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Electric Vehicle Magnetic Fields and Their Biological Relevance

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Authors' contributions

This work was carried out in collaboration between all authors. Author NGP designed the study and wrote the first draft of the manuscript. Authors NGP and AP managed the literature searches and estimation of biological effects. Authors YAK, VSI and AGK managed the electric vehicle magnetic field testing and analysis. All authors read and approved the final manuscript.

Original Research Article

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ABSTRACT

Public expectations to move towards electric mobility are driven by various factors such as climate policy, high oil prices, and pollutants due to internal combustion engines. On the other hand, there is extensive public concern about the possible adverse health effects of electromagnetic fields (EMF) generated by electric vehicles. As electrical power and power electronics systems become more prevalent in transportation, the need for examining biological relevance of such systems becomes ever more important. In particular, it is necessary to pay special attention to magnetic fields (MF), because biological studies suggest that magnetic rather than electric component could be biologically effective. In this paper we present a review of observed EMF on electric vehicles (EV) and possible biological effects together with our research on measurements and analysis of magnetic fields encountered onboard public DC- and AC-powered vehicles. Maximum automotive magnetic field magnitudes varied from a few μT to 120 μT. For members of the general public, this range of exposures in personal scale electric transportation systems is comparable in magnitude to exposures from other commonly encountered sources. However, electric vehicles exposures are totally different from common power line exposures; they are characterized by the complex frequency content

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and specific waveforms. The obtained measurement information allowed characterization of specific magnetic field features that could be biologically plausible: wide frequency range, intermittency, interaction with DC-field and other aspects. We consider these specific features of transport EMF in regard to their biological relevance. The careful mapping of magnetic fields inside the vehicle at different operating conditions derived to the recognition of the main sources of magnetic fields. This information could be important both for possible mitigation and for electromagnetic compatibility issues.

Keywords: Electric mobility; EMF biological effects; automotive magnetic field; geomagnetic field.

1. INTRODUCTION

This study represents one specific objective of the project ‘‘EMF safety by sensors developments and hazards mitigation by proper EV design’’ in the 7th framework European Union Program “ICT for the Fully Electric Vehicle” (granted to Prof. Ponzetto).

In XX century public electric transport systems (urban and interurban trains, trolleybuses, trams, subway etc) had been actively developing. We are now beginning to witness renewed interest in an individual electric transport - fully electrical and hybrid gasoline-electric vehicles (EV and EHV). Eco friendly electrically driven cars, so-called “green cars”, definitely benefit man and his environment.

On the other hand, a concern of media and public is the possible impact on the health of the vehicle occupants of the electromagnetic fields that are greatly generated by electric power. While all vehicles are subjected to externally produced EMF, including static geomagnetic field, electric transportation systems generate additional magnetic fields because of their design features. On-board electrical systems generate complex electromagnetic environment. Recent epidemiological studies suggest a link between electric transport magnetic fields and certain adverse health effects, including various kind of cancer, reproductive disorders, and Alzheimer disease, even though magnetic fields encountered on electrified transport systems are generally lower than international limits [1-5].

Since many people use daily public or individual electric vehicles, the need for examining biological relevance of such electromagnetic environment becomes ever more important. In particular, it is necessary to pay special attention to magnetic fields, because biological studies suggest that magnetic rather than electric component could be biologically effective.

In view of this, as a first step it is important to develop information about magnetic field onboard electric vehicles. Since electric automobile is new emerging technology, onboard EMF measurement data are still scarce, especially for fully electric car. However in variety of electrically powered transportation systems magnetic fields are generated due to the current flow through the circuits. Magnetic fields in all such systems have general common features that could be biologically relevant [2,5-7].

In summarizing and analyzing measurements in electric vehicles in relation to biological effects it is necessary to pay attention to problems that complicate the task:

1. Established biological effects are multivariable and depends on:

- Different parameters of magnetic field (amplitude and gradient of the field, frequency spectrum, intermittency, polarization, angle with geomagnetic field, amplitude-frequency “windows” etc).
- Position of the biological system with respect to the field.
- Exposure duration.
- Background electromagnetic fields EMF.
- Environmental conditions (temperature, light, humidity).

2. Absence of commonly accepted mechanism of interaction between weak electromagnetic fields (EMF) and biological objects. Thus it is not known what parameter of the field can be biologically important (component of the field, amplitude, gradients, special frequency, intermittency, polarization, wave form etc). As a result there is no guidance of what parameter of the magnetic field should be measured. Traditionally field-strength testing instruments were used; that did not allow evaluating all necessary magnetic field aspects that could be biologically important.
3. Measurement results depend on the testing equipment and procedure.
4. It is impossible to carry out accurate measurements of EMFs in vehicles according to a strict protocol because of the potential complexity of simultaneous factors in the environment and also because of the inherent fluctuation of the parameters in a vehicle, the reflections, doubling, etc. Thus any series of measurements is impossible to reproduce exactly.
5. To understand if measured magnetic fields inside electric transportation systems could result in health problems it would be necessary to perform further comparison with international and national EMF standards and limits. However, there are no commonly agreed international regulations limiting public or occupational EMF exposure. Those standards are uneven, they differ in many times. This confused situation is due to the fact that there is no established mechanism of biosystem-field interaction (see point 2) which could provide a basis for the standards. There is no theoretically or experimentally established thresholds for biological action (or health harmful effects) of environmental weak magnetic fields. Limits identified by international standards and guidelines are based only on acute thermal effects of EMF. Currently there is a tendency to reconsider existing standards through the implementation more strict safety limits in light of numerous public and governmental agencies objections.

Main objectives of this paper are the following: (1) to give a short review of the most up to date automotive EMF measurement information available; (2) to present results of our magnetic field surveys in various electric transportation systems; (3) to consider specific features of electric vehicle EMF in regard to their biological relevance. The focus will be on electric/hybrid automobiles.

2. EMF ONBOARD ELECTRIC CARS

The European project EHRFAN [8] on the base of literature review reported: “Various automobile components require electrical energy. This produces a low frequency magnetic field in the cables and components that conduct the electricity. The frequency range is wide, from few Hz to kHz. The new hybrid cars may produce higher magnetic fields than those with only petrol or diesel engines (WHO, 2007)”. It is noticed that the fundamental frequency of the magnetic fields in electric cars is 10–12 Hz at a speed of 80 km/h [8]; however higher harmonic frequencies were also measured [9,10].

Rotating tires with metallic inclusions generate alternating magnetic fields, usually below 20 Hz. According to [9] and [11] the static field of tires can exceed 500 μT, and the alternating fields can exceed 2.0 μT.

