differences between the control and experimental groups of rats in the overall level of c-Fos (a proto-oncogene) expression. A decrease in the number of cells containing μ-opioid receptors was observed under the influence of HMF (the most obvious change in the structures of thalamus and gray matter) [28].

When exposed to HCh (MSh: <200 nT, eT: 7 days), the permeability of plasma membranes increased, the cytoskeleton was reorganized due to the reallocation of alpha-actin, two-cell mouse embryos were observed, cell viability and their ability to adhere decreased, and cell monolayer morphology changed. In addition, the spatial orientation of blastomeres was disturbed, resulting in the development of two-cell embryos; thus, the blastocyst stage was not reached, and the development stopped [29].

3.3. Other biological objects

Exposure to HMF (HC, MSh: <100 nT, eT: 20 hours) leads to a significant increase in sensitivity in nerve cells from the first optical ganglion in a population of flies that developed from pupae [30]. In another experiment, Drosophila was exposed to HMF (HC, MSh: <100 nT, eT: 150 days) for 10 generations. In each generation of flies, a standard test of visual learning and memory was performed. As a result, it was found that the memory and learning ability of fruit flies deteriorated with each subsequent generation. As a result, the 10th generation of flies was completely disabled. The reverse process in natural conditions (the natural geomagnetic field of the Earth) led to the initial state of the fly population at the 6th generation [31]. The effect of HMF (HCh, MSh: <2 μT, eT: 20 hours) was observed even in fungal cultures. Significant time delay in the spore-bearing phase and/or inhibition of spore formation processes, morphological changes in fungal cells [32]. In the work [33], strong (1000 times) GMF shielding was performed (HCh + HC, MSh: <50 nT, exposure time: 1 day). Under these conditions, the fungal mycelium showed circular growth in contrast to normal magnetic conditions in which the mycelium growth was characterized [34]. Under similar conditions, the apical growth of mycelium of fungi, *Ulocladium œnsortiale, Neurospora crassa, Mucor sp.*, has a circular character in hypomagnetic conditions characteristic of those on the surface of the Moon. Under HMF conditions, (HCh+HC, MSh: <5 nT, exposure time: 5 days), there was a general slowdown in development and incorrect formation of the spine and eyes (curvature of the spine, ugly eyes). In an experimental group of Japanese tritons, double-headed and protruding intestines were also observed in some tritons [35]. It has been shown that some serious disorders occur in Japanese quail embryos when it is formed under hypomagnetic conditions (HC, MSh: <0.6 μT, exposure time: 4–10 days). In particular, serious disorders in the formation of the cardiovascular system were found. Disorders were observed in other systems of the embryo's body, and there was a noticeable lag in development [36].

Exposure to HMF conditions (HCh, MSh: 0.6 μT) for 1.5 months led to an increase in the mobility index (in the last stages of development of the mollusk). In HMF, the death or complete termination of the growth of juvenile mollusk was detected when the magnetic field induction sharply increased to the normal geomagnetic level [37]. In fish, there is a decrease in the proteolytic and amylolytic activity of the intestinal mucosa of carp [38].

The influences of HMF on plants [39–43] and various cell cultures [44–55] were also reported. However, even in the examples considered, the approaches to conducting research on biological objects and humans are completely different. Most biological objects underwent their entire life cycles under a strong weakening of the Earth's magnetic field. Experiments involving humans are limited in time and intensity of magnetic field shielding. As a result, we see completely different physiological responses to experimental conditions. While we see significant changes in experiments on biological objects, minor changes were observed in cognitive functions of humans. The effect of HMF on a person does not exceed 50 % and on average, 10–15 % (in the scale of exposure adopted in the work [10]), while for other objects of research, the impact could exceed 10,000 %.

We believe that this difference occurs due to several reasons:

1. The time of exposure to a person is disproportionately small compared with the human life cycle.

2. It is technologically very difficult to create suitable volume and size for GMF shielding for humans.

3. As the complexity of the biological system increases, different mechanisms contribute to respond to HMF.

Possible space flight durations to the Moon and Mars are not comparable to the time of the human life cycle. However, according to SanPiN 2.1.8/2.2.4.2489-09, GMF weakening by 75 % is already considered critical. For further analysis, it is necessary to discuss possible critical values of the magnetic field for biological objects.

4. Critical values of hypomagnetic field for bio-objects

According to a study [10], several critical external magnetic field strengths can be distinguished for biological objects. These critical magnetic field values are explained by different mechanisms that constitute the actions of magnetic fields. The quantum effect associated with ortho-para isomers of the water molecule is often discussed [56–59]. For this effect, the critical value of the magnetic field is about 1 nT. Such a small value of the magnetic field in terrestrial conditions is quite difficult to create. The value of the Moon's magnetic field is in the range of 0.1–100 nT [60], but on most of the surface, the field value exceeds 10 nT.

Another effect is associated with magnetic nanoparticles [61], for which the critical field can be 10–50 μT, which is comparable to GMF. The intensity of the magnetic field is most suitable to explain the phenomena associated with a slight decrease in GMF. However, we need a conductor of interaction for magnetic nanoparticles, which must be in a living organism.

Another biological effect of a weak magnetic field is possible at critical fields on the order of 1 mT. The effect is realized when it is based on the specifics of the interaction of free radicals in weak magnetic fields [62]. For further discussion, it is necessary to consider the features of HMF modeling.

