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Natural and man-made low-frequency magnetic fields as a potential health hazard

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Abstract. **Is human health affected by low-frequency low-intensity environmental magnetic fields? There is much die-hard evidence that it is. For this reason irregular, spectrally complex ULF (0 – 10 Hz) magnetic fields have recently come under scrutiny, typical of natural geomagnetic perturbations or electric transportation. Recent work shows that such fields do affect the nervous system and may even cause heart attacks.**

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1. Introduction

Human beings are constantly exposed to electromagnetic fields present throughout the environment and originating from both natural and man-made sources. The principal natural electromagnetic fields are atmospheric electricity, the Earth's static magnetic field (MF) and geomagnetic variations of interplanetary origin. Over the last few decades the intensity of the electromagnetic environment has dramatically increased: devices generating electromagnetic fields have proliferated in industrial plants, public transportation systems, office buildings, and homes. This new situation is often described as 'electromagnetic pollution' or 'electromagnetic smog'.

While the electromagnetic spectrum is in the range from 0 to above 10^{20} Hz, the main components of electromagnetic pollution are in the extra-low (ELF: 10 – 300 Hz) and in the ultra-low frequency bands (ULF: 0 – 10 Hz). In these frequency bands, electric and magnetic fields can be treated independently. Experimental and epidemiological data, as well as theoretical arguments, suggest that the magnetic rather than the electric component of the electromagnetic field may be relevant to the human organism because MF can penetrate freely within tissues [1 – 3]. In the past there was considerable controversy as to whether environmental electric and magnetic fields could cause significant biological effects. The intensity levels of MF at frequencies below 300 Hz, typical of our environment, are usually lower or of the same order of magnitude of the Earth's static MF ($\sim$ 50 mT) and are considered 'weak'. At the present time there is a broad consensus in the international scientific community that exposure to weak low-frequency electric and magnetic fields can produce biological effects, in spite of the fact that the energy involved is quite small (see, e.g., Refs [4 – 6]). Correspondingly, there has also been increasing concern that these biological effects may result in health problems. A series of publications under the sensational titles "Currents of Death" [7] and "Killing Fields" [8] brought the field of bioelectromagnetics to the attention of the general public. This question, still remaining the object of much controversy, became of worldwide interest and has been the subject of more than 20,000 published reports and papers. The main focus in studies of the potential health hazard of electric and magnetic fields has been on man-made fields at 50 and 60 Hz, particularly on power line fields, because of their possible association with increases in malignant diseases (see, e.g., Refs [9, 10]). More recently, MFs from electrified public transport, which constitute the main component of the magnetic environment in well-populated urban areas, have also come into consideration. Transport fields are different from power frequency MFs which are predominantly sinusoidal: they show complex frequency patterns with the greatest components mainly at frequencies lower than 15 Hz [11 – 14].

In the last decades many investigations have also been carried out into the possible health hazards of natural, solar variability-driven time variations of the Earth's MF. These field variations exhibit complex spectra and mainly cover the ULF frequency band (0 – 10 Hz). Physicists remain sceptical of the idea that natural geomagnetic field variations could have any effect on living systems because often the intensities involved are even smaller than those typical for man-made environmental MFs. On the other hand, one could expect a special sensitivity of living systems to naturally-occurring geomagnetic fields, since the magnetoreception of neural structures should be evolutionarily adjusted to these fields. Indeed, a number of investigations have showed a significant correlation between the incidence of clinically important pathologies and strong geomagnetic field variations. The main results seems to be on nervous and cardiovascular diseases (see, e.g., Refs [15 – 20]).

This review is selective: we will mainly discuss results on the health-related effects of ULF (0 – 10 Hz) MFs and will focus on biomedical effects of central nervous and cardiovascular systems, taking into account new developments. Special attention will be drawn to MFs from electric transport and their possible health effects. Results on the bioeffects of natural and man-made MFs will be considered not independently, but in a mutual light.

2. MF environment: general characteristics

MFs in our environment are produced by electric currents and the strength of these fields depends on the geometry of the circuit, the strength of current in the conductors and the distance of the observer from the circuit. In the simple cases of a long single wire, two parallel wires and a loop of wire, the MF B is proportional to $1/r^n$ where n is equal to 1, 2 and 3 for the three cases respectively. In reality, where more than one current is flowing and the circuit is of complex configuration, there are different orders of decay as a result of destructive or additive effects $\left[B = \sum(1/r^n)\right]$.

2.1 Natural magnetic fields

Natural MFs are the Earth's static field and the geomagnetic variations of interplanetary origin. The Earth's static MF is generated mainly by circulating currents of unknown origin well below the crust. The field magnitude varies over the Earth's surface from about 35 μT at the equator to 65 μT near poles. Natural phenomena, such as solar activity and related interplanetary large-scale perturbations, produce time-varying MFs of large planetary extent mainly in the ULF range. Pulsations in the frequency range 0.001 – 10 Hz are frequently observed in geomagnetic field records all over the world, with amplitudes between 0.1 – 100 nT; they are characterized by different 'regular' (*Pc*) and 'irregular' (*Pi*) waveforms.

Solar wind plasma flowing continuously past the Earth creates a region around the Earth which confines the geomagnetic field. This region which contains plasma and the Earth's MF is known as the magnetosphere (Fig. 1). The arrival of high-speed solar plasma (generated by solar nonstationary processes) and the associated shock wave near the Earth causes geomagnetic storms. The interaction of interplanetary disturbances with the magnetosphere results in reconnection of the interplanetary MF with the geomagnetic field and in a fluctuating size for the magnetosphere, which depends on the solar plasma momentum flux. This allows the entry of new particles into the magnetosphere or the acceleration of the ambient plasma to keV energy, thus forming a complicated system of currents in the magnetosphere and ionosphere. During big geomagnetic storms sudden fluctuations due to the superposition of equatorial ring current effects and auroral current effects can be

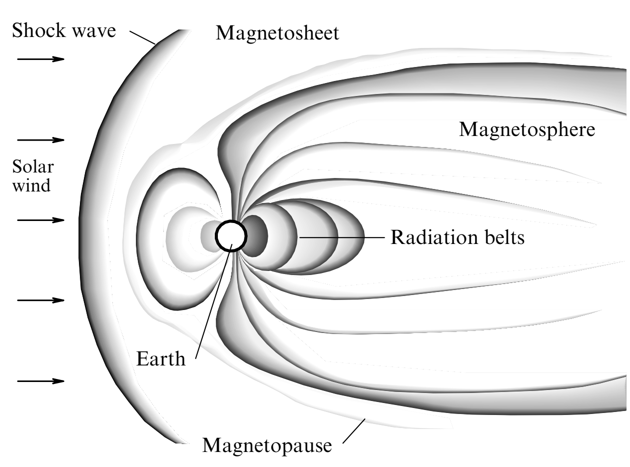

Figure 1. MF far from the Earth's surface is the combined contribution of the dipole field and of the solar wind. The long magnetic tail extends for some thousands of Earth radii.

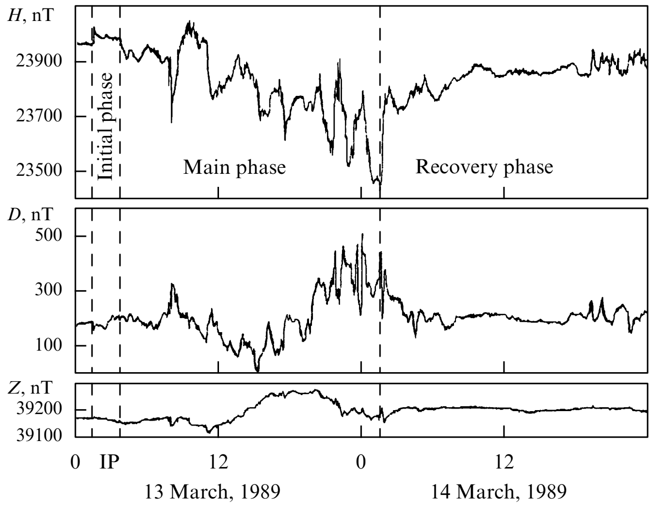

Figure 2. Geomagnetic storm detected at L'Aquila on March 13, 1989. The data are 1 min measurements of the MF components. The time interval labeled 'IP' corresponds to the initial phase of the storm [23].

observed for 1 – 2 days: they produce field variations as large as 200 – 300 nT at low latitudes and can exceed 1000 nT at high latitudes. Geomagnetic storms are associated with a dramatic power increase at all frequencies (see, e.g., Refs [21, 22]). Figure 2 represents the geomagnetic storm registered at L'Aquila (42N latitude) on March 13, 1989. For this particular event the hourly average power is higher than the corresponding background values by factors of the order of 10,000 for *Pc*1 pulsations (0.2 – 5 Hz) and 5,000 – 3,000 for *Pc*3 – *Pc*5 pulsations (frequencies less than 0.1 Hz) [23].

Several geomagnetic indexes have been devised to describe the intensity level of geomagnetic disturbances on a 3-hourly basis. The most widely-used index is the planetary index *Kp* which is derived from the local *K* index of a number of selected observatories for 3-hour intervals. The *K* index describes the MF variations on a logarithmic scale in such a way that the smallest and largest variations occurring at that observatory are represented by $K = 0$ and $K = 9$ respectively. The *Ap* index is a linear index derived from the 3-hourly planetary index *Kp* and it ranges from 0 to 400. A similar index, often used in solar-terrestrial physics, is the *aa* index in which the daily and annual variations are removed.

2.2 Man-made magnetic fields

Strong man-made MFs at 50 Hz (60 Hz in USA) can be encountered in the proximity of some home appliances: for instance, 1 μT from a refrigerator, 10 μT from a coffeemaker, 100 μT from a microwave oven [24]. There are a number of different hand-held electrical devices (electric razors, hair dryers, etc.) capable of generating 500 – 2000 μT MFs at their surfaces [25]. These fields mainly involve current loops of small diameter and fall off rapidly away from the device (within 0.5 m) to almost zero levels and, in any case, most people do not spend much time close to these bigger fields. MFs at 50 – 60 Hz of larger spatial extent can be found in some 'electrical worker' environments and from power lines. For instance, elevated MF levels in the range of 3 – 5 μT and up to 10 μT were found in work areas of steel production with electric furnaces [26]. Field intensities under 735 kV power lines were found to be of the order of 5 μT and about 1 μT at a distance of 50 m (Fig. 3) [27]. However, the contribution of power frequency MFs to the general environment is predominantly small, since the phases of alternating current (AC) fields are typically in close proximity to one another, largely canceling each other.

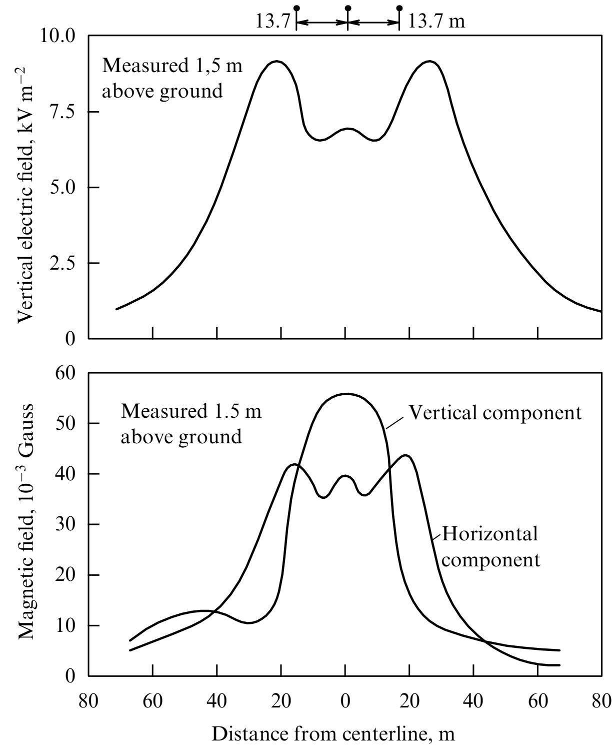

Figure 3. 60-Hz electric and MFs beneath a 765-kV transmission line. Plots are field measurements versus perpendicular distance from the centerline near midspan. For the electric field, the horizontal component, although present, is negligible relative to the component vertical to the earth's surface. For the MF, the horizontal component as shown is perpendicular to the centerline; the parallel component is negligible [27].

The highest fields of large spatial extent in densely populated urban areas and in the occupational environment are produced by public electrified rail transport. The calculated MFs for typical railroad currents are shown in Fig. 4 [24]. Measurements [28] have shown that ULF MFs are about 1 μT at a distance of 100 m from the train rails. MFs produced by electrically operated transport are quite different from power line fields with predominant frequencies at 50 or 60 Hz: they show great time changes, pulses and other transient phenomena, including intermittent components mainly at frequencies below 10 Hz [11 – 13, 29, 30]. Moreover, the rails of electrified transport, being part of an electric circuit, can produce ground leakage currents of large extent which generate significant MFs [31, 32]. These currents may contribute substantially to the level of environmental MFs: they are concentrated on the metal surfaces of underground pipelines, plumbing lines, communication cables, etc., that are characterized by higher electrical conductivity in comparison with ground. Figure 5 shows the distribution of ULF MF in the environment of a big industrial city, as a results of a magnetic survey in St. Petersburg and in two geomagnetic observatories located at 30 and 90 km from the city center [19, 33]. In the city the level of man-made MFs is greater than the level far from the city by a factor of 10^3. This figure also shows the mean levels of ULF MFs from different natural and man-made sources. For comparison the typical level of MF at 50 Hz measured under power lines at ground level and on the

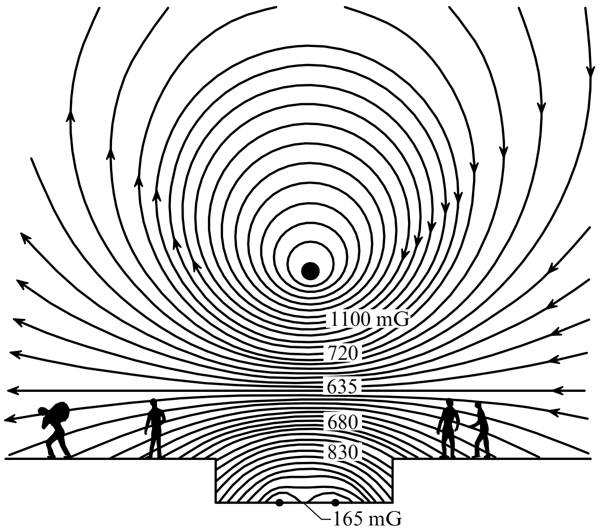

Figure 4. Electric trains produce among the highest ELF fields of large spatial extent in well-populated areas (1 mG = 0.1 mT). In this drawing a current of 500 A flows into the paper through the trolley wire and is returned in equal amounts by the rail [24].

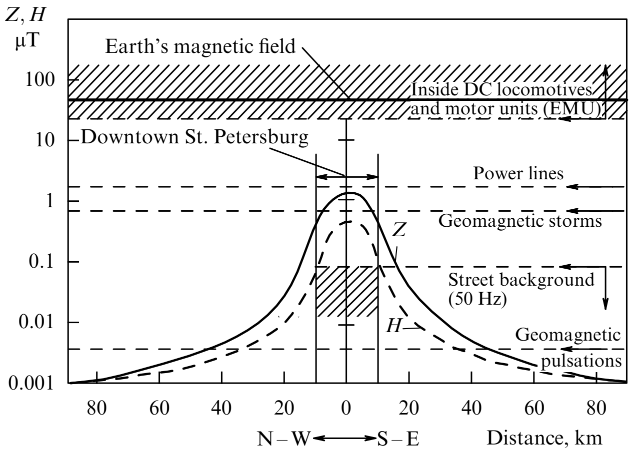

Figure 5. Spatial distribution of MF in the ULF range in the region of a big industrial city (St. Petersburg). MF values due to typical natural and man-made sources are given for comparison [19, 33].

street is shown. Measurements showed that the intensity of ULF MFs near and inside electric trains and subway carriages can increase up to $10^4 - 10^5$ times [13, 14, 34, 35]. Usually man-made MFs become comparable to natural MF variations at a distance of 30 – 100 m from the sources. However, the actual magnitudes of natural and man-made fields depend on many factors (latitude, geomagnetic activity, distribution and character of man-made sources, underground conductive lines etc.). Till now there has been a lack of systematic MF measurements inside cities, especially in the ULF band which constitutes the main component of the magnetic environment.