2.1 Static Magnetic Fields

All transportation systems are usually constructed using ferromagnetic materials which perturb and generally attenuate the geomagnetic field as it enters the vehicle [12]. The metallic parts of the car are not evenly distributed. In the engine compartment and on the axles the concentration is greater. The earth's magnetic field is essentially uniform over the dimensions of a car, but interaction between the vehicle structure and the earth's field results in a local magnetic field that varies in and around the car.

The extent of static field perturbation and shielding by the vehicle body is dependent upon the location in the vehicle and the orientation of the vehicle with respect to the geomagnetic field vector [13].

2.2 Alternating Magnetic Fields

Alternating magnetic fields in electric cars (mostly hybrids) were studied in various measurement projects in different countries. Below we present a summary of the results.

Sweden. Vedholm and Hamnerius [14] measured the low-frequency magnetic field (5–2000 Hz) in seven stationary cars (see Table 1.) In this way tire-generated fields were not taken into account.

Table 1. Magnetic field (5-2,000 Hz) averaged over the body [14]

Position	Magnetic field (μT)						
	Car1	Car2	Car3	Car 4	Car 5	Car6	Car7
Front left seat	0.11	0.12	0.15	0.22	0.14	2.6	3.2
Front right seat	0.15	0.13	0.33	0.37	0.11	1.1	0.78
Back left seat	0.04	0.06	0.03	0.03	0.06	2.4	14.0
Back right seat	0.1	0.11	0.04	0.04	0.03	0.3	1.5

Higher values were measured in cars 6 and 7, where the battery is situated in the boot or under the back seat. A maximum magnetic field of 14 μT, was measured at the back left seat at foot level.

Switzerland. Magnetic fields measurements were performed in two hybrid cars during driving through the town and in the laboratory under various driving conditions [10].

It was found that hybrid cars generate magnetic fields in wide frequency range from 5 to 500 Hz. The strength of the magnetic fields is dependent on the car operating regime (accelerating, braking etc)**.** The strength of the magnetic fields was similar for both vehicles: from 0.1 μT to 3 μT.

Greece. In a recent study [15] hybrid cars, the Lexus RX 400h and the Honda Civic IMA (2006 model), were being examined. In both car models, the battery is situated under the rear seats. Magnetic fields were measured in the frequency range from 0 Hz to 32 kHz. Measurements were performed in 4 different driving conditions: stationary, during travelling at 30–40 km/h, at 80–100 km/h and during high speed cruising. The static magnetic field varied from 0.08 mT to 0.95 mT during the different driving conditions. In the feet area of the passenger's seats in cars travelling at 80–100 km/h were measured the highest values of alternating magnetic fields, which sometimes reached 78.8% of limits established by International Non-Ionizing Radiation Committee (ICNIRP).

Australia. In [16] the magnetic field strength was measured at different points inside a hybrid car.

The magnetic field strength was found in the range of 0–3.5 μT. It was observed that the maximum magnetic field strength above 1 μT was radiated at 12 Hz. Magnetic fields registered in a hybrid car are shown in Fig. 1.

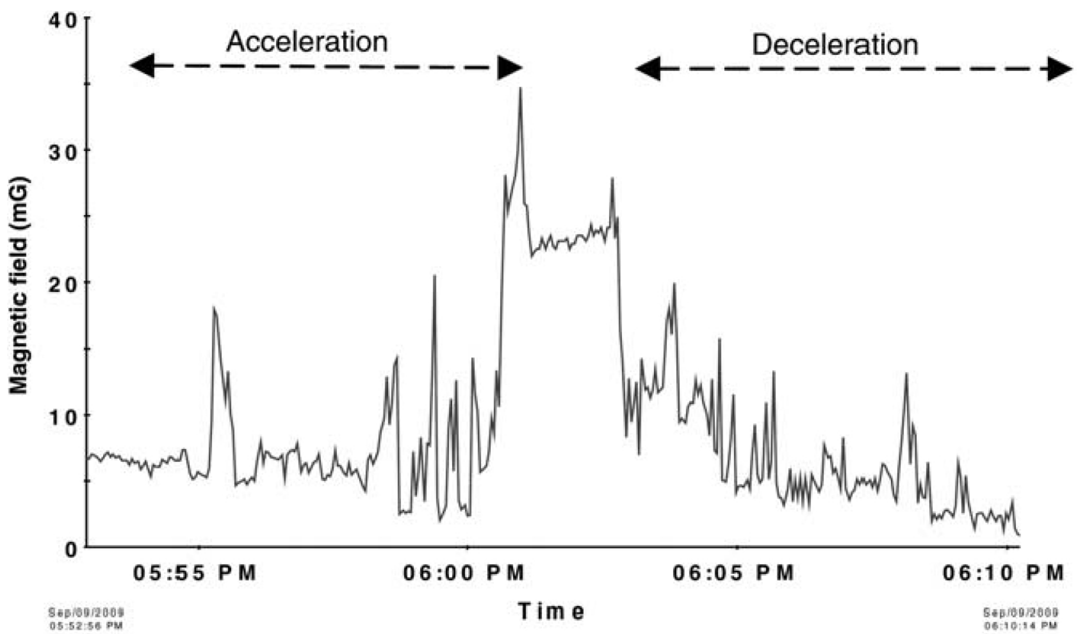

Fig. 1. Hybrid car: Magnetic fields in the left rear side at floor level [16].
(N.B. 10 mG = 1 μT)

USA. A summary of nine electric vehicle magnetic field measurements is given in [17]. These vehicles are powered by either AC or DC motors. The highest fields were measured during regenerative braking and maximum acceleration.

In the frame of a USA project "Magnetic Shielding for Electric Vehicles" [18] full waveform measurements (0-50 Hz, 0.1 μT to 1 mT) were performed in Chrysler vehicles with brushed DC and AC induction motors. USA researchers used for magnetic field measurements the following sensor suits:

Fluxgates magnetometers for low frequency measurements (0-1500 Hz); 2. Search coils for high frequency measurements (50 Hz to 50 kHz). Measurements were performed for 21 points non-uniformly distributed inside a vehicle. The analysis showed the dependence of the magnetic field values on the currents, and correspondingly on the operational conditions. It was found that the magnetic field reaches up to 120 μT. Exterior fields (taking into account geomagnetic field) reach up to 220 μT. This maximum value was observed around back seats. The spatial gradient reached up to 100 μT/m.