5. Specificity of shielding the magnetic field during experiments

Of the experiments discussed in this paper and a review article [10], approximately 1/3 of them were executed using a hypomagnetic chamber. However, these experiments do not show the role of shielding the Earth's magnetic field alone. The fact that hypomagnetic cameras also screen electromagnetic radiation was ignored. However, additional EMR shielding using hypomagnetic chambers leads to stronger effects than that using HCs [10]. It should be noted that experiments involving human subjects were carried out only with the use of HCs. In this regard, a series of experiments involving humans can be considered relevant to the stated goal (namely, to assess the effect of HMF on the human body). However, if we are going to consider the case of space mission, we must take into account the influence of the modified EMR. It is quite clear that the spectrum of natural EMR, for example, on the Moon will be radically different from that on Earth. Due to the existing seismic of the Earth, the EMR intensity will be higher and the spectrum will be wider than that on the Moon. Several experimental studies show the negative impact of shielding the Earth's natural EMR [63–66].

In the absence of the Earth's usual electromagnetic background, technogenic EMR formed by the spacecraft equipment will dominate. The mechanism of the EMF on living objects is well studied and understood [67–72]. EMR primarily affects the most susceptible systems of the human body: the nervous, immune, endocrine, and sexual systems [73]. There are studies that the human cardiovascular system can be strongly affected by EMR [74]. In this case, EMR is considered as an additional stress factor. In the modern world, technogenic EMR is in tens of thousands of times higher than the intensity of the Earth's natural electromagnetic background, which worries many researchers.

A temporary and spatial method of protection is recommended for the prevention of adverse effects of EMR of technogenic origin [SanPiN 2.2.4/2.1.8.055-96]. It is intended to limit the time spent at sources of technogenic EMR and to increase, if possible, the distance to them. However, in the conditions of a spaceship or on some special objects, these recommendations cannot be fulfilled. Therefore, it is necessary to look for ways to reduce EMR by the equipment of spacecraft and other devices.

6. Resource-effective approaches

SanPiN 2.1.8/2.2.4.2489-09 accepted in Russia involves significant changes in the working mode, where working conditions are associated with HMF. Industrial, military, and other facilities where SanPiN standards are applied already assume a special mode of work with appropriate consideration of working hours. The very existence of these standards leads to the topic of the high-level state regulation of hypomagnetic influence. However, previous research does not show a compelling evidence of an appreciable/irreversible effect on the human body, even for a strongly weakened GMF. Another fact is that there are no such sanitary standards in technologically developed countries. In our opinion, it is necessary to discuss the key parameters reflected in the SanPiN 2.1.8/2.2.4.2489-09. On the other hand, we can offer a resource-efficient way to prevent the hypomagnetic influence by using soft permanent magnets in clothing. This method is universal and suitable for all, including astronauts. Permanent, soft magnets can perform other functions (fixing, detecting, and marking). These magnets are easy to use and integrate into existing technological models; they are quite cheap, efficient, and reliable, do not require energy sources for their operation, and can work in any conditions.

Nowadays, resources are being spent on conducting experiments to study the effects of HMF on biological objects and humans. Methods for modeling HMF conditions and the cost of implementation depend on the magnitude of HMF attenuation. However, there is a technological limit (100 nT) above which it is difficult to deal with the inhomogeneities of the magnetic field in the experimental volume and requires expensive precision magnetometers. It should be noted that the cost of magnetometers increases sharply with increasing sensitivity to the magnetic field. To solve this problem, we suggest paying attention to one of the physical parameters of the magnetic field value, as discussed in Section 4. It will not be difficult to exceed the threshold of 1 nT even in the conditions of a mission to the Moon since every equipment of the spacecraft, spacesuits, communications equipment, and life support systems will produce magnetic fields that exceed the threshold of 1 nT. In conjunction with our proposal for the use of soft permanent magnets, we suggest a complete or partial deterioration of the magnetic "vacuum" during the exploration of the Moon. Therefore, it is worth considering 10–50 μT as the threshold for the magnetic field. This threshold is 1–5 times less than the Earth's magnetic field. These are the conditions of magnetic shielding that can be found in various industrial, specialized, residential, and public buildings and structures for military purposes. It is not difficult or costly to implement such experimental conditions. To save resources, it is advisable to conduct experiments focusing on the weakening of the Earth's natural magnetic field by 1–5 times.

To improve the quality of experimental results, we propose to take into account not only the type of research object and method of creating an HMF but also the method of registering the magnetic field, accuracy of the magnetometer, error measurement of the magnetometer, exposure time, and statistical significance of the parameters under study.

Unfortunately, most publications (on this topic) do not contain a complete set of data, and as a result, it is difficult to interpret their results.

Conclusion

We found that many studies on the influence of a weakened magnetic field on living organisms have been performed incorrectly because shielding electromagnetic radiation by a hypomagnetic chamber was not taken into account.

In the conditions of space flight, it seems that it is the electromagnetic radiation of onboard equipment, not the weakened magnetic field, which will create a real threat to the health of astronauts. We suggest focusing on studying the synergistic effects of ionizing and non-ionizing radiation and hypomagnetic conditions.

The disturbance in hypomagnetic conditions by permanent magnets is possible without the expenditure of energy resources, enabling the development of resource-efficient systems to prevent hypomagnetic effects when flying in interplanetary space.

To date, there is no unified approach to modeling HMF [75]. The methods of screening (HCs, hypomagnetic chambers), as well as the time and amount of screening, can vastly differ (up to 1000 times). We propose to standardize both the methodology and presentation of experimental data in HMF research.

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