3. Biomedical effects of natural geomagnetic fields

In recent decades many investigations have been carried out into the influence of geomagnetic field variations on human health. Data on mortality and morbidity of cardiovascular and nervous system, psychiatric wards admission and incidence rate of other different pathologies have been used as a basis for correlation with different indices of solar and geomagnetic activity (see, e.g., Refs [18, 20, 33] and refs. therein]. Even such exotic data as the number of hallucinations registered in the last century in the USA, has been used as material for biogeomagnetic study [36]. A number of review papers and books on the biomedical effects of geomagnetic fields were published in Russia where this area is traditionally popular (see, e.g., Refs [15, 37 – 39]). Recently two reviews of biogeomagnetic studies also appeared in the USA [16, 17].

In this section we will give only a summary of research results and focus our attention mainly on difficulties and methodological problems.

The most significant results have been those on cardiovascular and nervous system diseases, showing some association with geomagnetic activity [18, 19, 33, 40 – 49]. Starting from pioneer studies done as early as in 1941 [50, 51], a number of laboratory results on the correlation between the human blood system and solar and geomagnetic activity supported these epidemiological findings [52 – 55]. Recently, the monitoring of cardiovascular function among cosmonauts of the MIR space station revealed a reduction of heart rate variability during geomagnetic storms [56].

Some evidence has also been reported on the association between geomagnetic disturbances and increases in work and traffic accidents [20, 57 – 63]. These studies were based on the hypothesis that a significant fraction of traffic accidents could be caused by the incorrect or retarded reaction of drivers to the traffic circumstances, the capability of reacting correctly being influenced by the environmental magnetic and electric fields. For instance, in Refs [57, 58] the author found that increases in work and traffic accidents in Germany were associated with disturbances in atmospheric electricity and in the geomagnetic field (detected through sudden perturbations in radio wave propagation). On the basis of 25 reaction tests, it was also found that the human reaction time during these disturbed periods was considerably retarded. Retarded reaction in connection with naturally occurring ULF signals was also observed in Ref. [64].

However, there are significant discrepancies in the field. Different studies show opposite correlations between medical-biological parameters and geomagnetic activity. During increased geomagnetic activity some authors found an increase, while on the contrary, others found a decrease in mortality and morbidity of cardiovascular and nervous system diseases (see, e.g., Refs [37, 38] and refs. therein). For instance, increases were reported in hypertension crisis and brain strokes after [65], during [66] or even before [67] geomagnetic storms. In different studies, incompatible intensity levels of geomagnetic activity were found to be bioeffective. In Refs [40, 41, 43, 44] a high level, and conversely in Ref. [68] a low level of geomagnetic activity was found to be bioeffective. The analysis performed in Ref. [60] showed that traffic accidents were more frequent on days characterized by intermediate geomagnetic activity ($\sum K = 16-24$), while in Ref. [62] the number of traffic accidents was found to increase during low-intermediate ($\sum K = 8-16$) and very high ($\sum K > 32$) geomagnetic activity. Moreover, a similar volume of negative reports can also be assembled ([37, 69 – 71] and refs. therein). In general there are many discrepancies in the field and very often the results are doubtful for the following possible reasons:

(a) in many cases, inadequate statistical samples and incomplete statistical data treatment did not allow the achievement of clear statistical evidence supporting the correlation between solar-geophysical processes and human mortality;

(b) there has been often a non-critical approach to data gathered from second hand sources;

(c) different indices of solar and geomagnetic activity, which are related to different solar-geophysical processes, have been used in different studies;

(d) the multivariable character of the problem has not been taken into account;

(e) results of spectral analyses, which are frequently used in biogeomagnetic studies, have often been interpreted toward misleading conclusions.

A characteristic example is the remarkable correlation between heart attacks and magnetic activity found on the basis of medical data gathered in India [72]. Later [70] a similar study was carried out using UK data, but failed to find any correlation. Analysis of the Indian data showed that their distribution about the regression line was grossly sub-Poissonian. This means that the correlation was higher than would be expected even if magnetic activity were the sole cause of heart attacks, casting serious doubt on the authenticity of the data. The authors re-examined the hospital records and were unable to reproduce the data used in Ref. [72] that were received from second-hand sources; they apologized for publishing a misleading result [73].

More complicated is the situation with contradictory results found by Gnevishev and Novikova [43, 44] and Lipa with co-workers [69]. Gnevishev and Novikova analyzed the relationship between daily mortality due to heart attacks and brain strokes in Sverdlovsk and geomagnetic activity. A positive correlation was found, however no estimates of statistical significance were given. Lipa and co-workers performed similar statistical analyses using US data on mortality from infarctions for the entire nation and also for three individual cities. They did not get evidence for a statistically significant association between daily deaths and geomagnetic indices. Lipa relates the opposite results of these two studies (besides the possible statistical insignificance of Gnevyshev and Novikova result) to the difference in geomagnetic latitudes of the cities where the data were collected. To clarify this question a statistical analysis of mortality due to coronary heart disease was performed on the basis of data collected in hospitals of St. Petersburg, which is situated in the same latitudinal zone as Sverdlovsk [74]. The analysis did not show any statistically significant correlation between mortality and the level of geomagnetic activity indicating that the above discrepancy in the results was not connected to different latitudinal locations, but most likely to different criteria of data collection. Lipa used general mortality files. Gnevyshev and Novikova took into account not all mortality data, but a subset of special cases, so-called sudden deaths, that were extracted from original hospital records; their data selection was not formalized, therefore it was not possible to repeat their study in an exact way.

The controversial results in this subject indicate that the effect of geomagnetic disturbances on human diseases may be very small, if any. Therefore, to have a chance of determining rather small effects, one should increase the level of statistical power. This can be achieved by analyzing a great amount of data and by using appropriate indices of geomagnetic activity. A correct statistical approach should also take into account the multivariable character of the problem [75, 76]. Figure 6 [19] shows a scheme of the main environmental factors influencing the pathology rates: variations of social origin, geomagnetic field and meteorological variations. Social effects depend on local habits and on the technological development of the society and are generally dominant. Some examples of social effects in medical statistics data have been shown in [18 – 20, 33]. In Figure 7 we show the average behavior of street trauma, heart rhythm disturbance, hypertension (Moscow, 1979 – 1981) and infarction (St. Petersburg, 1981). All cases except infarctions have very prominent peaks associated with days of Soviet festivities (Soviet Army day on 23 February, Womens' Day on 8 March, Labor Day on 1 – 2 May, Victory Day on 9 May, Revolution Day on 7 November). The incidence of infarction does not show such distinctive peaks and has an extremely regular pattern with a weekly periodicity of social origin that will be discussed in detail in Section 5.2.

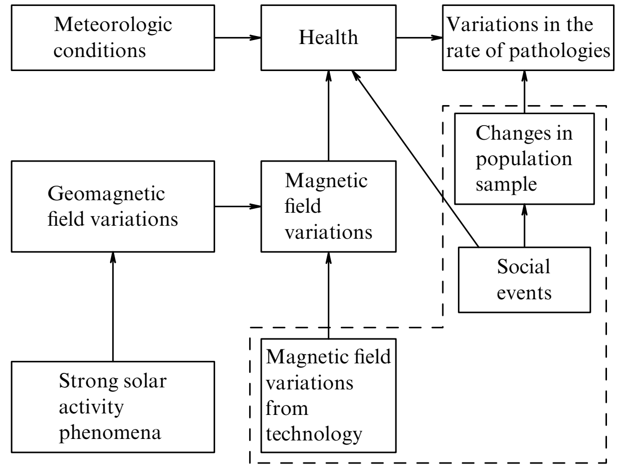

Figure 6. Scheme of the main environmental factors influencing the pathology rates [19].

We suggest that, in studies of possible effects of geomagnetic fields in biomedical data, natural magnetic fields should be considered innocent until proven guilty. This means that, first, one should take into account the influence of all possible social and technological factors and meteorological effects, and, only after that, one may think about a possible role for geomagnetic fields.

In the next section we will present a data analysis approach which recently led to an increased reliability of results [18 – 20, 33, 74] in the controversial field of biogeomagnetic studies.

4. Bioeffective geomagnetic storms and cosmic ray intensity variations

The most important problem in biogeomagnetic research is the definition of the characteristics of geomagnetic activity that are more related to health effects. To describe geomagnetic field fluctuations on various time scales, several geomagnetic indices, based on ground measurements at geomagnetic observatories, have been devised for statistical studies in solar-terrestrial physics. Moreover, some parameters of interplanetary medium perturbations can be used for characterizing the geomagnetic activity level and also some short-term cosmic ray intensity variations, related to

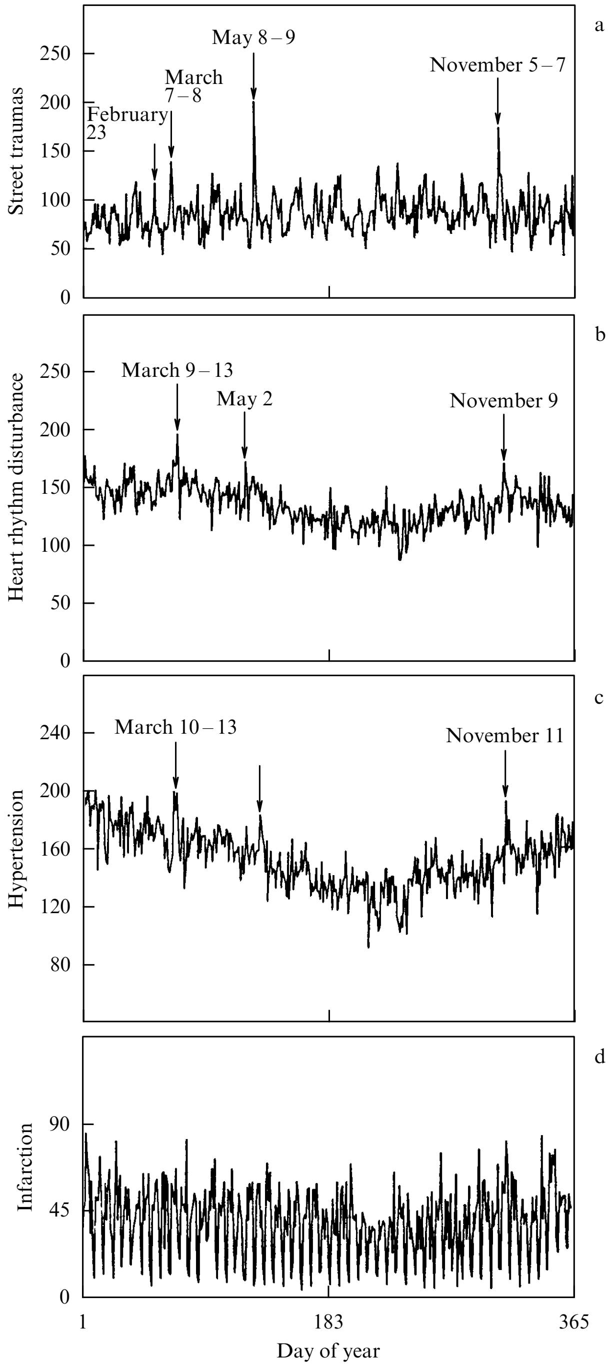

Figure 7. Average annual behavior of different pathology rates in Moscow (1979 – 1981): (a) street trauma (non-vehicle); (b) heart rhythm disturbance; (c) hypertension, and in St. Petersburg (1981): (d) myocardial infarction. Note the bi-monthly waves in (a), big weekly variations in (d) and increases in (a), (b) and (c) during public festivities [18, 19].

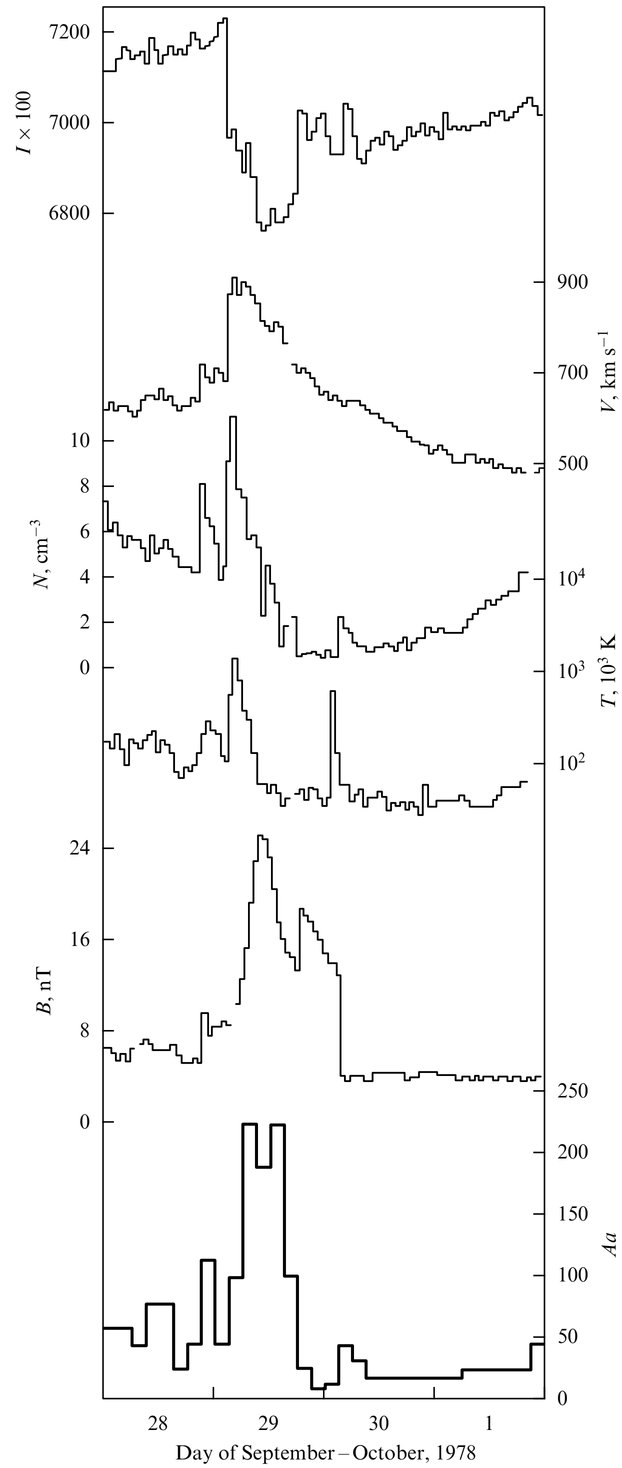

Figure 8. Time profiles of cosmic-ray neutron intensity (I), bulk-speed (V), proton density (N) and temperature (T) of solar wind, interplanetary MF magnitude (B) and geomagnetic index Aa are plotted from top to bottom during a flare-related Forbush-decrease event in cosmic ray intensity [77].

interplanetary disturbances (Fig. 8) [77], may provide an alternative indication. However at the present time there is no commonly accepted mechanism of interaction between external MFs and living organisms. Without an established mechanism, there is no guideline for determining which attributes of the field are hazardous: magnitude, frequency, wave form, duration of exposure, etc. With such uncertainties it is difficult to define *a priori* the most appropriate index. This problem is conceptually identical to the search for peculiar features of man-made MFs that could be used in exposure assessment. One possible approach for solving this problem has been proposed in Refs [14, 78]. It involves two stages of analysis:

(i) definition of typical geomagnetic field disturbances, if any, that could be considered hazardous to human health;

(ii) determination of the health-hazardous attributes of such fields. In this section we present results and proposals related to this approach; moreover, we discuss the possibility of forecasting the occurrence of the most bioeffective geomagnetic storms.

4.1 Medical statistical data and storm-related cosmic-ray Forbush decreases

4.1.1 Analysis of medical data. The number of daily cases of selected diseases collected in Moscow (1979 – 1981) [18, 79] and in St. Petersburg (1981, 1989 – 1990) [19, 74] have been analyzed, together with the number of daily cases of traffic accidents in St. Petersburg (1987 – 1989) [20]. These cases have been registered by Medical Emergency Services and divided for different diseases according to the diagnosis of the services' doctors. For some diseases in St. Petersburg, the number of daily cases verified by medical diagnosis in hospital was also available. The following pathology data have been analyzed:

(i) for Moscow 1979 – 1981: Total Ambulance calls (6,304,000 cases), Myocardial Infarction (85,819), Brain Stroke (98,625), Hypertension (165,699), Bronchial Asthma (161,617), Sudden Death (71,753), Heart Rhythm Disturbance (146,545), Automobile Trauma (19,422), Street Trauma (non-vehicle) (93,069), Epilepsy (53,613);

(ii) for St. Petersburg 1981: Total Ambulance (1,314,200 cases), Myocardial Infarction (14,248), Verified Myocardial Infarction (3,924), Total Trauma (84,533), Trauma due to Alcoholism (32,990), Psychiatric (14,067), Verified Psychiatric (8,517);

(iii) for St. Petersburg 1987-1989: Traffic Accidents (17,005 cases);

(iiii) for St. Petersburg 1989 – 1990: Myocardial Infarction in hospital (15,543 cases) and Death for Infarction in hospital (3,065 cases).