Dietrich and Jacobs [12] reported on static and low frequency magnetic field levels associated with conventional and electric cars, trucks and busses, electrified trains, ferries, jetliners, airport shuttle trams, escalators and moving sidewalks. Positioning of detectors was standardized so as to capture information about field levels at various locations (e.g. head, waist, ankles), standing or seated at a series of selected passenger or worker positions within vehicles, at entrances to vehicles and, where applicable, on platforms. Rather than being representative of each specific transportation mode in a statistical sense, the measurement protocol might best be characterized as a sampling of typical levels associated with various operating scenarios for a broad spectrum of transportation modes.

In most of the transportation systems, including electric cars, examined by [12] the vehicle was constructed using ferromagnetic materials which perturb and generally attenuate the geomagnetic field as it enters the vehicle. The extent of static field perturbation and shielding by vehicle body dependent upon location in the vehicle and the orientation of the vehicle with respect to the geomagnetic vector.

Recently in USA a special study to assess magnetic field levels in electric compared to gasoline-powered vehicles has been conducted [19]. Magnetic fields were measured with an EMDEX Lite broadband meter (Enertech Consultants, Campbell, CA), which has a 40–1,000 Hz bandwidth. The testing was based on log-transformed values of the magnetic field, with the geometric mean (GM) and geometric standard deviation (GSD) serving as the parameters of interest.

For seven electric cars, the GM of all measurements was 0.095 μT with a GSD of 2.66, compared to 0.051 μT for four gasoline-powered cars ($P < 0.0001$) [19]. The GM for the electric truck was 0.146 μT compared to 0.081 μT for the two gasoline powered trucks ($P < 0.0001$).When electric vehicles were compared to gasoline-powered vehicles within the same model, the GMs for the electric vehicles (all hybrid electric vehicles, HEV) were greater: 0.059 μT versus 0.049 μT for one model; 0.126 μT versus 0.055 μT for a second; and 0.146 μT versus 0.088 μT for a truck ($P < 0.0001$).

To put the results of this study [19] in the context of magnetic field exposures which people experience in their everyday life, the authors extracted data from a study of personal exposure to magnetic fields in frequency band from 40 Hz to 800 Hz, in 218 residences distributed across eight regions of the U.S. [20]. It was found that magnetic field levels in electric vehicles were within the range of magnetic fields found in this residential study.

3. MF TESTING ONBOARD PUBLIC ELECTRIC TRANSPORT

Since electric automobile is new emerging technology, there is a lack of detailed information on spectra and field geometry, source identification etc. We present here results of our magnetic surveys taken in various public electric transport systems. Since magnetic fields in public electric transport as well as in electric/hybrid cars are generated by the current flow through the circuits and depends on driving scenario, all transport fields have common features. We did extensive measurements and analysis of magnetic fields in a variety of electrified Russian and Swiss transport systems. Measurements were done by a waveform magnetometric system. Russian public transport (railways, trolleybus, tram) have an overhead DC 3 kV supply. Measurements were done in 0.03–50 Hz frequency range. Partly results were presented in [5,21-23]. Swiss railways has 16.67 Hz AC supply.

In Figs. 2-4 we present examples of our measurements.

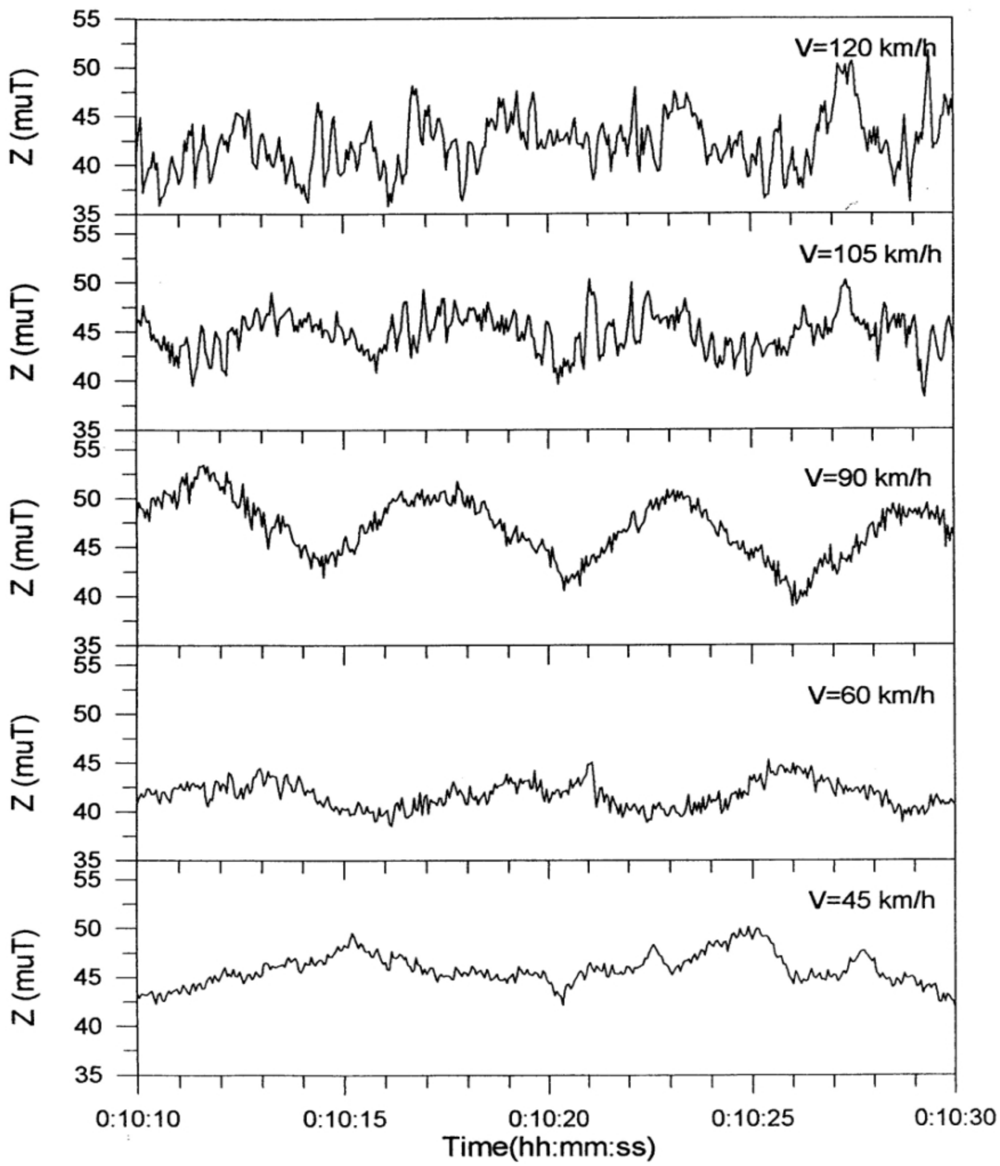

Fig. 2. Magnetic field onboard Russian DC-powered locomotives under various train's speed

Amplitudes and frequencies were dependent on the vehicle's speed. Fig. 2 shows variations of magnetic fields measured along the same route under various train speed regimes from 45 to 120 km/hour. It is visible that higher frequencies and amplitudes were observed under higher speeds.