The large amount of data available made it possible, in principle, to investigate rather small variations; therefore, for studying the effect of geomagnetic storms, it was necessary to clean up the data for big periodical variations of social and meteorological origin.

Three main recurrent variations have often been observed in different pathologies: annual, 15.3-day and 7.0-day. The 15.3-day period is due to a semi-monthly signal most likely related to the discrete payment of wages in Russia. The 7.0-day periodicity is due to a very stable non-sinusoidal signal connected to the weekly structure of social life; the minimum values are usually found on Sundays and public holidays. An example of recurrent variations of social origin is given in Fig. 9. The data processing procedure was based on the evaluation of the average amplitudes and phases of recurrent social and meteorological variations, and the correction of the data for these effects.

4.1.2 Correlation with geomagnetic indices. The data, cleaned up by annual, weekly and semi-monthly effects, were analyzed in connection with interplanetary disturbances, by using different indices of magnetospheric and geomagnetic activity. It was found that only myocardial infarction, brain stroke and traffic accidents rates were sensitive to geomagnetic perturbations. In Figure 10 the obtained results for different indices of the geomagnetic perturbation are shown: different levels of geomagnetic activity usually correspond in regular way to different levels in pathology rates. The most remarkable and statistically significant effects have been observed, as a rule, during days of geomagnetic perturbations determined by the days of the declining phase of Forbush decreases (FDs) in cosmic-ray (CR) intensity. These results are given in Table 1, showing that during days of geomagnetic perturbations, determined by the cosmic ray index, the average numbers of infarctions, brain strokes and

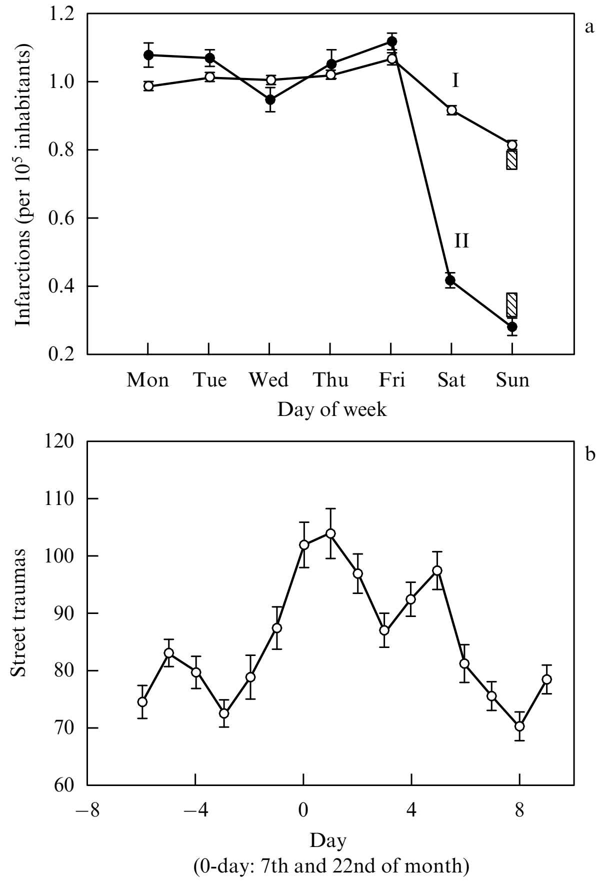

Figure 9. (a) Weekly average variation in the infarction rate in Moscow 1979 – 1981 (*I*) and St. Petersburg 1981 (*II*); the rectangular symbols indicate the mid-week festivity average values for the two cities. (b) The bi-monthly average variation in Street Trauma (non-vehicle) in Moscow (1979 – 1981) [18, 19].

Table 1. The effect of strong geomagnetic field disturbances on mortality data. Results from [18 – 20, 74]. The probability P that the distribution of the data in FD days could be obtained as a casual sample of the total data distribution is given.

Data	A,† %	B,‡ %
Infarction, Emergency Service, St. Petersburg, 1981	14.0 ± 5.5 ($P = 2 \times 10^{-2}$)	
Infarction, Emergency Service, Moscow, 1979 – 1981	12.5 ± 1.5 ($P = 10^{-10}$)	10.5 ± 1.2
Infarction, Hospital Admission, St. Petersburg, 1989 – 1990	6.5 ± 2.0 ($P = 2 \times 10^{-3}$)	
Brain stroke, Emergency Service, Moscow, 1979 – 1981	7.0 ± 1.7 ($P = 10^{-4}$)	7.0 ± 1.7
Traffic Accidents, Emergency Service, St. Petersburg, 1987 – 1989	17.4 ± 3.1 ($P = 7 \times 10^{-7}$)	17.4 ± 3.1

† A — the ratio of infarctions, brain strokes and traffic accidents at FD days to those at non-FD days.
‡ B — the average incidents of infarctions, brain strokes and traffic accidents at FD days relative to non-FD days.

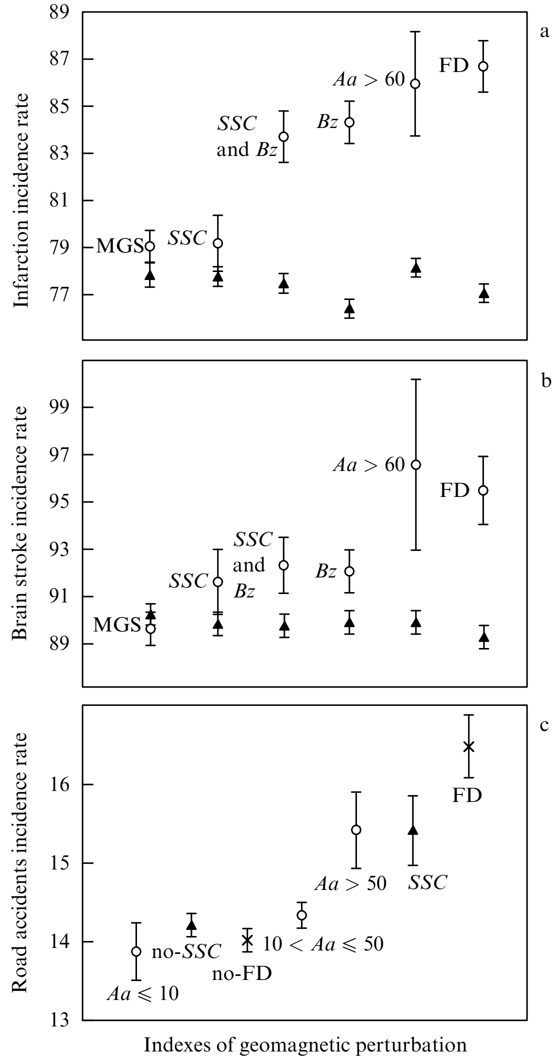

Figure 10. Daily mean incidence rate for myocardial infarction (a), brain stroke (b) (Moscow, 1979 – 1981) and traffic accidents (c) (St. Petersburg, 1987 – 1989) during geomagnetic disturbances defined by different indices described in the text. MGS, major geomagnetic storms; *SSC*, sudden commencement of geomagnetic storms; *Bz*, vertical component of the interplanetary geomagnetic field; *Aa*, geomagnetic activity index; FD, decreasing phase of Forbush effects in cosmic ray intensity. For (a) and (b) the filled triangles indicate the mean values of myocardial infarctions and strokes computed during quiet days (days not included in the corresponding criterion of selection) [20, 79].

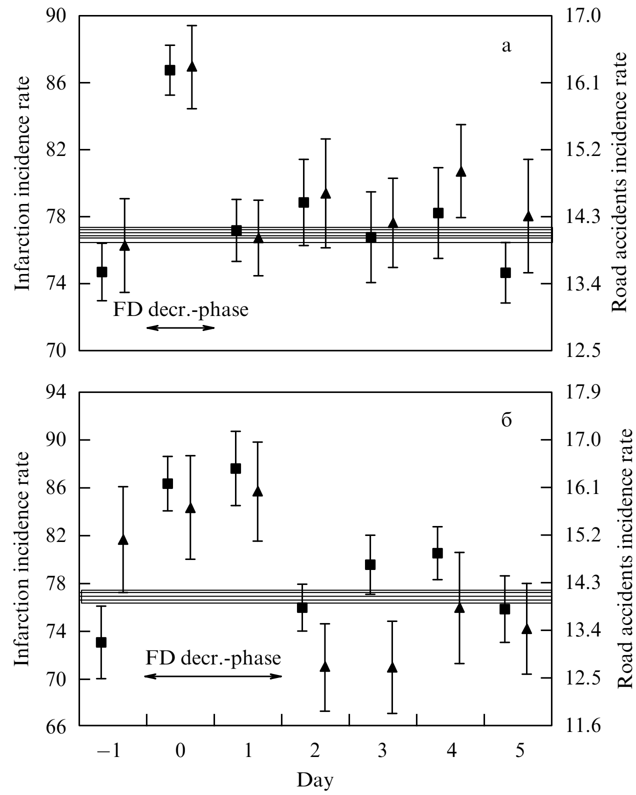

Figure 11. Incidence rate of myocardial infarction (filled squares, Moscow, 1979 – 1981) and road traffic accidents (filled triangles, St. Petersburg, 1987 – 1989) during the time development of Forbush decreases (FDs), for different duration T of the FD decreasing phase: (a) $T < 1$ day (25 FDs for infarctions and 55 for accidents); (b) $1 < T < 2$ days (30 FDs for infarctions and 30 for accidents). The shaded band indicates the average incidence rate of infarctions and accidents on quiet days (i.e. not in the descending phase of FDs) [80].

traffic accidents increase by a factor 1.105 ± 0.012, 1.070 ± 0.017 and 1.174 ± 0.031 respectively.

4.2 Incidence of infarction and traffic accident rates during FDs

In Ref. [80] the authors showed in more detail the effect on pathology rates during the time development of FDs. All FDs have been divided into three groups, according to the time duration T of the decreasing phase; the first group: $T < 1$ day; the second group: $1 < T < 2$ days; the third group: $2 < T < 3$ days; then, the average incidence of infarctions and traffic accidents was computed beginning from one day before the FD-onset till 5 days after. In Figure 11 we show the results of this computation only for the first and second groups, the number of events in the third one being too small. For the first group the average daily incidence of infarctions and traffic incidence increases only on the first day of FDs; no effect is observed during the recovery phase (that usually lasts for several days). Also for the second group the increase in incidence rates is observed only during the 2-day period of the decreasing phase of FDs. These results can be understood if one takes into account the commonly accepted mechanism of formation of FDs (see, for instance, Ref. [81]). The declining phase of FDs is observed when the Earth is crossing an interplanetary region characterized by strong disturbances in solar wind velocity, plasma density and frozen-in solar plasma MF (interplanetary shock waves, discontinuities in solar plasma streams, coronal ejected magnetic clouds, etc.), generated by energetic solar flares (see Fig. 8). Long-lasting (> 1 day) disturbances are often associated with more than one solar flare. The interplanetary disturbances interacting with the Earth's magnetosphere produce big geomagnetic storms and geomagnetic field fluctuations over a wide frequency range. When the disturbed region of solar plasma, with frozen-in MF, overtakes the Earth, the CR intensity starts to recover by diffusion processes from undisturbed regions. In the region of solar plasma between the flare-generated disturbance and the Sun there are usually quiet conditions, and no big geomagnetic perturbations are observed when this plasma reaches the Earth. Therefore, it is understandable why we observe a connection between FDs and some pathology rates only during the declining phase of CR intensity. We wish to emphasize that FDs are merely indicators of special geomagnetic storms, characterized by MF perturbations especially bioactive. In other words, FDs appear to help us distinguish this special category of health-hazardous geomagnetic storms from all other types.

4.3 Forecasting bioeffective geomagnetic storms with cosmic rays

In the previous section we concluded that the main cardiovascular diseases, as myocardial infarction and brain stroke, and also car accidents show a statistically significant increased frequency during a special kind of geomagnetic storm. The indicators of these bioeffective geomagnetic disturbances are Forbush decreases in CR intensity and the most health-hazardous days correspond to the decreasing phase of such events. If we take into account that the average duration of the decreasing phase is about 1.5 days, for each Forbush decrease the average increase in pathology rates is expected to be: 15% for infarction, 10% for brain stroke and 25% for car accidents. The absolute number of people involved could be rather large, because of the world-wide nature of strong geomagnetic storms. Moreover, it is well known that geomagnetic storms adversely affect high technology systems. High frequency radio communications are disrupted, electric power distribution grids are blacked out when geomagnetically induced current causes safety devices to trip, and atmospheric warming causes increased drag on satellites [82, 83]. It would be rather important to develop a method able to forecast the occurrence of big Forbush decreases. By the analysis of CR data we can 'see' the moving magnetic clouds and interplanetary shocks 15–20 hours before they reach the Earth, measure their velocity and other parameters and predict with high probability if a magnetic storm will be observed on Earth or not, giving the expected time of commencement the geomagnetic storm, and the expected duration and strength. In this way it would be possible to apply proper preventive procedures to road traffic and people subject to cardiovascular risk and also to technological devices.

The main features observed in CR intensity that can be used for FD forecasting are the following (Refs [80, 84] and refs. therein):

(i) the CR increase occurring before the beginning of FDs [85, 86]. The discovery of this effect stimulated the development of theories [87, 88] and further analyses [89, 90], showing that this effect is produced by particle interaction and acceleration by interplanetary shock waves;

(ii) the CR decrease occurring before the beginning of FDs [91, 92]. This effect was analyzed recently both theoretically [89] and experimentally on the base of the network of CR stations [90]. The predecrease effect may be due to the magnetic connection of the Earth with regions (moving from the Sun) with reduced CR density; this lower density may be observed at the Earth along the actual direction of MF lines [93–97].

(iii) the CR fluctuations before FDs. Many authors have found peculiarities in the behavior of CR fluctuations before FDs: changes in the frequency spectrum; the appearance of peaks in the spectrum at some frequencies; and variations in some special parameter introduced for characterizing the variability of fluctuations [98, 99]. The results obtained are often contradictory; sometimes CR fluctuations appear as reliable phenomena for FD prediction, as expected from additional Alfven turbulence produced by the kinetic stream instability of low-energy particles accelerated by shock waves [100], sometimes not [80].

The origin of all these phenomena is known, although adequate mathematical models have not yet been developed. Experimental analyses of these precursory effects are very difficult because of the small amplitude and short duration of the phenomena. Also theoretical studies are complicated because of the complex origin of these phenomena. For a practical realization of geomagnetic storm forecasting it will be necessary to get data from most CR stations in real-time (at present the data are available only after some months). The organization of this real-time data collection and computer processing, for providing a reliable forecast-service of FDs and other dangerous space phenomena [84], is under investigation.

5. Biomedical effects of man-made ULF – ELF electromagnetic fields

The biological effects of artificial ultra-low frequency (ULF: 0.001 – 10 Hz) and extra-low frequency (ELF: 10 – 300 Hz) MFs have been investigated at several levels: human studies (basically epidemiological), animal experiments, and cellular studies.

5.1 Epidemiological studies

Reports of symptoms such as headache, fatigue, pain in the region of the heart, dizziness and insomnia in extra high voltage switchyard workers occupationally exposed to low-frequency electric and magnetic fields appeared in the 1960s. Beginning from 1979 with a study by Werthmeier and Leeper [101] a body of epidemiological evidence suggested an association between residential or occupational exposure to electromagnetic fields and an increased incidence of cancer in children and adults (see review papers [3, 4, 9, 102, 103]).

The observed effects found in numerous epidemiological studies are illustrated in Table 2. However, a similar volume of negative results can also be found (see, e.g., Refs [1, 2, 128]). In particular no correlation was found between acute myocardial infarctions and the actual intensities of 50 Hz MFs in the places of residence [129].

The major weakness in many epidemiological studies was the lack of measurements of MF exposures. Exposure estimates for residential studies were based on 'wire code', a coding system devised by the researchers to describe the size and configuration of the nearby electrical distribution lines, as well as the distance from those lines. Exposure estimates in occupational studies were mostly based on job titles. In recent papers there are sometimes measurements of MFs at the site; however, exposure assessment is still a weak point in the research in the field of possible influence of MFs on humans, as will be discussed in Section 7.2.

5.2 Biological studies

In vivo and *in vitro* studies of the effects of weak ULF – ELF electric and magnetic fields have been carried out to address the areas of interest indicated by the results from epidemiological studies. The most significant effects observed in humans and animals exposed to electric and magnetic fields appear to be directly or indirectly associated with the nervous system. This relationship might be anticipated, since the nervous system is composed of tissues and processes that are very sensitive to electrical signals. In addition, both the structure and function of this system are fundamentally

Table 2. Effects from exposure to electromagnetic fields observed in epidemiological studies.

Field sources	Observed effects	Ref.
Power substations, 50 Hz	Headache, fatigue, pain in the region of the heart, dizziness and insomnia among workers	[104 – 107]
Industrial fields, 50, 60 Hz	Strong headache, increased exhaustibility, depression and suicides	[108 – 113]
Pulsed electromagnetic field and MF, 60 Hz	Increased mortality in exposed workers due to accidents	[113]
Power lines, 50, 60 Hz	Increase in the incidence of coronary heart disease in people living near main electrical supply cables;	[106]
	Increased risk (1.5 – 3 fold) of leukaemia and brain tumours among children and adults living near power lines	[114 – 117]
'Electrical' workplaces	Increased level of some forms of leukaemia, brain tumor, and male breast cancer for some electrical occupations	[112, 113, 118 – 121]
MF from trams	Excess in male breast cancer among exposed workers	[122]
MF from AC (16.67 Hz) trains	Increased risk (2 – 3 fold) in chronic and acute lymphocytic leukaemia among engine drivers and conductors	[123, 124]
	2-fold increased risk of leukaemia mortality among engine drivers	[125, 126]
MFs from DC trains	Increased risk of cardio-vascular disease among exposed workers	[13, 14, 127]

Table 3. Effects from exposure to electromagnetic fields observed in biological studies on nervous and cardiovascular functions.

Field conditions	Observed effects	Ref.
MF, ELF – ULF 40 μT – 1.3 mT	Alterations in electroencephalogram, in humans and animals	[130, 131]
MF 50 Hz, 100 μT	Decreased reaction time, no effect on cardiovascular function in humans	[132]
MFs 5 Hz	Adverse effects on verbal memory	[133]
MF 0.2 Hz, 0.5 – 1.1 mT	Increase in reaction time in humans	[134]
MF 50 Hz modulated by MF at 1 Hz, 40 μT – 1.26 mT	Impairment of the learning ability in humans	[131, 135]
Electric and MFs (9 kV m^{-1}, 20 μT)	Decrease in the cardiac rhythm in humans	[111, 136, 137]
MF 60 Hz, 20 μT	Decrease in heart rate variability in humans	[138, 139]
MF 60 Hz, 10 Hz	Enhancement in memory functions in rats	[140, 141]
MF 60 Hz, 50 μT	Impairment of task performance in rats	[142]
MF 50 Hz, 2 T	Stimulation of the heart's diastolic phase in dogs	[143]
Time-varying MF inducing current densities > 1 A m^{-2}	Neural excitation, irreversible biological effects, such as cardiac fibrillation	[144 – 146]
MF ELF with magnitudes typical of geomagnetic variations	Increase in the cardiac rhythm of variations sedentary pigeons	[147]
Pulsed MF with repetition rate (4.5 – 50 Hz, 10 mT)	Increase in beating rate of rat and canine cardiac tissue; dysrhythmia at some particular frequencies	[148]
Electromagnetic fields 8 Hz, 1 V m^{-1}	More intensive development of infarction in rabbits	[149]

involved in the interaction of a living being with the environment.

Some effects observed in humans, animals and tissues exposed to ULF – ELF MFs are summarized in Table 3. No effects of MFs on blood pressure have been found [132, 138]. Overall, these studies suggest that nervous and cardiovascular functions appear to be significantly susceptible to low-frequency MFs.

No evidence suggesting a direct effect of electric or magnetic field exposure on mutagenesis or cancerogenesis have been observed for *in vivo* studies in animals exposed to sinusoidal 60 Hz (see, e.g., Ref. [5]). However, tumour growth was inhibited in a few experiments in which animals were exposed to pulsed MFs [150].

Another possible approach has been suggested: a cocancerogenesis system in which the electromagnetic field exposure is used as a promoter following an initiating event (chemical or ionizing radiation) (see reviews [5, 10]). For instance, it was reported recently [151, 152] that exposure to electromagnetic fields may enhance the development of cancer in animals that have been treated with chemical cancirogens.

At the cellular level, there is growing consensus that the cell membrane is the site of action for the fields (Refs [10, 153, 154] and refs. therein). It appears that signal transduction occurs at the cell membrane, and that many of the effects observed in studies with cultured cells may be a consequence of changes in membrane-bound ion channels or receptors [155].

5.3 Results relevant to bioeffective characteristics of MFs

We will focus upon the following findings from biological studies that may be important in determining the bioeffective parameters of both natural and man-made MFs.

(i) 'Window' effects. Many results lead to the conclusion that biological effects of MFs take place only at particular combinations of frequencies and magnitudes and, in many cases, depend on the polarity of the field relative to the Earth's MF, the so-called window effect (see, e.g., Refs [3, 39, 153, 156]).

(ii) ULF range. There are indications that in some cases, especially when central nervous and cardiovascular systems are involved, the biological effects may be more pronounced for ULF fields than for higher frequencies [157]. For instance, neurophysiological effects in monkeys were observed to have different field intensity thresholds at different frequencies: for a 7-Hz field (ULF) the threshold is lower than for fields at 60 Hz and 75 Hz (ELF) [158]; the authors linked this result to the fact that ULF fields are in the frequency range of normal brain wave activity. A recent study [159] of field effects on a specific brain activity known as rhythmic slow activity, or theta rhythm, which occurs in 7 – 15 s bursts, provided evidence that a 1 Hz MF (56 and 560 μT, but not 5.6 μT) triggered an irreversible destabilization of the theta rhythm in the brain tissues of rats. Fields at 60 Hz did not show statistically significant results. It was also reported that 0.01 T MFs (4.5 – 6 Hz, 20 – 25 Hz and 40 – 55 Hz) can modify spontaneous rhythms of the mammalian myocardium (rats and dogs) with an adverse correlation between the cardiac mass and the effective frequency of a pulsed MF [148].

Studies of some parameters of the blood system of rats exposed to MFs in the frequency band 0.01 – 100 Hz (0.005, 0.05 and 5 μT) revealed that bioeffects are predominantly significant at frequencies lower than 12 Hz; in particular it was found that the frequencies 0.02, 0.5 – 0.6, 5 – 6, 8 – 11 Hz were the most bioeffective [157]. Special experiments on volunteers [160] where the frequency was varied from 1 to 75 Hz (0.001 – 0.75 μT) revealed that their sensitivity to MFs was more pronounced at 10 Hz frequency.

(iii) Irregular waveforms, transients, sharp changes. Research on human subjects [131, 138, 160], as well as several other studies (see, e.g., Ref. [161]) have suggested that intermittent fields (i.e. changes in the steady state of the field) and irregular wave forms of fields, are more biologically effective than steady state fields with regular sinusoidal wave forms. In humans, for example, the effects of exposure on the cardiac interbeat interval [111] and on electroencephalograms [131] were more pronounced when the subjects were exposed to an intermittent MF, compared with exposure to a steady state field of the same flux density. Disruption of the nocturnal rise in the hormone melatonin in rats due to sudden inversions of the DC MF level and to pulsed MFs have been reported [162, 163]. Intermittent exposure may produce stronger effects because the subject might be more sensitive to the transient signals created when the field is switched on and off [132]. Indeed, on the basis of a study on mortality among telephone-line men, it was found that individuals working in an occupational environment characterized by high intermittent peak exposures and by rapid changes in MF direction, are at higher risk of leukaemia than those with a constant exposure level [120].

In conclusion, there is evidence, from studies mainly performed on central nervous functions, electro-encephalograms and the cardiac interbeat interval, that intermittent fields and components in the ULF (0 – 10 Hz) band may be more bioeffective than the predominantly sinusoidal power line fields at 50 – 60 Hz.

6. Transport MFs and cardiovascular diseases

In Section 5 it was shown that at least central nervous and cardiovascular systems are rather sensitive to sharp changes in amplitude and direction of MF and to components at frequencies lower than 15 Hz. In Section 2 it was shown that these characteristics are typical of natural geomagnetic fields: they exhibit a complex superposition of variations with different amplitudes and frequency composition, predominantly in the ULF band, irregular waveforms and transients (see Fig. 2). In the present section we will consider man-made sources of such irregular fields in our environment.

6.1 Man-made ULF MF environment: complex-spectra fields from electric transport

6.1.1 Temporal and spatial characteristics of ULF MF environment. Measurements performed in Refs [28, 164] revealed that the DC operated San Francisco Bay Area Rapid Transit System (BART) was a powerful generator of ULF MFs detectable throughout the Bay Area (100 km). The primary source was identified to be the large current loops formed by the third rail, the BART trains, the running coils, and the substations, providing the DC power. The MF measured at a location 100 m from the tracks is predominantly vertical and has irregular variations, but it is possible to distinguish periodic bursts of heavy activity at 0.002 – 0.003 Hz which correspond to the schedule of trains (Fig. 12, upper plot). The amplitudes for the Wednesday field data are much greater than the corresponding amplitudes for the Sunday data (the BART system did not work on Sundays during the time of measurement, in March 1978) (see Fig. 12). Geomagnetic activity was moderate on Sunday, March 29 ($Ap = 14$) and high on Wednesday, March 26 and March 27 ($Ap = 49$ and 70) because a geomagnetic storm began on March 26. Having this information in mind, the authors concluded that BART increased the ULF MF amplitudes by 2 – 3 orders of magnitude.

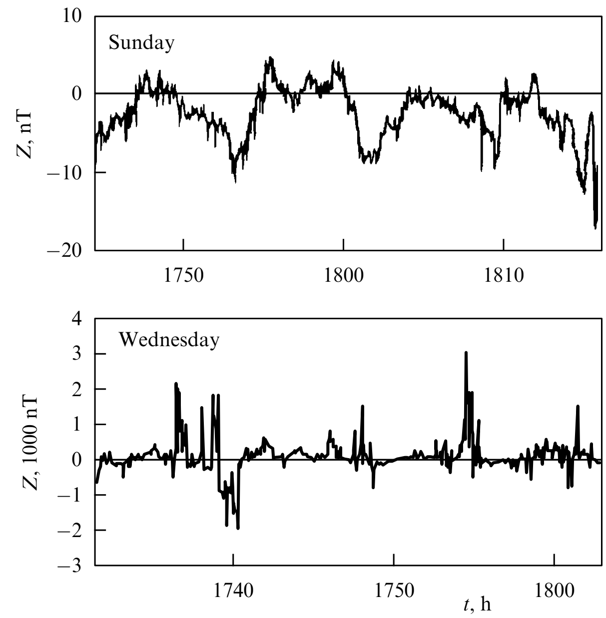

Figure 12. Time domain plots of the variation of the vertical component of the MF measured at Laney College on Sunday, March 26, 1978 (top panel), when BART was not in operation, and on Wednesday, March 29, 1978 (bottom), when BART was operating. A bandwidth of 0.001 – 4 Hz was used for these recordings. Note the large difference in the size of the units used for the two vertical MF scales [28].

To recognize the characteristic peculiarities, the dynamics and distribution of ULF MFs in a big industrial city, special continuous monitoring of the magnetic environment in the frequency range 0.001 – 10 Hz was performed in St. Petersburg [19, 33]. Measurements were done downtown at a point located ∼ 100 m from the tram and subway lines during January – February 1994. The summarizing results are presented in Fig. 13. Measurements revealed that man-made MFs in this frequency range were mainly produced by trams and subway trains powered by direct currents (DC). The maximum man-made amplitudes were registered in the Z-component from moving trams. The most prominent signals look like peaks in the Z-component in the frequency range 0.05 – 0.2 Hz with amplitudes up to 1 μT. These peaks often appear in sequences, with duration of 3 – 30 min, and in

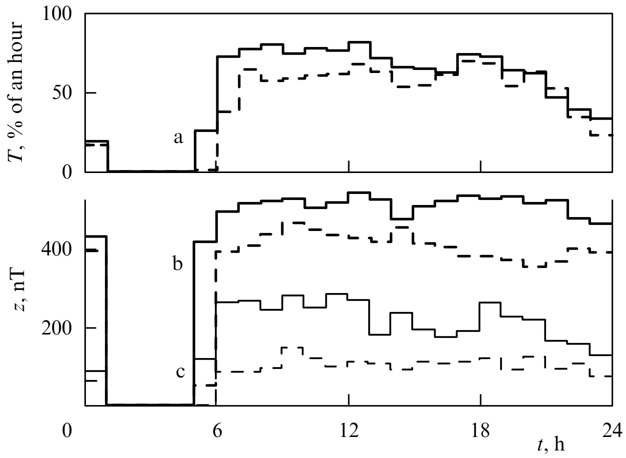

Figure 13. Diurnal variation of the MF vertical component features measured in the center of St. Petersburg during working days (full lines) and week-ends (dotted lines): hourly occurrence rate (a) and average amplitude (b) of peaks (0.05 – 0.2 Hz); hourly average amplitude (c) of slow variations (0.0013 – 0.005 Hz) [19]. T, % of the time over which the peaks were observed.

general they look like natural $Pc2 - Pc3$ pulsations, but with a much greater amplitude. For instance they are greater, by a factor of $10^3 - 10^4$, than $Pc2 - Pc3$ pulsations observed during moderate geomagnetic activity (local K-index equal 3).

The second type of prominent fluctuations, observed in the Z component, consist of long periods (200 – 800s) of increased field amplitude; these long-period ‘waves’ are similar to natural $Pc5$, $Pc6$, $Pi3$ geomagnetic pulsations (below 0.005 Hz). These technological long-period MF ‘waves’ have positive polarity and can be as strong as 0.5 μT.

In general, transport-related MFs in the ULF range recorded at tens of meters from transport lines look similar to records of natural MFs during geomagnetic disturbances. The magnitudes of MF fluctuations during big interplanetary-driven geomagnetic storms can be 0.4 – 0.5 μT at the latitude of St. Petersburg. The intensity levels of transport-related MFs decrease with distance from the sources; they become of the same order of magnitude as natural MF variations at a distance of 50 – 100 meters.

6.1.2 MFs on board and near electric trains

(a) General characteristics. There have been some studies in recent years on MFs produced by electric traction. The measurements were made in traditional electric trains and in modern Maglev-type (magnetic levitation) high-velocity trains. Usually, the instruments used for MF surveys were sensitive only to a relatively narrow frequency band, centered either on 50 (60) Hz or on other specific frequencies (e.g. 16.67 Hz). These devices have been successfully utilized for measuring sinusoidal MFs from power lines, industrial and domestic electrical appliances. Recently, more sophisticated magnetometric systems, such as ‘Multiwave’ [165], have been developed. From measurements made by this kind of instrumentation it appeared that MFs from electric traction are different from power line fields: they exhibit complex frequency spectra that are highly variable with time. Typically, the greatest components of transport MFs are below 15 Hz [154, 165]. In Maglev TR-07 about 80% of the time-varying MFs were at frequencies below 47.5 Hz [11].

The amplitudes of transport fields depend on the particular railway system, frequency range and point of measurement. Measurements at 16.67 Hz [166] made on a platform directly above the contact wire for electric traction, revealed MF amplitudes in the range of 10 – 20 μT when an AC train passed (Germany). Measurements performed inside two types of locomotives of the AC Swiss railway system (16.67 Hz) revealed that in the more modern types the maximum MFs were less than 200 μT; in the other engine-type locomotives the maximum field strength is in the range 1640 – 6170 μT [167]. In Sweden, measurements in electric locomotives (AC, 16.67 Hz) showed fluctuations of about 0.5 – 100 μT in the frequency range 10 – 1000 Hz [168]. Static MFs, in the range 16 – 64 μT and up to 15 mT, were observed in the British DC electric transport system; time-varying MFs were recorded in the range 5 – 50 μT at 50 Hz and up to 15 mT at 100 Hz near facilities [34]. MFs measured in the last carriage of an Amtrak train in the USA showed amplitudes of up to 30 μT at 60 Hz and up to 65 μT at 25 Hz [24]. Measurements performed in Japan [35] revealed that transport MFs were as follows: substation 0.3 – 3 μT; railway station 0.2 – 10 μT; DC train 0.5 – 5 μT (static MF: 50 – 200 μT); AC train 0.2 – 150 μT (static MF: 100 – 4000 μT); AC/DC train 0.5 – 75 μT (static MF: 200 – 1000 μT); and AC/DC locomotive less than 4 μT (static MF: 50 μT). The maximum values around facilities and power-running devices were several times greater than these [35].