We see that frequency and amplitudes of magnetic variations are proportional to train speed: higher frequencies and amplitudes were observed under higher speeds.

Similar measurements and analysis was done onboard other transport technologies. It shows that MF on all studied electric transport (DC and AC powered railways, metro, train, trolleybus and tram) present complex and variable structure.

The greatest changes in the DC level in DC trains were observed in the horizontal Y component perpendicular to rails (or catenary contact wire) during acceleration phase or passing substations. The most probable DC levels in DC trains were in the range of 40 μT. Peak-to-peak values reached 150 μT in electric locomotives. In trolleybus maximum levels were found near driver's head where they reached up to 325 μT. In trams the highest field levels of 500–1000 μT were found in passenger's coach. Significant quasi-static field variations were observed in St. Petersburg metro. Peak-to-peak values were 425 μT in the driver's coach, and 50–325 μT on platforms.

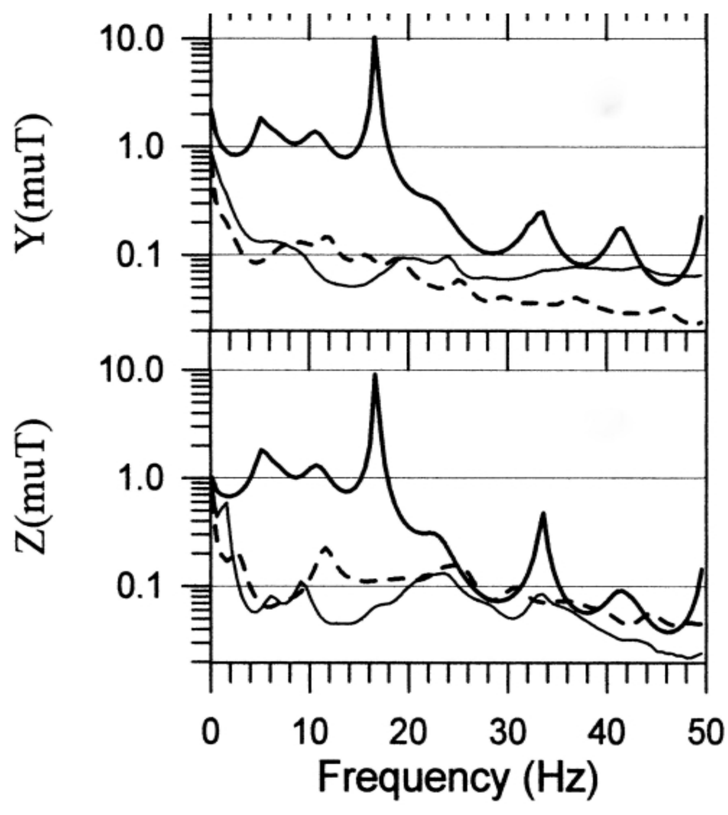

Fig. 3. Amplitudes of magnetic field spectral densities in an DC electric locomotives (dashed line), DC suburban trains (thin line) and AC electric locomotives (thick line)

In Fig. 3 we present average "typical" spectral densities of magnetic field amplitude in DC Russian electric locomotives (EL), in electric interurban trains (EMU) and in AC Swiss engine. Averaging was done over all obtained measurement files. We see magnetic field variations in all investigated frequency ranges. For AC Swiss locomotive the dominant frequency at 16.7 Hz can be clearly identified.Higher harmonics were also present. With regard to the frequency range below 16 Hz, the results show distinct peaks around 5 Hz and 12 Hz as was observed in electric/hybrid cars.

Very similar spectral structure has been also observed in other electric technologies (not shown here): EMU, metro, tram and trolleybus.

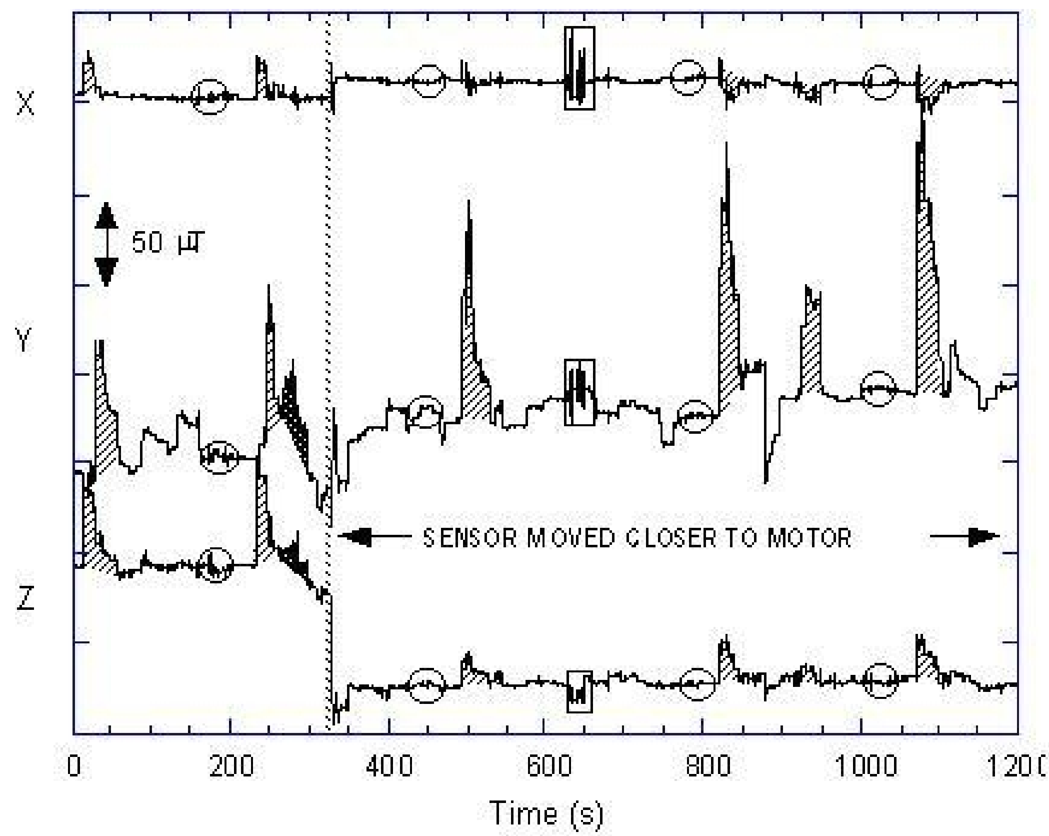

Fig. 4. Magnetic field (X, Y, Z components) in a vehicle (with motors) of a DC electric motor unit (EMU) train. *Dashed area*: Acceleration phase; *black area*: power substation; *square*: oncoming train; *circle and ellipse*: braking phase

In Fig. 4 changes of magnetic field level in dependence on driving scenario (acceleration, braking, oncoming ferromagnetic objects etc) are shown.