In passenger compartments of the Maglev TR07 train (Germany) the average field levels ranged for alternating fields from approximately 10 μT near the floor of the vehicle to approximately 2 μT at standing head level [11]. Except for the strong height dependence (Fig. 14), the MFs did not depend strongly on the location within the passenger compartment. The static MF level near the floor was ∼ 80 μT and reduced to 50 μT at standing level. Static fields were more spatially variable, but slightly more stable over time than alternating or time-varying fields. Within the waiting area of the passenger station time-varying MF levels produced by the passing vehicles were approximately 2 μT.

(b) ULF range. In the present section we will show the results of magnetic measurements on board electric trains of the Russian railway system [13, 14, 129] by means of a special computer-based magnetometric system designed by SPbFIZ-

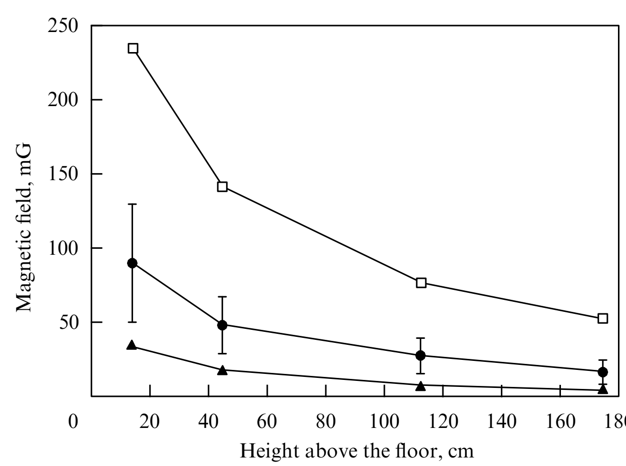

Figure 14. Minimum (▲), average (●), and maximum (□) time varying MF in the low-frequency (5 – 45 Hz) band measured in the passenger compartments of the TR07 vehicle for various heights above the floor [11].

MIRAN (Russia) that allows the recording of fields in 0 – 200 Hz frequency band. Particular attention was paid to MFs in the ULF band for the following reasons: (i) the ULF band has been poorly studied in the past; (ii) this frequency band may have a significant biological meaning, as indicated by biological studies; (iii) natural geomagnetic field variations in the ULF band show significant correlation with increases in coronary heart disease, brain strokes and car accidents (see Section 4).

Measurements were performed in DC electric locomotives (EL) and suburban trains (EMU). Suburban trains are made up of a number of electric motor units and units without motors; the drivers' carriages are not motor units. Both type of trains have an overhead 3000 V supply; the current return is via the running rails. The three components of the MF, X and Y in the horizontal plane (with X oriented along the rails) and vertical Z oriented downward, were recorded with a time resolution of 0.1 s. Figure 15 [14] shows a MF record in the range below 2 Hz in a driver's carriage of an EMU train. We can see here that the MF records show pulses of different amplitude, duration and repetition rate with main components in the range 1 – 20 s.

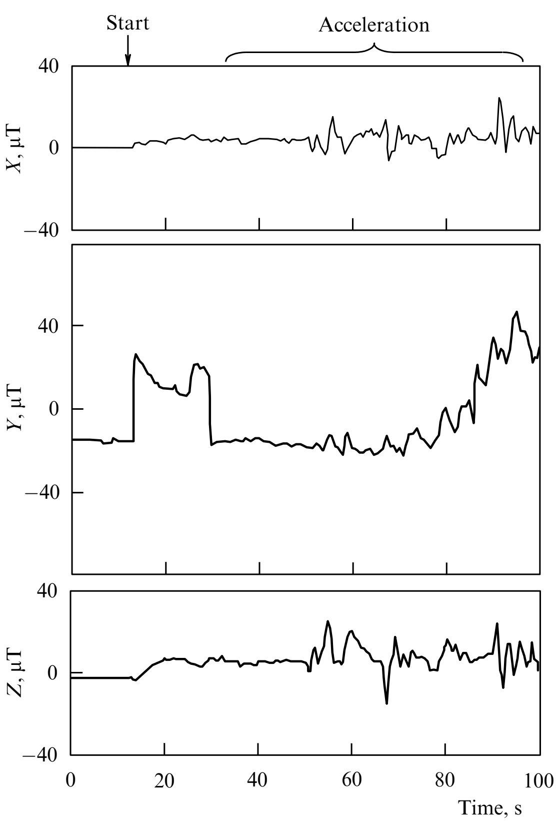

Figure 15. ULF magnetic fields (X, Y, Z components — see text) in the driver's carriage of a moving DC electric-motor-unit (EMU) train [14].

Figure 16 [169] shows the MF variations measured in the driver's carriage (without a motor) and in motor carriages of an EMU-train during a 100-min route.

The highest MFs have been found in the horizontal Y component perpendicular to rails. Typical MF fluctuations in the driver's cab of an EMU-train were found to be 10 – 20 μT, with maximum values of 50 – 60 μT in the Y-component. Fluctuations in the X and Z components are usually several times lower. In a motor-carriage of an EMU and in the

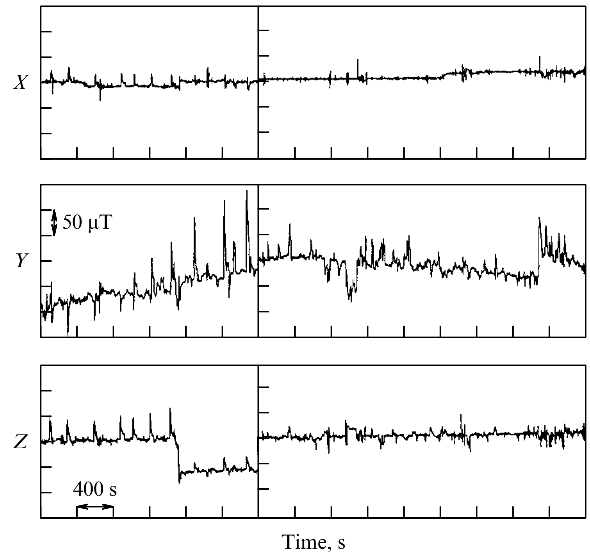

Figure 16. ULF magnetic fields (X, Y, Z components — see text) measured 1 meter above the floor in different locations inside an Electric Motor Unit (EMU) train. Left panels: inside carriages with engines; right panels: inside carriages without engines. Adapted from [169].

driver's cab of an EL average levels of MF fluctuations are of the same order of magnitude, 80 – 120 μT; maximum levels can be much higher.

Overall these measurements show that transport MFs are quite different from the predominantly sinusoidal power line fields, they exhibit a complex combination of irregular variations, sharp changes in amplitudes and direction during acceleration or when passing substations. The level of transport MFs is considerably higher than for power lines, comparable and often much higher than the Earth's MF (35 – 65 μT).

6.2 Weekly variation of myocardial infarction and transport MFs

Since MFs from electric transport show irregular complex-spectra patterns, as do natural magnetic storms, health effects through coronary heart diseases (CHD) can also be expected in a population exposed to such fields, namely engine drivers and passengers. Let us consider such a possibility in this section.

Analyzing the medical statistical data from the Emergency Services of Moscow and St. Petersburg it was found in Refs [18, 19] that the most remarkable feature in the periodic structures of the medical data of pathologies connected to nervous and cardiovascular systems, such as infarction and brain stroke, was the presence of a 7-day variation with the minimum at weekends. The most pronounced effect is observed in the myocardial infarction data from St. Petersburg. The incidence decreases at weekends by 70% in St. Petersburg infarction data, by 20% in Moscow infarction data (see Fig. 9a) and by 10% in Moscow brain stroke data (not available for St. Petersburg). The authors considered the possible reasons for such weekly behavior in infarction and brain stroke rates. The absence of a 7-day periodicity in some other diseases indicates that the main origin of this periodicity with a minimum on Saturdays and Sundays is not connected with a decrease in the population level during these days. Moreover, infarction and brain stroke show an average incidence, during mid-week holidays, equal, within the statistical errors, to their average Sunday-value. This result shows that the 7-day periodicity cannot be considered as a social synchronization of an endogenous 7-day rhythm, but is related to the social organization of life based on periods of working days and days of vacation. It seemed unreasonable that a large percentage of people affected by these diseases don't call the doctor on Sundays; in that case one should expect a maximum number of calls on Mondays, but that doesn't occur.

The more obvious explanation for the weekly variation is the lower labor stress at weekends. To analyze this possibility it is very important to compare the Moscow and St. Petersburg data. For the St. Petersburg infarction data the very big reduction (70%) in pathology-rate during weekends is surprising. Supposing that for Moscow data the lower labor stress could be responsible for a great part of the 20% decrease in infarction rate during Sundays and mid-week holidays, one can assume that the maximum estimate for the labor-stress related decrease is not bigger than 20%. Thus, for St. Petersburg data the $\sim 70\%$ reduction in infarction incidence cannot be explained by labor stress effect only and in any case, it is difficult to understand why, during week-ends, people living in Moscow should be much more stressed than people living in St. Petersburg.

To explain the weekly variation in the myocardial infarction rate, it was suggested in Refs [19, 33] to consider the possible influence of technological MFs in the ULF(0 – 10 Hz) range, mainly produced by electrified transport. Figure 17 presents the weekly behavior of both incidence of infarctions and MFs in ULF range. From this plot it is clear that the dynamic pattern of man-made MF and the incidence rate of infarctions in St. Petersburg have the same characteristic features: they are almost constant during working days and have a big decrease at weekends. Therefore, in Refs [19, 33] it was concluded that possibly the decrease in infarction rate in St. Petersburg during weekends and festivities could be attributed to the decrease, during these days, of man-made MF disturbances, and also to the decrease in the population level highly exposed to transport MFs (less people using electrified transport at weekends). The lower decrease in the infarction rate in Moscow during weekends could be due partly to an increased magnetic background, in comparison with St. Petersburg, and the number of people using electric transport on these days.

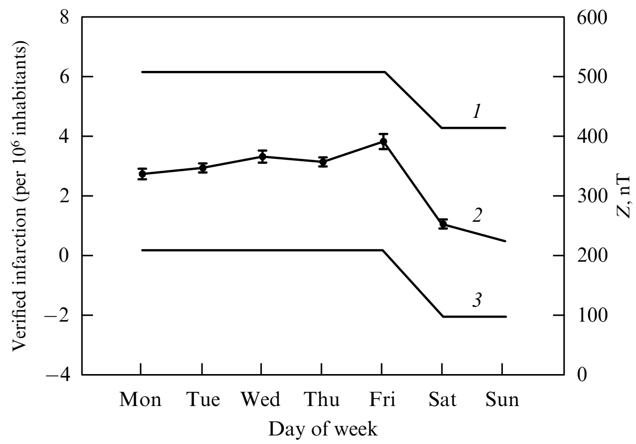

Figure 17. Average weekly variation in the amplitude of prominent fluctuations in Z-component of MF measured in the center of St. Petersburg. (*1*) peaks (0.05 – 0.2 Hz); (*3*) slow variations (0.0013 – 0.005 Hz). (*2*) the average weekly variation in the incidence rate of verified infarctions (St. Petersburg, 1981) [19].

6.3 MFs from electric transport and coronary heart disease among engine drivers

The evidence for a possible link between the man-made ULF environment and myocardial infarctions was found on the basis of the total population of St. Petersburg [19] (see Section 6.2), whereas to relate MFs to health hazards and risks in a more conclusive way, there was a need to identify a specifically exposed population, or at least populations with different exposures. In Refs [13, 14, 29, 127] the authors presented the results of a study of the relationship between ULF MF fluctuations produced by electrified railways and cardiovascular mortality (CVD) among railway workers, in particular, among engine drivers.

As was shown in Section 6.1, MFs in EL and EMU differ by a factor 2 – 4. Therefore, drivers of different types of trains can be considered differently exposed to MFs. Thus the authors performed a comparative analysis of mortality among subpopulations of drivers operating EL and EMU trains. Morbidity data according to sick-leave certificates (sick-pay to employees) were collected in railroad clinics located in different geographic zones of the former Soviet Union. The data were for 12,000 age-specified and train-specified drivers for three years (1975 – 1977). In Table 4 we show the data on the total and CVD mortality rates among EL and EMU drivers. It is seen that for each age group the mortality rate for all diseases is the highest among EMU drivers; the average mortality is 1.35 ± 0.01 times greater than in EL drivers. These differences are mainly attributable to different mortality rates in respiratory- and gastric-tract diseases, in skin diseases, in trauma and accidents. For

Table 4. Morbidity (in per thousand per year) among drivers of different types of trains: DC electric locomotive (EL), DC electric motor units (EMU). Collected from sick-leave certificates, former Soviet Union 1975 – 1977. Adapted from Ref. [14].

Disease (9th ICD)	Workplace	Age				Average
		20 – 29	30 – 39	40 – 49	50 – 59	
All cardiovascular diseases	EL	15.8	29.5	67.0	149.7	58.9 + 2.2
(CVD) (390 – 458)	EMU	–	48.4	36.3	161.3	57.6 + 2.2
Coronary heart disease	EL	1.6	2.7	13.9	40.8	12.4 + 1.0
(CHD) (410 – 414)	EMU	–	–	5.2	21.5	6.2 + 0.7
Hypertension	EL	9.5	12.0	36.5	86.2	32.0 + 1.6
(400 – 404)	EMU	–	—	25.9	129.0	35.0 + 1.7
All diseases	EL	987	1519	1298	1513	1315 + 10
(000 – 999)	EMU	1000	2484	1554	1915	1774 + 12

cardiovascular disease the situation is completely different (see Table 4). For hypertension, a regular pattern of mortality rate was not found in the different age groups and there were no significant differences, within the statistical errors, in the average mortality rates. On the contrary, for coronary heart disease (CHD), there was always the same regular pattern of mortality rate: the highest incidence being observed in EL engine drivers and the lowest in EMU engine drivers in every age group. The occupational CHD risk between these two subpopulations of engine drivers differs by a factor 2.00 ± 0.27. Moreover, the CHD incidence among EMU drivers is observed only after 40 years of age, while among EL drivers there were some cases even before 30.

The authors [13, 14, 29, 127] examined the possible roles of different risk factors for these diseases and found that the two groups of drivers were most likely equally exposed to labor-stress risks, as they were to the other 'classic' cardiovascular risk factors, related to nutrition and smoking habits, labor stress, work conditions, etc. The most remarkable difference in work conditions among the subgroups of drivers was the different exposure to ULF MFs, with the greatest level of exposure observed in the EL workplace. Consequently, it was reasonably concluded that the elevated CHD risk in EL drivers indeed could be associated with an elevated occupational exposure to ULF MFs. The lack of a significant difference between drivers for hypertension may indicate that the hypertension mortality rate does not depend on MF exposure. This agrees with the results of a statistical analysis of the influence of natural geomagnetic field variations (big geomagnetic storms) on mortality rates for different diseases [18]: there was a noticeable effect on myocardial infarction and brain stroke rates, but no effect on the hypertension rate (see Section 3.1). This was also supported by the results of biological studies in which no changes in blood pressure in humans exposed to MFs have been found [132, 138]. It should be emphasized that the contrast in CHD mortality among drivers of different types of trains is likely to be unbiased, since the medical data collection in the above studies was performed blindly, with no regard to MF exposure. These medical data were collected 15 years ago. At that time the findings were not understandable, because, generally, the EL drivers were supposed to have healthier work conditions than the EMU drivers. Consequently, it was easy to explain the lower mortality rate for all diseases in EL drivers by the better job conditions. However, this viewpoint was inconsistent with the observation of opposite results in CHD mortality, i.e. the 2-fold increased risk in EL drivers in comparison with EMU drivers. The explanation of this intriguing fact, given in Refs [13, 14, 29, 127], suggested that electric traction MFs may play an important role in initiating and promoting CHD.

7. Physical interaction of MFs with humans

7.1 Mechanisms of interaction

MFs can penetrate right through bodies since the body tissues produce a negligible reduction of the MF strength. In fact the amplitude of MF harmonics at a frequency ω in a closed loop at a depth h inside the body will be reduced by a factor f_s,

$$f_s(\omega, h, \sigma, \mu) = \exp\left(-\frac{h}{\delta}\right) , \qquad (1)$$

where the attenuation depth δ depends, according to Ref. [170], on the permeability μ (≈ 1) and conductivity σ: $\delta = c(2\pi\mu\omega\sigma)^{-1/2}$. For $\omega < 10^6$ c^{-1} we have $\delta > 10^3$ cm, then, for $h \leqslant 10$ cm we get $f_s \approx 1$.

Two general types of effects from exposure to MFs have been postulated by theoretical calculations: magnetomechanical and electromagnetic [171]. Magnetomechanical effects can lead to changes in the orientation or displacement of particles having magnetic properties. In recent years clusters or chains of magnetite crystals ('magnetosomes') were found in several living systems [172], including the human brain [173, 174]. A body of scientific evidence has been obtained indicating that these magnetic elements in migratory birds, fish and insects are capable of sensing the geomagnetic field and using this information for orientation and navigation.

The torque exerted by MF on single-domain crystals, or the elastic effects of interactive forces between smaller, supermagnetic crystals, are somehow transduced into neural impulses that convey the relevant information to specific processing centers in the brain [174–176].

The fact that an electrically conducting fluid moving in the presence of a MF produces electric currents, gave rise to several studies of magnetohydrodynamic mechanisms resulting in changes in the cardiovascular circulatory system [177, 178]. The interaction between a MF and an electric current produces forces which oppose or accelerate the movement of the conducting fluid, depending upon whether the speed of the moving MF is higher or lower than that of the liquid. For instance, in the case of static MFs and blood flow, the movement will be retarded. To produce measurable effects the MF should be in the range of 1–10 T.

Another possibility is provided by Faraday's law of induction that states that time-varying MFs generate electric fields in a closed conducting loop.

The magnetic field B includes the natural geomagnetic field B_{n} and man-made MF B_{m} and can be divided into two parts, the constant field $B_{\mathrm{c}} = B_{\mathrm{nc}} + B_{\mathrm{mc}}$ and the variable one $B_{\mathrm{v}} = B_{\mathrm{nv}} + B_{\mathrm{mv}}$:

$$B = B_{\mathrm{c}} + B_{\mathrm{v}} = B_{\mathrm{n}} + B_{\mathrm{m}} = B_{\mathrm{nc}} + B_{\mathrm{nv}} + B_{\mathrm{mc}} + B_{\mathrm{mv}} . \qquad (2)$$

The magnetic flux Φ through a closed loop with length L and surface $S = Sn$, where n is the unit vector normal to the surface, is

$$\Phi = B \times S = BS\cos\alpha , \qquad (3)$$

α being the angle between B and S. The induced electromotive force Ψ in the closed loop will be, according to Faraday's law, in the MSKA system:

$$\Psi = \int_L E\,\mathrm{d}l = -\frac{\mathrm{d}\Phi}{\mathrm{d}t}$$
$$= -S\cos\alpha\,\frac{\mathrm{d}B}{\mathrm{d}t} - B\cos\alpha\,\frac{\mathrm{d}S}{\mathrm{d}t} - BS\,\frac{\mathrm{d}\cos\alpha}{\mathrm{d}t} . \qquad (4)$$

Equation (4) shows that there are three mechanisms of generation of Ψ in closed loops within a body:

(a) time changing MF intensity inside the body,

(b) time changing of the cross-section of a closed loop in the presence of a MF,

(c) time changing of the angle α between the MFand the normal to the closed loop.

In the next chapters we will consider in detail these different possibilities to generate electromotive forces, by taking into account rotations and movements of loops related to body movements.

7.2 Electromotive forces Ψ produced by time changing MF intensity within the body

Let us consider in more detail the first term on the right-hand side of Eqn (4):

$$\Psi_1 = -S\cos\alpha\,\frac{\mathrm{d}B}{\mathrm{d}t} = -S\cos\alpha\left(\frac{\partial B}{\partial t} + \frac{\partial B}{\partial r}\,V\right)$$
$$= -S\cos\alpha_{\mathrm{v}}\,\frac{\partial B_{\mathrm{v}}}{\partial t} - S\cos\alpha_{\mathrm{c}}\,\frac{\partial B_{\mathrm{c}}}{\partial r}\,V - S\cos\alpha_{\mathrm{v}}\,\frac{\partial B_{\mathrm{v}}}{\partial r}\,V\,. \quad (5)$$

Here V is the velocity of the closed loop (which in most cases coincides with the velocity of the body) relative to the system of coordinates in which the MF is considered. The first term on the right-hand side of Eqn (5) reflects the influence of the variable part of the MF:

$$\Psi_{11} = -S\cos\alpha\,\frac{\partial B_{\mathrm{v}}}{\partial t} = -S\cos\alpha_{\mathrm{n}}\,\frac{\partial B_{\mathrm{nv}}}{\partial t} - S\cos\alpha_{\mathrm{m}}\,\frac{\partial B_{\mathrm{mv}}}{\partial t}$$
$$= S\sum_{i=1}^{l}\omega_{\mathrm{n}i}B_{\mathrm{n}i}\sin(\omega_{\mathrm{n}i}t - \varphi_{\mathrm{n}i})\cos\alpha_{\mathrm{n}i}$$
$$+ S\sum_{k=1}^{p}\omega_{\mathrm{m}k}B_{\mathrm{m}k}\sin(\omega_{\mathrm{m}k}t - \varphi_{\mathrm{m}k})\cos\alpha_{\mathrm{m}k}\,, \quad (6)$$

where we assumed that

$$B_{\mathrm{nv}} = \sum_{i=1}^{l}B_{\mathrm{n}i}\cos(\omega_{\mathrm{n}i}t - \varphi_{\mathrm{n}i})\,,$$
$$B_{\mathrm{mv}} = \sum_{k=1}^{p}B_{\mathrm{m}i}\cos(\omega_{\mathrm{m}i}t - \varphi_{\mathrm{m}i})\,, \quad (7)$$

and considered that the angle α may be different for different harmonics: $\alpha_{\mathrm{n}i}$ for the natural geomagnetic field and $\alpha_{\mathrm{m}k}$ for a man-made MF.

Let us consider the second term of Eqn (5), i.e. the case in which Ψ is produced by the movement of the loop in the presence of a space gradient in the constant part of the MF:

$$\Psi_{12} = -S\cos\alpha\,\frac{\partial B_{\mathrm{c}}}{\partial r}\,V$$
$$= -S\cos\alpha_{\mathrm{n}}\,\frac{\partial B_{\mathrm{nc}}}{\partial r}\,V - S\cos\alpha_{\mathrm{m}}\,\frac{\partial B_{\mathrm{mc}}}{\partial r}\,V\,. \quad (8)$$

In this case the contribution of the geomagnetic field B_{nc}, even in the case of a body moving with great velocity (for instance, the 8×10^3 m s^{-1} of spacecraft) is very small due to a very small value of $\partial B_{\mathrm{nc}}/\partial r$, while the contribution of the man-made MF in Eqn (8) may be much more important. The characteristic frequency of this Ψ will be $\nu_{\mathrm{mc}} \approx V/r_{\mathrm{mc}}$, where r_{mc} is the characteristic distance for the man-made MF to change by a factor e. For example, if a person runs with $V \approx 4$ m s^{-1} and $r_{\mathrm{mc}} \approx 2$ m, then $\nu_{\mathrm{mc}} = 2$ Hz which can be near to the self-frequencies of the human body. This is the case in which the resonance interaction can be realized. Let us assume that

$$\frac{\partial B_{\mathrm{c}}}{\partial r}\,V \approx \frac{\partial B_{\mathrm{mc}}}{\partial r}\,V = \sum_{r=1}^{x} b_{\mathrm{c}r}\cos(\omega_{\mathrm{c}r}t - \varphi_{\mathrm{c}r})\,, \quad (9)$$

and introduce this value into Eqn (8), thus obtaining

$$\Psi_{12} = -S\sum_{r=1}^{x} b_{\mathrm{c}r}\cos\alpha_{\mathrm{c}r}\cos(\omega_{\mathrm{c}r}t - \varphi_{\mathrm{c}r}) \quad (10)$$

for the influence of about constant part of MF, where it is accounted for that the angles $\alpha_{\mathrm{c}r}$ can be different for different harmonics $\omega_{\mathrm{c}r}$.

Now we consider the last term in Eqn (5),

$$\Psi_{13} = -S\cos\alpha\,\frac{\partial B_{\mathrm{v}}}{\partial r}\,V$$
$$= -S\cos\alpha_{\mathrm{n}}\,\frac{\partial B_{\mathrm{nv}}}{\partial r}\,V - S\cos\alpha_{\mathrm{m}}\,\frac{\partial B_{\mathrm{mv}}}{\partial r}\,V\,, \quad (11)$$

which is determined by the movement of the closed loop in presence of a gradient in the variable part of the MF. Also in this case the contribution of the natural geomagnetic field can be neglected, then the only relevant effect is due to the gradient of the variable part of the man-made MF on the moving body. Assuming that, as in Eqn (7)

$$B_{\mathrm{v}} \approx B_{\mathrm{mv}} = \sum_{k=1}^{p} B_{\mathrm{m}k}\cos(\omega_{\mathrm{m}k}t - \varphi_{\mathrm{m}k})$$

and that, as in Eqn (9),

$$\frac{\partial B_{\mathrm{m}k}}{\partial r}\,V = \sum_{j=1}^{q} b_{\mathrm{m}kj}\cos(\omega_{\mathrm{m}kj}t - \varphi_{\mathrm{m}kj})\,, \quad (12)$$

we obtain:

$$\Psi_{13\mathrm{v}} = -S\sum_{k=1}^{p}\sum_{j=1}^{q} b_{\mathrm{m}kj}\cos\alpha_{kj}\cos(\omega_{\mathrm{m}k}t - \varphi_{\mathrm{m}k})$$
$$\times\cos(\omega_{\mathrm{m}kj}t - \varphi_{\mathrm{m}kj})$$
$$= -S\sum_{k=1}^{p}\sum_{j=1}^{q} b_{\mathrm{m}kj}\cos\alpha_{kj}\Big\{\cos\big[(\omega_{\mathrm{m}k} + \omega_{\mathrm{m}kj})t$$
$$- (\varphi_{\mathrm{m}k} + \varphi_{\mathrm{m}kj})\big] + \cos\big[(\omega_{\mathrm{m}k} - \omega_{\mathrm{m}kj})t - (\varphi_{\mathrm{m}k} - \varphi_{\mathrm{m}kj})\big]\Big\}\,. \quad (13)$$

Equation (13) shows that in this case there is interference of harmonics contained in B_{mv}, according to Eqn (7), and harmonics arising from the body's movement, according to Eqn (12). As a result of this interference the induced Ψ in the closed loop is formed by harmonics of frequencies $\omega_{\mathrm{m}k} \pm \omega_{\mathrm{m}kj}$ and amplitudes $Sb_{\mathrm{m}kj}\cos\alpha_{kj}$.

7.3 Induced Ψ caused by changes in the cross-section of closed loops in the presence of MFs of natural and man-made origin

We consider here the second term in Eqn (4):

$$\Psi_2 = -B\cos\alpha\,\frac{\mathrm{d}S}{\mathrm{d}t} = -B\cos\alpha\,\frac{\partial S}{\partial t} - B\cos\alpha\,\frac{\partial S}{\partial r}\,V\,. \quad (14)$$

The first part reflects the Ψ produced by time variations of the effective cross section of closed loops (for example, the rhythmical changes in breathing, in heart beating, etc.) in natural and man-made MFs. The second part reflects the situation when the change in S is caused by the change in position of a closed loop with velocity V (e.g. the case of a moving body).

In the first part of Eqn (14), due to the change of S with time,

$$\Psi_{21} = -|B_{\mathrm{nc}} + B_{\mathrm{mc}}| \cos\alpha \frac{\partial S}{\partial t} - |B_{\mathrm{nv}} + B_{\mathrm{mv}}| \cos\alpha \frac{\partial S}{\partial t}, \quad (15)$$

the contribution of both constant MFs, of natural and man-made origin, are present and the Ψ strength is proportional to the total intensity of natural and man-made MF. Supposing that the change of S with time can be described by

$$S(t) = \sum_{j=1}^{q} S_j \cos(\omega_{sj} t - \varphi_{sj}), \quad (16)$$

the contribution of the constant MF to Ψ_{21} will be

$$\Psi_{21\mathrm{c}} = |B_{\mathrm{nc}} + B_{\mathrm{mc}}| \cos\alpha \sum_{j=1}^{q} \omega_{sj} S_j \sin(\omega_{sj} t - \varphi_{sj}). \quad (17)$$

The approximately constant part of man-made MFs in specific places, for instance inside public transport, can be much bigger than the natural field and can generate much bigger Ψ in the rhythmically changing closed loops according to Eqn (17). Let us assume that, for the effect of changes of S with time in the presence of a variable MF, the variable MF can be represented as in Eqn (7) and the change of S by Eqn (16). In this case we obtain:

$$\begin{aligned}
\Psi_{21\mathrm{v}} = & \sum_{i=1}^{l}\sum_{j=1}^{q} B_{\mathrm{n}i}\omega_{sj}S_j \cos\alpha_{ij} \cos(\omega_{\mathrm{n}i} t - \varphi_{\mathrm{n}i}) \sin(\omega_{sj} t - \varphi_{sj}) \\
& + \sum_{k=1}^{p}\sum_{j=1}^{q} B_{\mathrm{m}k}\omega_{sj}S_j \cos\alpha_{kj} \cos(\omega_{\mathrm{m}k} t - \varphi_{\mathrm{m}k}) \sin(\omega_{sj} t - \varphi_{sj}) \\
= & \sum_{i=1}^{l}\sum_{j=1}^{q} B_{\mathrm{n}i}\omega_{sj}S_j \cos\alpha_{ij} \Big\{ \sin\left[(\omega_{\mathrm{n}i} + \omega_{sj})t - (\varphi_{\mathrm{n}i} + \varphi_{sj})\right] \\
& + \sin\left[(\omega_{sj} - \omega_{\mathrm{n}i})t - (\varphi_{sj} - \varphi_{\mathrm{n}i})\right] \Big\} \\
& + \sum_{k=1}^{p}\sum_{j=1}^{q} B_{\mathrm{m}k}\omega_{sj}S_j \cos\alpha_{kj} \Big\{ \sin\left[(\omega_{\mathrm{m}k} + \omega_{sj})t - (\varphi_{\mathrm{m}k} + \varphi_{sj})\right] \\
& + \sin\left[(\omega_{sj} - \omega_{\mathrm{m}k})t - (\varphi_{sj} - \varphi_{\mathrm{m}k})\right] \Big\}. \quad (18)
\end{aligned}$$

Equation (18) reflects the nonlinear interference of different harmonics of both variable natural and man-made MF, with harmonics describing the change in time of closed loops. This interference will produce new harmonics at frequencies $\omega_{\mathrm{n}i} \pm \omega_{sj}$ and $\omega_{\mathrm{m}k} \pm \omega_{sj}$ with amplitudes $B_{\mathrm{n}i}\omega_{sj}S_j \cos\alpha_{ij}$ and $B_{\mathrm{m}k}\omega_{sj}S_j \cos\alpha_{kj}$.

We now consider the second term on the right-hand side of Eqn (14), which reflects the situation when the change of S is caused by the change in position of a closed loop in space with velocity $V = \mathrm{d}r/\mathrm{d}t$. This change of S can be rhythmical as, for example, may occur during walking, running and exercising:

$$\Psi_{22} = -|B_{\mathrm{nc}} + B_{\mathrm{mc}}| \cos\alpha \frac{\partial S}{\partial r} V - |B_{\mathrm{nv}} + B_{\mathrm{mv}}| \cos\alpha \frac{\partial S}{\partial r} V. \quad (19)$$

Assuming that $(\partial S/\partial r)V$ can be represented as

$$\frac{\partial S}{\partial r} V = \sum_{j=1}^{x} s_j \cos(\omega_{\mathrm{v}j} t - \varphi_{\mathrm{v}j}) \quad (20)$$

in the presence of roughly constant parts of the natural (B_{nc}) and man-made (B_{mc}) MFs, the contribution of B_{c} to Ψ_{22} can be written as

$$\begin{aligned}
\Psi_{22\mathrm{c}} = & -B_{\mathrm{nc}} \cos\alpha_{\mathrm{nc}} \sum_{j=1}^{x} s_j \cos(\omega_{\mathrm{v}j} t - \varphi_{\mathrm{v}j}) \\
& - B_{\mathrm{mc}} \cos\alpha_{\mathrm{mc}} \sum_{j=1}^{x} s_j \cos(\omega_{\mathrm{v}j} t - \varphi_{\mathrm{v}j}). \quad (21)
\end{aligned}$$

Here we have allowed that the angles α_{nc}, α_{mc} between the normal to the closed loop and the direction of MF may be different for the natural and man-made fields. In Eqn (21) the first term on the right-hand side reflects a mostly natural situation, to which people have adjusted by long-term evolution. The second term, which reflects the influence of the constant part of the man-made MF, can be more important, especially in urban and technological areas, including public transport.