Analysis of measured MF variations allowed defining multiple sources of onboard magnetic fields and classifying them as follows:

- Static geomagnetic field;

- distortion of static magnetic field due to the iron/steel mass of electric train and ferromagnetic objects within the vehicle;
- Varying magnetic field from catenary and rails current needed by the train itself and by all other trains in motion between two closest substations;
- Varying magnetic field from different current systems onboard electrical train;
- Varying magnetic field arising when passing different nearby stationary and moving ferromagnetic objects and along the wayside (oncoming trains, railway switches, bridges, etc.). In this case geometry of fields (relative position) is important.
- Varying magnetic fields from a variety of ground-based man-made current sources;
- Varying geomagnetic field;
- Varying magnetic field caused by variable induced current generated by train movement (change in direction, accelerations, braking, etc) through the static geomagnetic field.

Magnetic fields encountered on electrified transportation systems presented complex variations in wide frequency range, which were produced by multiple sources. They were highly variable with time (milliseconds) and space (≈100 μT/m). Quasi-static magnetic fields were the major portion of the magnetic fields encountered on various electric transport systems. Levels of quasi-static fields (<0.03 Hz) varied considerably due to current changes in accordance with power needs. The most probable levels of quasi-static fields were in the range 0–35 μT. Electromagnetic fields in all electric transport technologies were intermittent and characterized by irregular waveforms.

4. SUMMARY OF MF MEASUREMENT RESULTS

There is no strict protocol of EMF testing in electric vehicles, although there were attempts to formalize collecting and analyzing data from electric vehicles. For instance, US Department of Energy recently approved a program of collecting and analyzing data from electric vehicle ("The Fleet Test and Evaluation Procedure" ( ) and "Measurement and Evaluation of Magnetic Fields and Electromagnetic Radiation Generated by Hybrid Electric Vehicles" ( ). In examined studies measurement systems and procedure differed significantly. Authors focused in different frequency ranges. Also methods of analysis differed to a great extent. Since measurement results depend on the testing equipment and procedure, it is necessary to be careful in the comparison of measurement results performed in different studies.

However we tried to gather main characteristic features of electric vehicle EMF that were found in our survey and in other studies.

4.1 Characteristic Features of EMF Patterns in Electric Vehicles

Main characteristic features of EMF in electric automotive environments are similar to fields onboard other electric transport systems. On the other hand, they differ from 50 (60) Hz power lines fields which are predominantly sinusoidal. Electric vehicle magnetic field patterns are characterized by:

- complex combination of static and time-varying components up to kHz and higher
- irregular waveforms
- intermittency (changes in the steady state of the field)
- high variability with time

- high variability in space

These features are determined by two reasons:

(1) These fields originate from many different onboard and outboard sources.
(2) Frequency content and intensity are continuously changing in accordance with motion characteristics (speed range, acceleration, braking, turning, etc.).

In some studies it was found that in hybrid cars, as well as in DC/AC trains, there is a local maximum in recorded magnetic field strength at 12 Hz.

4.2 Magnitudes

The magnitudes of electric vehicle fields depend on the particular model, driving conditions, frequency range and point of measurement. Those fields could much differ, they range from a few units up to hundreds μT. Space gradients could be about 100 μT/m.

Measurements performed in different transport technologies show that most part of MF energy is distributed in the lowest frequency ranges (static, quasi-static and ELF).

Maximal static fields in electric railway systems varied from hundreds μT to thousands μT depending on specific technology and time of construction. Automotive static fields are less investigated, but it seems that they vary from few μT up to few hundreds μT depending upon location in the vehicle and the orientation of the vehicle with respect to the geomagnetic vector. Below we summarize maximum levels of alternating magnetic field intensities in the quasi-static (<5 Hz) frequency range that were found in our survey and in variety of studies mentioned above:

- Tram 500 μT
- Metro 425 μT
- Trolleybus 325 μT
- Electric Comuter AC Train 196 μT
- Electric DC locomotive 150 μT
- Electrified (hybrid) car 120 μT
- Light track 104 μT
- Electric shuttle bus 80 μT

Thus, magnetic fields found in hybrid/ electric cars are lower or within the range of fields found in other electric transport technologies.

When electric vehicles are compared to gasoline-powered vehicles within the same model, the geometrical means for the electric vehicles (all hybrid electric vehicles, HEV) are greater.

Level of magnetic fields in various electric/hybrid models is lower than ICNPR limits. When comparing with everyday residential exposures, it was found that exposure levels in electric vehicles (for frequencies from Hz 40 to 800 Hz) were within the range of personal exposure to magnetic fields in US residences.

5. BIOLOGICAL RELEVANCE

To study the societal dimension of using electric transport we need to estimate how important measured MF could be for life or living organisms. For this it is necessary to consider specific features of automotive EMF (summarized in paragraph 5) in the context of biological relevance. A central problem that arise in this regard is how sufficiently large signal-to-noise ratio can be obtained to enable the living cell to detect the signal. For strong signals, the biological effects are well understood due to their thermal effect. These thermal effects define a basis for international limits. However, for weak electromagnetic signals (as in electric vehicles) no commonly agreed theoretical explanation for their biological action has emerged so far.

A number of innovative ideas have been advanced to explain the basis for coupling of electromagnetic fields to living cells and tissues, many of which involve resonance, transduction and amplification phenomena occurring at the cell membrane (see e.g., [24] and references therein). Additionally, Funk and co-authors [25] emphasized one general aspect that could be important. According to a novel approach molecules in the cell can be interpreted as bio-nanodevices working by their charges (electric properties, and while moving also magnetic properties). Material science has recently recognized this potential in organic molecules and found that these molecules are comparable, e.g. to transistors in a microchip, the fields is called now 'molecular electronics' [26,27].