We now consider the second term on the right-hand side of Eqn (19), i.e. the influence of the variable part of the MF on a changing S caused by movement of the loop, by taking into account Eqns (20) and (7) for the variable part of MF. We obtain:

$$\begin{aligned}
\Psi_{22\mathrm{v}} = & -\sum_{i=1}^{l}\sum_{j=1}^{q} B_{\mathrm{n}i} s_j \cos\alpha_{\mathrm{n}i} \cos(\omega_{\mathrm{n}i} t - \varphi_{\mathrm{n}i}) \cos(\omega_{\mathrm{v}j} t - \varphi_{\mathrm{v}j}) \\
& - \sum_{k=1}^{p}\sum_{j=1}^{q} B_{\mathrm{m}k} s_j \cos\alpha_{\mathrm{m}k} \cos(\omega_{\mathrm{m}k} t - \varphi_{\mathrm{m}k}) \cos(\omega_{\mathrm{v}j} t - \varphi_{\mathrm{v}j}) \\
= & \frac{1}{2}\sum_{i=1}^{l}\sum_{j=1}^{q} B_{\mathrm{n}i} s_j \cos\alpha_{\mathrm{n}i} \Big\{ \cos\left[(\omega_{\mathrm{n}i} + \omega_{\mathrm{v}j})t - (\varphi_{\mathrm{n}i} + \varphi_{\mathrm{v}j})\right] \\
& + \cos\left[(\omega_{\mathrm{v}j} - \omega_{\mathrm{n}i})t - (\varphi_{\mathrm{v}j} - \varphi_{\mathrm{n}i})\right] \Big\} \\
& + \frac{1}{2}\sum_{k=1}^{l}\sum_{j=1}^{q} B_{\mathrm{m}k} s_j \cos\alpha_{\mathrm{m}k} \Big\{ \cos\left[(\omega_{\mathrm{m}k} + \omega_{\mathrm{v}j})t - (\varphi_{\mathrm{m}k} + \varphi_{\mathrm{v}j})\right] \\
& + \cos\left[(\omega_{\mathrm{v}j} - \omega_{\mathrm{m}k})t - (\varphi_{\mathrm{v}j} - \varphi_{\mathrm{m}k})\right] \Big\}, \quad (22)
\end{aligned}$$

where the two parts reflect the influence of the variable natural (n) and man-made (m) MF, respectively. Equation (22) shows that instead of harmonics with frequencies $\omega_{\mathrm{n}i}$, $\omega_{\mathrm{v}j}$ and $\omega_{\mathrm{m}k}$, $\omega_{\mathrm{v}j}$ we obtain, after the interaction of the variable MF with the rhythmical movement of body, a Ψ in moving closed loops characterized by harmonics with frequencies $\omega_{\mathrm{n}i} \pm \omega_{\mathrm{v}j}$ and amplitudes $(1/2)B_{\mathrm{n}i}s_j \cos\alpha_{\mathrm{n}i}$ for the natural MF and $\omega_{\mathrm{m}k} \pm \omega_{\mathrm{v}j}$ and $(1/2)B_{\mathrm{m}k}s_j \cos\alpha_{\mathrm{m}k}$ for the man-made MF.

7.4 Induced Ψ FEs in closed loops caused by changes of the angle between the normal to the loop and the MF direction

We consider here the third term in Eqn (4), which reflects the generation of induced Ψ in closed loops caused by changes of the angle α between the normal to the loop and the MF direction:

$$\Psi_3 = -BS\,\frac{\mathrm{d}\cos\alpha}{\mathrm{d}t} = -BS\,\frac{\partial\cos\alpha}{\partial t} - BS\,\frac{\partial\cos\alpha}{\partial r}\,V\,. \quad (23)$$

The first part on the right-hand side reflects the generation of induced Ψ in closed loops caused by changes with time of the angle α, and the second part the induced Ψ caused by the body movement accompanied by changes in α. We consider the first term on the right-hand side of Eqn (23):

$$\Psi_{31} = -BS\,\frac{\partial\cos\alpha}{\partial t} = S|B_{\mathrm{nc}} + B_{\mathrm{mc}}|\sin\alpha\,\frac{\partial\alpha}{\partial t} + S|B_{\mathrm{nv}} + B_{\mathrm{mv}}|\sin\alpha\,\frac{\partial\alpha}{\partial t}\,. \quad (24)$$

Let us suppose that the body rotates over some relatively short time period and this rotation can be characterized by a frequency ω_{r} and phase φ_{r}: $\alpha = \omega_{\mathrm{r}}t - \varphi_{\mathrm{r}}$. In this case the first part on the right-hand side of Eqn (24) will be

$$\Psi_{31\mathrm{c}} = S|B_{\mathrm{nc}} + B_{\mathrm{mc}}|\omega_{\mathrm{r}}\sin(\omega_{\mathrm{r}}t - \varphi_{\mathrm{r}})\,. \quad (25)$$

For the part in Eqn (24), which reflects the role of variable part of the MF of natural and man-made origin, if we suppose again that the body over some relatively short time period rotates with frequency ω_{r} characterized by a phase φ_{r}, we obtain for the variable MF described by Eqn (7):

$$\Psi_{31\mathrm{v}} = S\sum_{i=1}^{l}\omega_{\mathrm{r}}B_{\mathrm{n}i}\cos(\omega_{\mathrm{n}i}t - \varphi_{\mathrm{n}i})\sin(\omega_{\mathrm{r}}t - \varphi_{\mathrm{nr}}) + S\sum_{k=1}^{p}\omega_{\mathrm{r}}B_{\mathrm{m}k}\cos(\omega_{\mathrm{m}k}t - \varphi_{\mathrm{m}k})\sin(\omega_{\mathrm{r}}t - \varphi_{\mathrm{mr}})\,, \quad (26)$$

which can be written as

$$\begin{aligned}\Psi_{31\mathrm{v}} = S\omega_{\mathrm{r}}\frac{1}{2}\Bigg\{&\sum_{i=1}^{1}B_{\mathrm{n}i}\Big[\sin\big((\omega_{\mathrm{r}} + \omega_{\mathrm{n}i})t - (\varphi_{\mathrm{n}r} + \varphi_{\mathrm{n}i})\big)\\ &+ \sin\big((\omega_{\mathrm{r}} - \omega_{\mathrm{n}i})t - (\varphi_{\mathrm{nr}} - \varphi_{\mathrm{n}i})\big)\Big]\\ &+ \sum_{k=1}^{p}B_{\mathrm{m}k}\Big[\sin\big((\omega_{\mathrm{r}} + \omega_{\mathrm{m}k})t - (\varphi_{\mathrm{mr}} + \varphi_{\mathrm{m}k})\big)\\ &+ \sin\big((\omega_{\mathrm{r}} - \omega_{\mathrm{m}k})t - (\varphi_{\mathrm{mr}} - \varphi_{\mathrm{m}k})\big)\Big]\Bigg\}\,. \quad (27)\end{aligned}$$

Also in this case harmonics of the induced Ψ will be generated with amplitudes $(1/2)S\omega_{\mathrm{r}}B_{\mathrm{n}i}$ and frequencies $\omega_{\mathrm{r}} \pm \omega_{\mathrm{n}i}$ for the variable natural MF and with amplitudes $(1/2)S\omega_{\mathrm{r}}B_{\mathrm{m}k}$ and frequencies $\omega_{\mathrm{r}} \pm \omega_{\mathrm{m}k}$ for the variable man-made MF.

We now consider the second term on the right-hand side of Eqn (23) which described the induced Ψ in closed loops caused by movement of the human body with velocity $V = \mathrm{d}r/\mathrm{d}t$ together with changing α:

$$\Psi_{32} = -S|B_{\mathrm{nc}} + B_{\mathrm{nv}}|\frac{\partial\cos\alpha}{\partial r}\,V - S|B_{\mathrm{mc}} + B_{\mathrm{mv}}|\frac{\partial\cos\alpha}{\partial r}\,V\,. \quad (28)$$

The first term describes the role of the constant and variable MF of natural origin, whose gradient at the Earth's surface is very small. This term is expected to be negligible ($\Psi_{32\mathrm{n}} \approx 0$) even for great velocities (for instance in a plane or spacecraft). The second term shows the role of the constant and variable MF of man-made origin, that can be often characterized by rather big gradients. In such a case, if we write

$$\frac{\partial\cos\alpha}{\partial r}\,V = \sum_{j=1}^{x}A_{\mathrm{mc}j}\cos(\omega_{\mathrm{mc}j}t - \varphi_{\mathrm{mc}j}) + \sum_{j=1}^{y}A_{\mathrm{mv}j}\cos(\omega_{\mathrm{mv}j}t - \varphi_{\mathrm{mv}j})\,, \quad (29)$$

we obtain

$$\Psi_{32\mathrm{mc}} = -SB_{\mathrm{mc}}\sum_{j=1}^{x}A_{\mathrm{mc}j}\cos(\omega_{\mathrm{mc}j}t - \varphi_{\mathrm{mc}j})\,, \quad (30)$$

$$\begin{aligned}\Psi_{32\mathrm{mv}} &= -S\sum_{k=1}^{p}B_{\mathrm{m}k}\cos(\omega_{\mathrm{m}k}t - \varphi_{\mathrm{m}k}) \times \sum_{j=1}^{y}A_{\mathrm{mv}j}\cos(\omega_{\mathrm{mv}j}t - \varphi_{\mathrm{mv}j})\\ &= \frac{1}{2}S\sum_{k=1}^{p}\sum_{j=1}^{y}B_{\mathrm{m}k}A_{\mathrm{mv}j}\Big\{\cos\big[(\omega_{\mathrm{m}k} - \omega_{\mathrm{mv}j})t - (\varphi_{\mathrm{m}k} - \varphi_{\mathrm{mv}j})\big]\\ &\quad + \cos\big[(\omega_{\mathrm{m}k} + \omega_{\mathrm{mv}j})t - (\varphi_{\mathrm{m}k} + \varphi_{\mathrm{mv}j})\big]\Big\}\,, \quad (31)\end{aligned}$$

where for the variable part of the man-made MF we took into account Eqn (7). Equation (30) shows that, for a body moving in presence of a large MF gradient, the expected harmonics of Ψ for an almost constant man-made MF will have amplitudes $SB_{\mathrm{mc}}A_{\mathrm{mc}j}$ with frequencies $\omega_{\mathrm{mc}j}$, and from variable man-made MF, according to Eqn (31), will have amplitudes $SB_{\mathrm{m}k}A_{\mathrm{mv}j}$ with frequencies $|\omega_{\mathrm{mv}j} \pm \omega_{\mathrm{m}k}|$.

7.5 On the resonance interaction of self-electromotive forces Ψ in closed loops with Ψ induced by MFs of natural and man-made origin

Let us suppose that in a closed loop S there are self-electromotive forces Ψ such that

$$\Psi_s = \Psi_{s0}\sin(\omega_s t - \varphi_s)\,. \quad (32)$$

Expression (32) is the solution of the equation

$$\ddot{\Psi} = -\omega_s^2\Psi_s \quad (33)$$

with the initial conditions

$$\Psi_s(t=0) = -\Psi_{s0}\sin(\varphi_s)\,, \qquad \dot{\Psi}_s = \Psi_{s0}\cos(\varphi_s)\,.$$

Equation (33) is analogous to the equation $F = -aX$ of mechanical oscillations, where $F = m\ddot{X}$ so that

$$\ddot{X} = -\omega_s^2 X\,, \quad (34)$$

and $\omega_s^2 = am$. Let us remember that if in the presence of mechanical oscillations there are external forces

$$F_{\mathrm{e}} = -A_{\mathrm{e}}\omega_{\mathrm{e}}^2\sin(\omega_{\mathrm{e}}t - \varphi_{\mathrm{e}})\,,$$

then Eqn (34) will be transformed into

$$\ddot{X} = -\omega_s^2 X - A_{\mathrm{e}}\omega_{\mathrm{e}}^2\sin(\omega_{\mathrm{e}}t - \varphi_{\mathrm{e}})\,, \quad (35)$$

with the solution for forced oscillations

$$X = \frac{A_e \omega_e^2 \sin(\omega_e t - \varphi_e)}{|\omega_e^2 - \omega_s^2|} . \qquad (36)$$

If we take into account that each eigenfrequency will have some halfwidth Γ_s, solution (36) will be transformed into

$$X = \frac{A_e \omega_e^2 \sin(\omega_e t - \varphi_e)}{|\omega_e^2 - \omega_s^2| + \Gamma_s^2} . \qquad (37)$$

The resonance interaction will be important for all the cases considered above (see Sections 7.3 – 7.5). For example, let us consider the self-resonance interaction in closed loops with Ψ induced by the variable part of natural and man-made MFs (see Section 7.2). For this it is necessary to add to the right-hand side of Eqn (33) additional terms analogous to (35) on the basis of Eqn (6):

$$\frac{d^2\Psi_{11}}{dt^2} = -\omega_s^2 \Psi_{11} - S \sum_{i=1}^{l} \omega_{ni}^3 B_{ni} \sin(\omega_{ni} t - \varphi_{ni}) \cos \alpha_{ni} - S \sum_{k=1}^{p} \omega_{mk}^3 B_{mk} \sin(\omega_{mk} t - \varphi_{mk}) \cos \alpha_{mk} . \qquad (38)$$

The solution of Eqn (38), taking into account Eqn (37), will be

$$\Psi_{11} = S \sum_{i=1}^{l} \omega_{ni}^3 \frac{B_{ni} \sin(\omega_{ni} t - \varphi_{ni}) \cos \alpha_{ni}}{|\omega_{ni}^2 - \omega_s^2| + \Gamma_s^2} + S \sum_{k=1}^{p} \omega_{mk}^3 \frac{B_{mk} \sin(\omega_{mk} t - \varphi_{mk}) \cos \alpha_{mk}}{|\omega_{mk}^2 - \omega_s^2| + \Gamma_s^2} . \qquad (39)$$

Solution (39) differs from (6) only in the frequency range near the eigenfrequency ω_s, for which the background spectrum of induced Ψ will be increased by a factor $\approx \omega_s^2/\Gamma_s^2$ due to the resonance effect. For example, if $\Gamma_s \approx 0.1\omega_s$, then the increase will be by about 100 times; this means that the induced Ψ at this frequency will be amplified about 100 times by the resonance effect. If some closed loops have several eigenfrequencies $\omega_{s1}, \omega_{s2}, \ldots, \omega_{sn}$ with halfwidths $\Gamma_{s1}, \Gamma_{s2}, \ldots, \Gamma_{sn}$, then there will be several resonance increases in electromotive forces Ψ, by $\omega_{s1}^2/\Gamma_{s1}^2, \omega_{s2}^2/\Gamma_{s2}^2, \ldots, \omega_{sn}^2/\Gamma_{sn}^2$ times, induced by the variable parts of natural and man-made MFs at the eigenfrequencies $\omega_{s1}, \omega_{s2}, \ldots, \omega_{sn}$, respectively.

8. Research gaps

8.1. Biophysical interaction between weak MFs and living systems

No commonly agreed theoretical explanation for the biological action of weak, ambient EMFs to which humans are routinely exposed in homes or workplaces has yet emerged. This area of research is characterized by a significant gap between experimental results and biophysical theory [146, 179]. The authors of Refs [24, 180] argued that the electric fields induced by weak MFs in tissue at the level of individual cells would be too weak to overcome the effects of thermal noise in cell membranes. This conclusion is now being challenged on the ground that these simple treatments are based on models that probably have very limited validity for pertinent biological systems [181, 182]. They also fail to consider non-equilibrium phenomena, such as cooperative transitions, through which extremely weak signals could exert significant effects on cell membrane properties [141, 183, 184]. A number of innovative ideas have been advanced to explain the basis of coupling of electromagnetic fields to living cells and tissues, many of which involve transduction and amplification phenomena at the cell membrane (see, e.g., Refs [4, 144]).