On the other hand, this field of research is characterized by a significant gap between biophysical theory and experimental results. Although we are far from understanding the biology of biosystem-field interactions, a number of experimental results have emerged reliably showing that exposure to low-frequency, low-intensity MFs can produce biological effects [28-32].

In Fig. 5, taken from [7], are shown magnetic field values for various frequencies encountered in the hybrid car. In this figure there are also shown magnetic field reference levels recommended by the [33] for general public exposure, and frequencies and intensities of magnetic fields at which biological effects have been observed. According to some experiments, as is shown in Fig. 5, biological effects are evident at these frequencies and magnetic field strengths, in spite of the fact, that magnetic fields encountered in a hybrid car are lower than recommended levels [33].

Below we will outline some biological experimental results in regard to the specific features typical of automotive magnetic field patterns.

In Fig. 5 biological effects are shown only for frequencies f>5Hz, since in [7] measurements were performed for f>5Hz. However biological effects of MF at f<5Hz are also can be found [34-36].

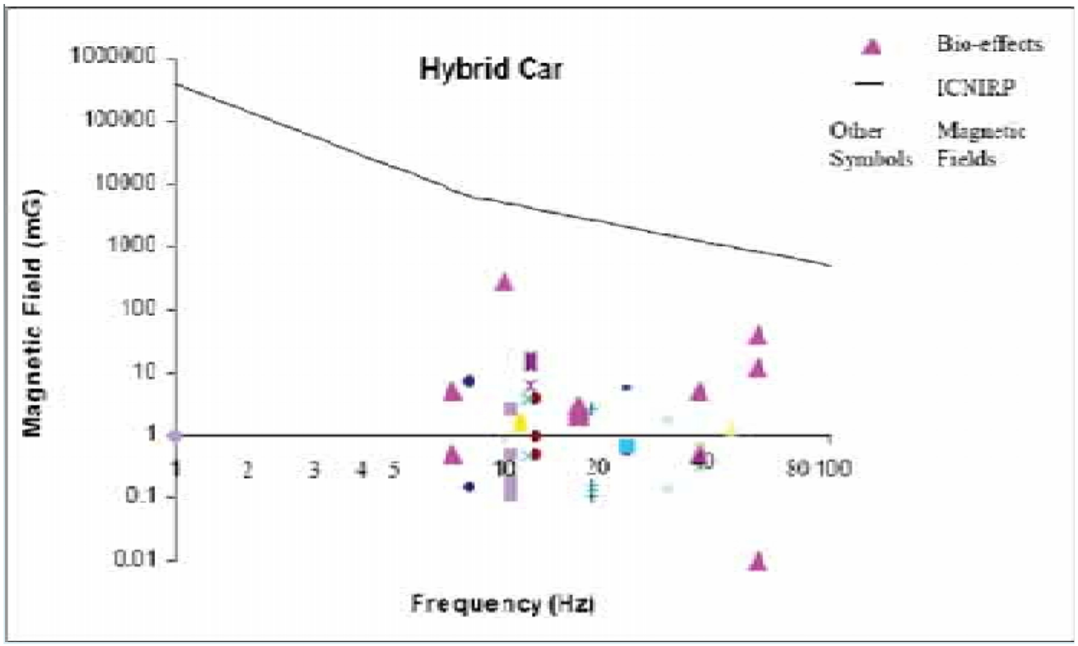

Fig. 5. Observed biological effects with regard to hybrid car magnetic fields and international limits ICNIRP [7]. (N.B. 10 mG = 1 μT)

Dominance of the lowest frequencies (<15 Hz) encountered in the studied electric vehicles may be of importance in the context of MF biological effects, since there are indications that in some cases, especially when central nervous and cardiovascular systems are involved, the biological effects could be more pronounced for frequencies lower than 15 Hz [37-39].

5.1 Intermittent Patterns and Irregular Wave Forms

Research on human subjects [40-41] as well as several recent studies [28] have found that intermittent fields and irregular wave forms are more biologically effective than steady state fields. This is important regarding biological relevance of automotive fields, because, as it was reported above, irregular waveforms and intermittent patterns are the most essential features of MF encountered in electric vehicles.

5.2 Static Magnetic Fields

Lower static magnetic fields (attenuated geomagnetic field) could be found inside electric vehicle, depending on the shielding properties of vehicle body, location within the vehicle, and the orientation of the vehicle with respect to the geomagnetic vector. There is some evidence to suggest that these kinds of fields can be biologically significant [42,43]. A decrease in human cognitive processes in hypo-geomagnetic fields was reported in [44]. Changes in cell growth and differentiation were also observed by [45,46]. In a recent work [47], it was shown that hypo-geomagnetic exposure significantly accelerates the proliferation of human neuroblastoma (SH-SY5Y) cells.

5.3 Specific Combinations of DC-AC Fields

Automotive magnetic field patterns are characterized by highly variable and complex combination of static and time-varying components. This results in many combinations of DC-AC fields that could have the potential to be biologically effective.

There is now a body of evidence that specific combinations of DC and AC magnetic fields can cause biologically significant effects. The combinations of DC and AC magnetic fields are defined by the cyclotron resonance conditions of the selected ion [7,9,16,48,49]. A particular combination of weak static and time-varying fields could influence tumor growth in mice [39].

6. CONCLUSION

We summarized available results of magnetic surveys taken in variety of electrically powered transportation systems, with the focus on automotive exposures. Maximum automotive magnetic field magnitudes in different studies varied from a few units μT to 120 μT. For members of the general public, this range of exposures in personal scale electric transportation systems is comparable in magnitude to exposures from other commonly encountered sources. However, electric vehicles exposures are totally different in comparison to common power line exposures (predominantly sinusoidal 50 Hz) in regard to the frequency content and waveforms. The specific automotive EMF features are similar to those in other electrified transport technologies and these are: (1) complex combination of static and time-varying components in wide frequency ranges up to kHz; (2) the frequencies and field strengths vary with speed and these are higher during acceleration and braking; (3) the maximum levels of magnetic field strength are found for static and quasistatic fields; (4) EMF exposures are irregular, intermittent and highly variable in time and space (up to 100 μT/m).

Our results indicate that magnetic fields similar to those that are encountered in electric vehicles do produce biological effects, in spite of the fact, that they are lower than international limits. However, there is no consensus if these biological effects lead to adverse health effects.

This uncertain situation is described in the recent EU project EMF-NET [50]: **"***in spite of the great number of proposed models, there is not yet a specific mechanism able to link the action of the EM field at different complexity levels, from the first interaction step, at molecular level, up to some adverse effects on organism health. Therefore, except for the thermal effects, present knowledge does not allow quantification of a threshold value for the field (guidelines), below which the probability of occurrence of health effects is negligible. However, one cannot assume that long term effects will not be seen. In this context, further research work, including both theoretical and experimental activities, seems to be necessary*".

We have shown that, at least in the extremely low field frequency range, biological effects are specific for combinations of frequency, intensity and geomagnetic field. However, a consensus on the set of intensities and frequencies which are typical of all electric vehicles (and should therefore be tested with great attention) is lacking. Moreover, what is almost completely missing in the information coming from electric vehicles are polarization and vectorial components of the AC fields. Indeed these might be extremely relevant data.

Shielding of the geomagnetic field has been shown to exert some effects and this could encourage the reduction in the use of ferromagnetic materials for the skeleton of the vehicle. Measurement of these shielding effects might be of relevance also for electric vehicles, in particular considering that this static field might interact with the generated DC and AC.

We may conclude that it would be important to repeat for electric vehicle fields those biological experiments which have been done for electric power frequencies (50-60 Hz). In this context intermittent patterns and irregular wave forms that might be replicated on cultured cells should be provided for biological tests. For biological experiments it would be useful to have a “typical” EV magnetic pattern to be tested *In vitro*: “average” or/and “maximum” pattern during several minutes, which includes acceleration, braking etc

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Alfredsson L, Hammar N, Karlehagen S. Cancer incidence among male railway engine-drivers and conductors in Sweden, 1976-90. Cancer Causes Control. 1996;l7:377–381.
2. Ptitsyna NG, Villoresi G, Dorman LI, Iucci N, Tyasto MI. Natural and man-made low-frequency magnetic fields as a health hazard. Physics-Uspechy (Advances in Physical Sciences). 1998;41(7):687-709.
3. Minder CE, Pfluger DH. Leukemia, brain tumors, and exposure to extremely low frequency electromagnetic fields in Swiss railway employees. Am J Epidemiol. 2001;153:825–835.
4. Röösli M, Lörtscher M, Pfluger D, Schreier N. Cancer and neurodegenerative disease mortality among swiss railway employees exposed to extremely low frequency magnetic fields: 31 years of follow up. Neuroepidemiology. 2007;28:197-206.
5. Ptitsyna NG, Ponzetto A. Magnetic Fields Encountered in Electric Transport: Rail Systems, Trolleybus and Cars. IEEE Conference Publications. Proceedings of the Electromagnetic Compatibility (EMC EUROPE). International Symposium on Fields, Waves & Electromagnetics, Rome, Italy. 2012;1–5.
DOI: 10.1109/EMCEurope.2012.6396901
6. Muc AM. “Electromagnetic fields associated with transportation systems, radiation health and safety consulting”. Contract Report 4500016448, Air Health Effects Division, Healthy Environments and Consumer Safety Branch Health, Canada. 2002;52.
7. Halgamuge MN, Abeyrathne CD, Mendis P. Measurement and Analysis of Electromagnetic Fields from Trams, Trains and Hybrid Cars. Radiation Protection Dosimetry. 2010;141(3):255-268.

8. Thuróczy G, Bakos J, Ravazzani P. Report on the level of exposure (frequency, patterns and modulation) in the European Union, Part 2: Extremely low frequency (ELF) fields. Deliverable Report D4 of EHFRAN project; 2011.
9. Stankowski S, Kessi A, Bécheiraz O, Meier-Engel K, Meier M. Low frequency magnetic fields induced by car tire magnetization. Health Phys. 2006;90(2):148-53.
10. FOPH, EMF fact sheets. Cars, hybrid cars. Non ionizing Radiation Competence and Information Centre. Switzerland; 2009.
Available:
http://www.bag.admin.ch/themen/strahlung/00053/00673/02377/index.html?lang=en
11. Milham S, Hatfield JB, Tell R. Magnetic Fields from Steel-Belted Radial Tires: Implications for Epidemiologic Studies. Bioelectromagnetics. 1999;20:440-445.
12. Dietrich FM, Jacobs WL. Survey and Assessment of Electric and Magnetic Field (EMF) Public Exposure in the Transportation Environment. US Department of Transportation. Federal Railroad Administration, Report No. PB99-130908; 1999.
13. Daubaras A, Zilus M. Vehicle detect ion based on magneto-resistive magnetic field sensor. Electronics and Electrical Engineering. 2012;170(2):118.
14. Vedholm K, Hamnerius JK. Personal exposure resulting from low level low frequency electromagnetic fields in automobiles, Abstract F-9, Second World Congress for Electricity and Magnetism in Medicine and Biology, June 8-13, Bologna, Italy; 1997.
15. Karabetsos E, Kalampaliki E, Tsanidis G, Koutounidis D, Skamnakis N, Kyritsi T, Yalofas A. EMF Measurements In Hybrid Technology Cars. Proceedings of 6th International Workshop on Biological Effects of Electromagnetic Fields, Istambul; 2010.
Available: http://www.istanbul.edu.tr/6internatwshopbioeffemf/cd/index.html
16. Halgamuge M, Abeyratne C, Mendis P. Influence of Combined AC-DC Electromagnetic Fields on Cell Plasma Membrane. Proc. 31st Annual Conference of Bioelectromagnetics Society (BioEM'09), Davos, Switzerland; 2009.
17. Berisha A, Shahin H, Karady G., Raed R., Hobbs R., Karner D. Magnetic Field Generated From Different Electric Vehicles. Electric Transportation Application; 1995. DOI: 10.4271/951934.
18. Snyder M. Magnetic Shielding for Electric Vechicles. Program Review. Contract DAAE07-93-C-R107. Army TACOM, Chrysler Corp; 1995.
Available:http://engineeringmatters.com/Magnetic%20Shielding%20for%20Electric%20Vehicles.pdf
19. Tell RA, Sias G, Smith J, Sahl J, Kavet R. ELF magnetic fields in electric and gasoline-powered vehicles. Bioelectromagnetics. 2013;34(2):156–161.
20. Rankin RF, Bracken D, Russell S, Kavet R, Montgomery JH. Results of a multisite study of U.S. residential magnetic fields. Journal of Exposure Analysis and Environmental Epidemiology. 2002;12:9–20. 10.1038/sj/jea/7500196.
21. Villoresi G, Iucci N, Ptitsyna NG, Kopytenko YA, Tyasto MI, Kopytenko EA, Voronov PM, Zaizev DM, Ismaguilov VS. Fine structure of magnetic field variations (0–10 Hz) onboard electrified trains. Proc Int Symp on Electromagnetic Compatibility, Roma, Italy. 1998;1:58–62.
22. Ptitsyna NG, Kopytenko YA, Villoresi G, Pfluger DH, Ismaguilov VS, Iucci N, Kopytenko EA, Zaitzev DB, Voronov PM, Tyasto MI. Waveform magnetic field survey in Russian DC- and Swiss AC-powered trains: A basis for biologically relevant exposure assessment. Bioelectromagnetics. 2003;24:546-556.
23. Ptitsyna NG, Kopytenko YA, Villoresi G, Ponzetto A. Analysis of Magnetic Fields Onboard Electric Transport Systems in Regard to Human Exposure. IEEE Conference Publications. Proceedings of the Electromagnetic Compatibility (EMC EUROPE) International Sympo; 2012. DOI: 10.1109/EMC Europe.2012.6396902.

24. Stavroulakis P. (Ed.). Biological Effects of Electromagnetic Fields. Springer Verlag, Heidelberg, Berlin. 2003;578.
25. Funk RH, Monsees T, Özkucur N. Electromagnetic effects – From cell biology to medicine. Progress in Histochemistry and Cytochemistry. 2009;43:177–264.
26. Piva PG, DiLabio GA, Pitters JL, Zikovsky J, Rezeq M, Dogel S, Hofer WA, Wolkow RA. Field regulation of single-molecule conductivity by a charged surface atom. Nature. 2005;435:658–61.
27. Kushmerick JG, Blum AS, Long DP. Metrology for molecular electronics. Anal Chim Acta. 2006;568:20–7.
28. REFLEX project reports.
Available://www.itis.ethz.ch/downloads/REFLEX_Final%20Report_171104.pdf
Available:http://omega.twoday.net/stories/436703/
Available:http://www.buergerwelle.de/pdf/genetic_effects_of_nonionizing_electromagnetic_fields.pdf
Available:http://www.wave-guide.org/library/lai.html
29. Belova NA, Ermakova ON, Ermakov AM, Rojdestvenskaya ZY, Lednev VV. The bioeffects of extremely weak power frequency alternating magnetic fields. Environmentalist. 2007;27(4):411–416.
30. Fathi E, Farahzadi R. Effect of electromagnetic field on acetylcholinesterase activity: In vitro study. Afr J Biochem Res. 2012;6:8-13.
31. Fathi E, Farahzadi R. Investigation of the effect of sodium selenate on acetylcholinesterase activity under extremely low frequency electromagnetic field. J Biol Life Sci. 2013;4:41-52.
32. Fathi E, Farahzadi R, Pishgahzadeh H. Sodium selenate decreased acetylcholinesterase activity under 217Hz, 300µT electromagnetic field. Int J Recent Sci Res. 2012;3:657-661.
33. ICNIRP (International Commission on Non – Ionizing Radiation Protection) Guideline for limiting exposure to time – varying electric, magnetic and electromagnetic fields (up to 300 GHz). Health Physics. 1998;74:494-522.
34. Ramon C, Powell MR. Preliminary report: Modification of cardiac contraction rate by pulsed magnetic fields. Bioelectromagnetics. 1992;13:303–311.
35. Lyskov E, Juutilainen J, Jousmaki V, Partanen J, Medvedev S, Hanninen O. Effects of 45-Hz magnetic fields on the functional state of the human brain. Bioelectromagnetics. 1993;14:87–95.
36. Rosenspire AJ, Kindzelskii AL, Simon BJ, Petty HR. Real-time control of neutrophil metabo-lism by very weak ultra-low frequency pulsed magnetic fields. Biophys J. 2005;88:3334–3347.
37. Gavalas-Medici R, Day-Magdaleno S. ELF weak electric field effects scheduled-controlled behavior of monkeys. Nature. 1976;261:256-259.
38. Makeev VB, Temuryantz NA. Research of frequency dependence on biological activity of magnetic field in geomagnetic pulsations range 0.01–100 Hz, In Problemi kosmicheskoy biologii [Problems of Cosmobiology] Nauka. Moscow, Russia. 1982;43:116-129.
39. Novikov VA, Fesenko EE. Effect of weak combined static and extremely low-frequency alternating magnetic fields on tumor growth in mice inoculated with the Ehrlich ascites carcinoma. Bioelectromagnetics. 2009;30(5):343–351.
40. Lerchl A, Nonaka KO, Stokkan RJ, Reiter N, Marked rapid alterations in nocturnal pineal serotonin metabolism in mice and rats exposed to weak intermittent magnetic fields. Biochem Biophys Res Commun. 1990;169:102–108.
41. Sastre A, Cook MR, Graham C. Nocturnal esposure to intermittent 60 Hz magnetic fields alters human cardiac rhythm. Bioelectromagnetics. 1998;19:98.

42. Conley CC. Effects of Near-Zero Magnetic Fields upon Biological Systems. In "Biological Effects of Magnetic Fields". Ed. Barnothy MF, Springer. 1995;29–51.
43. Prato FS, Robertson JA, Desjardins D. Daily repeated magnetic field shielding induces analgesia in CD-1 mice. Bioelectromagnetics. 2005;26(6):109–117.
44. Sarimov RM, Binhi VN, Milyaev VA. The influence of geomagnetic field compensation on human cognitive processes. Biophysics. 2008;53:433–441.
45. Sandodze V. Influence of hypomagnetic medium on proliferation activity of the hippocampal fascia dentata and ammon's horn suprafimbrial cells in early and late ontogenesis. Radiation Studies. 2000;5:188–196.
46. Martino CF, Portelli L, McCabe K, Hernandez M, Barnes F. Reduction of the Earth's magnetic field inhibits growth rates of model cancer cell lines. Bioelectromagnetics. 2010;31:649–655. DOI: 10.1002/bem.20606.
47. Mo WC, Zhang ZJ, Liu Y, Bartlett PF, He R. Magnetic Shielding Accelerates the Proliferation of Human Neuroblastoma Cell by Promoting G1-Phase Progression. PLoS ONE. 2013;8(1):e54775. DOI: 10.1371/journal.pone.0054775. Available:http://www.plosone.org/article/info%3Adoi%2F10.1371%2Fjournal.pone.0054775
48. Lednev V. Possible mechanism for the influence of weak magnetic fields on biological systems. Bioelectromagnetics. 1991;12:71.
49. Coulton LA, Barker AT. Magnetic fields and intracellular calcium: Effects on lymphocytes exposed to conditions for 'cyclotron resonance'. Phys Med Biol. 1993;38(3):347–60.
50. EMF-NET. Effects of the exposure to electromagnetic fields. From science to public health and safer workplace. Available: http://www.jrc.cec.eu.int/emf-net

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