Several experimental results suggest a resonance mechanism through which a weak static MF, comparable in strength to the geomagnetic field, and a time-varying MF in the low-frequency range could produce considerable biological effects [185 – 187]. Thus, when a superposition of static (DC) MFs, for instance static geomagnetic, and time-varying MFs ($B_{Dc} + B_{Ac} \cos \omega t$, where ω is the angular frequency of the time-varying field) is applied to a biosystem, biological effects are observed at the frequency

$$\omega_c = \frac{q_i B_{Dc}}{m_i} , \qquad (40)$$

where ω_c is the cyclotron resonance frequency, and q_i and m_i are the charge and mass of ions present in tissue. Since expression (40) corresponds, at least formally, to the cyclotron frequency for the given ion, changes in the functional properties of biosystems at the frequency $f_c = \omega_c/(2\pi)$ have been called ion cyclotron resonances in biosystems [188]. For the typical range of the geomagnetic field (35 – 65 μT), the resonance frequencies of many biologically important ions (potassium, calcium, sodium, vanadium, magnesium, lithium, hydrogen ions etc.) fall within the ULF – ELF range. However, it is known that the real cyclotron motion of ions in liquids cannot take place even in rather high amplitude MFs [188]. There are models that try to overcome this difficulty. In Refs [185, 186] such a mechanism is proposed: the MF (the Lorentz force) provides selective pathways to K^+ Mg^{++} and Ca^{++} ions traversing the membrane ion channels (in which collision kinetics is less important). In Ref. [189] a special water-repellent area on the membrane surface was postulated, making it possible to use equations for ion interactions with MFs as in a vacuum. In a model [190], derived from a theoretical work [191], the resonant effects of combined static and ELF fields are visualized as resulting from an effect on the vibrational energy levels of an ion, with a resulting effect on its interaction with ligand binding sites (receptors). This approach can be considered as a peculiar analogue of the phenomenon known in atomic spectroscopy as parametric resonance [192]. In the proposed resonance mechanisms the magnitude of varying MFs is not necessarily the determining factor; for different models the response of the biosystem depends on different relationships between DC and AC fields (their magnitude and direction) and on the AC frequency. This also offers a plausible explanation why biosystems may sometimes be more sensitive to special natural magnetic variations than to the larger man-made fields.

However, all these theoretical models have limitations and shortcomings, they have been criticised on the basis of classical physical principles (see, e.g., Refs [193 – 196]).

8.2 The problem of exposure assessment

Without an established mechanism of biosystem-field interaction there is no guidance to what attributes of the field are hazardous: magnitude, frequency pattern, wave form, duration of exposure, or a special combination of these. Also it is not known what range of values are relevant. In other words, the functional relationships between MF exposure and health effects are not known. Most epidemiological studies assume that health effects are proportional to the time average of the field strength (time-weighted averages TWA), or to the product of field strength and time. TWA and their surrogates have been often used because they are easy to assess and fit into the concept of a dose which has been successfully used in radiation biology and toxicology. Nevertheless, there is now a great deal of relevant laboratory and clinical data indicating that the TWA method might not be the best MF exposure metric [26, 197]. Unlike ionizing radiation and most chemical factors, the effect of MFs at low frequencies appears to be highly non-linear, as indicated by the presence of 'windows' in intensity range and resonance-like phenomena. Intermittence, transients and possibly the contribution of the geomagnetic field may play a role. The dose-effect relationship is little known so far. Some research suggests that peak, rather than cumulative exposure, could be of importance. In particular, peaks could be significant for acute coronary heart disease. Several alternative exposure indices have been proposed to take into account non-linear exposure-response relationships, including field threshold or window-type dependencies on the exposure parameter: the effects might be proportional to the time spent above a threshold or within an 'intensity window' [118, 198]. However, there is no consensus among experts in the bioelectromagnetic research community on which exposure metric is more plausible [198].

9. Summary

Although we are far from understanding the biology of biosystem-field interactions, a number of results have emerged reliably showing that exposure to low-frequency, low-intensity MFs can produce biological effects, in spite of the fact that the energy involved is quite small. There is some ambiguity in the research results, but it is apparent that these biological effects may result in adverse health effects. The main focus in these studies was on ELF (10 – 300 Hz) fields, however, recently ULF (0 – 10 Hz) fields have been considered.

(a) *Natural geomagnetic fields*. Natural MFs mainly cover the ULF range (0 – 10 Hz). During big geomagnetic storms, MF records show irregular patterns with complex frequency spectra due to the superposition of variations with different amplitudes at different ULF frequencies, irregular pulses and other transient phenomena. Possibly, the ULF range of the magnetic environment has a significant biological meaning, corresponding to basic physiological rhythms (EEG, ECG, breath rate, etc.). A number of investigations have shown positive correlations between the incidence of cardiovascular and nervous system diseases and geomagnetic disturbances. In particular it was found that the incidence of myocardial infarction, brain stroke and traffic accidents increased significantly during a special class of natural geomagnetic disturbances, i.e. storms accompanied by decreases in cosmic ray intensity, so-called Forbush decreases. This type of geomagnetic storm, linked to solar activity and solar wind perturbations, could be considered as a potentially health-hazardous phenomenon.

(b) *Man-made magnetic fields*. The initial interest was in MFs from power transmission lines because of their relatively large spatial extent and possible association with increases in malignant diseases. More recently, electrified transportation modes have also come under consideration. It appears that fields produced by public electrified transportation systems exhibit the greatest large-scale MF intensity levels in densely populated urban areas and in the occupational environment. The amplitudes are different for different kind of trains, varying from some μT to hundreds of μT. In particular, in Russian DC trains the average levels of MFs in the drivers workplace have been found to be about 50 – 70 μT in suburban trains (EMU) and 2 – 3 times greater in electric locomotives (EL). MFs produced by electrified transport systems are quite different from those at 50 Hz in our environment and they show irregular patterns with main components at frequencies in the ULF range, as for natural geomagnetic perturbations. Due to these features, health effects in cardiovascular disease (CVD) could also be expected. Indeed, it was found that engine drivers of different types of Russian DC trains, in particular electric motor unit (EMU) and electric locomotive (EL) trains, have different risks of coronary heart disease (CHD). EL drivers have a 2-fold increased risk (2 ± 0.27) in comparison with EMU drivers. The analysis showed that the elevated CHD-risk among EL drivers could be attributed to the increased level of ULF MFs found in EL workplaces.

10. Research planning: multidisciplinary aspects

To investigate the possible health-related effects of transport MFs and geomagnetic-storm fields, biological research, done mostly for sinusoidal 50 and 60 Hz fields, should be repeated under exposure to ULF fields with complex frequency spectra, particular pulse-shape characteristics, transients and intermittence. Thus, there is a need to identify typical patterns and understand what features could be more related to bioeffects. However, since it is not known how the human body interacts with MFs, there is no preference for different attributes of MFs: amplitude, frequency, etc.

Recent results reported in Sections 4 and 6 provide a basis for future research in this field. They indicate that: (i) there is a particular class of health-hazardous geomagnetic disturbances (accompanied by Forbush decreases in cosmic ray intensity) and (ii) there is a particular class of health-hazardous man-made MFs (produced by electrified transport). These findings give an anchor in revealing health-hazardous attributes of ULF MFs. It is necessary to compare the frequency and peak structures of both natural and man-made fields. The differences revealed and common features could help in identifying the biologically important peculiarities of MFs in the ULF range. As soon as this information is achieved, it will be possible to simulate MF patterns with these characteristics and use them for laboratory studies.

We wish to emphasize that this research has an essentially interdisciplinary character. In the framework of such a multidisciplinary approach an international team of various experts — physicists, dosimetric and medical specialists, biologists and epidemiologists (7 Institutions from 5 countries) — are beginning to work on a joint project supported by the European Commission. New methods of exposure assessment will be developed to take into account specific features of transport MFs. On this basis the effects of exposure to specific transport MF patterns on cardiovascular and central-nervous functions in animals and humans will be examined. An extensive epidemiological study on the Swiss railway population will be conducted to examine the possible linkage between MF exposure and health effects in coronary heart disease. The findings of this project will provide basic elements for future comparison with natural MF patterns for the most bioeffective geomagnetic storms.

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References

1. Wertheimer N W, in *Mechanisms of Carcinogenesis* (Ed. E K Weisburger) (Dordrecht: Kluwer Academic Publishers, 1989) p. 188
2. Kaune W T, Anderson L E, in *Extremely Low Frequency Electromagnetic Fields: the Question of Cancer* (Eds B W Wilson, R G Stevens, L E Anderson) (Columbus, OH: Battele Press, 1989) p. 17
3. Goldberg R B, Creasey W A *Med. Hypoth.* **35** 265 (1991)
4. Foster K R *Health Phys.* **62** 429 (1992)
5. Anderson L E *Am. Ind. Hyg. Assoc. J.* **54** 186 (1993)
6. Liburdy R P *Radio Sci.* **30** 179 (1995)
7. Brodeur P *Currents of Death* (New York: Simon and Shuster, 1989); see also *The New Yorker*, 7 December 1992, p.86
8. Coghill R *Killing Fields, Electronics World + Wireless World* **2** 112 (1990)
9. Savitz D A *Am. Ind. Hyg. Assoc. J.* **54** 165 (1993)
10. Kavet R I *Bioelectromagnetics* **17** 339 (1996)
11. Dietrich F M et al., in *Electricity and Magnetism in Biology and Medicine* (Ed. M Blank) (San Francisco: Press Inc., 1993) p. 267
12. Kaune W T et al., in *17th Annual Meeting of Bioelectromagnetics Society, Abstracts* (Boston, MA, USA, 1995) p. 66
13. Kudrin V A et al. *Gigiena i Sanitariya* (3) 13 (1995)
14. Ptitsyna N G et al. *Bioelectromagnetics* **17** 436 (1996)
15. Vladimirskiĭ B M *Biofiz.* **40** 950 (1995)
16. Roederer J G *EOS, Transactions, American Geophysical Union* **76** 441 (1995)
17. Roederer J G *Space Medicine & Medical Engineering* (Jpn) **9** 7 (1996)
18. Villoresi G et al. *Phys. Med.* **10** 79 (1994)
19. Villoresi G et al. *Phys. Med.* **10** 107 (1994)
20. Ptitsyna N G et al. *Phys. Med.* **11** 93 (1995)
21. Polk C, Fichten F *J. Res. NBS* **66D** 313 (1962)
22. Nishida A *Geomagnetic Diagnosis of the Magnetosphere* (New York, Berlin: Springer Verlag, 1978)
23. Villante U et al. *Annales Geophysicae* **8** 337 (1990)
24. Bennett W R (Jr) *Phys. Today* **47** (4) 23 (1994)
25. Gauger J *IEEE Transactions on Power Apparatus and Systems* **104** 2436 (1985)
26. Bracken T D *Am. Ind. Hyg. Assoc. J.* **54** 165 (1993)
27. Kavet R I, Banks R S *Environ. Res.* **39** 386 (1986)
28. Ho A M, Frazer-Smith A C, Villard Jr O *Radio Sci.* **14** 1011 (1979)
29. Ptitsyna N G et al. *Meditsina Truda i Promyshlennaya Ekologiya* **12** 22 (1996)
30. Ptitsyna N G et al., in *2nd World Congress for Electricity and Magnetism in Biology and Medicine, Abstracts* (Bologna, Italy, 1997)
31. Kazuo U, in *Memories of the Kakioka Magnetic Field Observatory* (Suppl.) **7** 17 (1977)
32. Vishnev V S, D'yakonova A G, Hachaĭ O A *Geologiya i Geofiz.* **36** 122 (1995)
33. Tyasto M I et al. *Biofiz.* **40** 839 (1995) [*Biophys.* **40** 829 (1995)]
34. Allen S G et al. in *Review of Occupational Exposure to Optical Radiation and Electric and Magnetic Fields with Regard to the Proposed CEC Physical Agents Directive* (Chilton, Didcot, Oxon OX11 ORQ, National Radiological Protection Board, 1988) p. 31
35. Nakagava M, Koana T, in *Electricity and Magnetism in Biology and Medicine* (Ed. M Blank) (San Francisco: Press Inc., 1993) p. 264
36. Randall W, Randall S *Bioelectromagnetics* **12** 67 (1991)
37. Temur'yants N A, Makeev V B, Tishkin O G *Sovetskaya Medicina* **10** 66 (1980)
38. Komarov F I et al. *Itogi Nauki i Tekhniki: Meditsinskaya Geografiya* **18** 172 (1989)
39. Temur'yants N A, Vladimirskiĭ B M, Tishkin O G *Sverkhnizkochastotnye Signaly v Biologicheskom Mire* (Extra Low-Frequency Signals in Biological World) (Kiev: Naukova Dumka, 1992)
40. Friedman H, Becker R O, Bachman C H *Nature* (London) **200** 626 (1963)
41. Friedman H, Becker R O, Bachman C H *Nature* (London) **205** 1050 (1965)
42. Novikova K F et al. *Kardiologiya* **8** (4) 109 (1968)
43. Gnevyshev M N, Novikova K F, in *Vliyanie Solnechnoĭ Aktivnosti na Atmosferu i Biosferu Zemli* (Influence of Solar Activity on Atmosphere and Biosphere of the Earth) (Moscow: Nauka, 1971) p. 179
44. Gnevyshev Û N, Novikova˜ F *Interdisciplinary Cycle Res.* **3** 99 (1972)
45. Novikova K F et al. *Problemy Kosmicheskoĭ Biologii* **43** 9 (1982)
46. Stoupel E, Shimshoni M, in *Proc. Workshop on Solar-Terrestrial-Predictions* (Meudon, France, 1984) p. 596
47. Kuritzky A et al. *Headache* **27** 87 (1987)
48. Stoupel E et al., in *Proc. Workshop on Solar-Terrestrial Predictions* Vol. 2 (Leuta, Australia, 1989) p. 152
49. Stoupel E, Finkelstein M, in *Proc. Regional Symposium on Electromagnetic Compatibility* (Tel-Aviv, Israel: IEEE, 1992) p. 3.1.3
50. Takata M *Archiv fur Meteorologie, Geophysic and Bioklimatologie B* **2** (2) 486 (1941)
51. Takata M, Murasuga T *Bioklomat. Beibl.* **8** 17 (1941)
52. Beran G J *Interdisciplinary Cycle Res.* **3** 207 (1972)
53. Andronova T I, Deryapa N R, Solomatin A P *Geliometeopaticheskie Reaktsii Zdorovykh i Bol'nykh Lyudeĭ* (Heliometeotropic Reactions of Healthy and Sick People) (Leningrad: Medicina, 1982)
54. Temur'yants N A, Tishkin O G *Laboratornoe Delo* **2** 3 (1983)
55. Gurfinkel' Yu I et al. *Biofiz.* **40** 793 (1995) [*Biophys.* **40** 777 (1995)]
56. Baevsky R M et al., in *Proc. MEFA International Fair of Medical Technology and Pharmacy* (Brno, Czech Republic, 1996) (in press)
57. Reiter R *Arch. Phys. Therap.* **6** 210 (1954)
58. Reiter R *Phys. Blaetter* **11** 453 (1955)
59. Bhaskara Rao D S, Srivastava B J *Bull Nat. Geophys. Res. Inst.* (*India*) **8** 32 (1970)
60. Srivastava B J, Sahena S *Indian J. of Radio and Space Phys.* **9** 121 (1980)
61. Zaguskin Yu, Ivanov V *Problemy Kosmicheskoĭ Biologii* **43** 59 (1982)
62. Strestik J, Prigancova A *Acta Geodaet. Geophys. et Montanist. Hung.* **21** 155 (1986)
63. Finkelstein M, Brenner S, Ne'eman E, in *Proc. 5th Int. Conf. of Ecology and Environmental Quality Sciences* (Jerusalem, Israel, 1992) p. 18
64. Koenig H, Ankermueller F *Naturwissenschaften* **17** 47 (1960)59 (1982)
65. Ermolaev G T, in *Vsesoyuznyĭ Nauchno-Tekhnicheskiĭ Simpozium po Fiziko-Matematicheskim i Biologicheskim Problemam Deĭstviya Elektromagnitnykh Poleĭ i Ionizatsii Vosdukha* (Proc. Symp. Phys.-Math. and Biological Problems of Electromagnetic Field Effects and Air Ionization) (Yalta) **2** 74 (1975)
66. Belen'kaya R M, Karadzhaeva S A *Zh. Nevropatologii i Psikhiatrii* **78** 1329 (1978)
67. Bardov V G, Gabovich R D, Nikberg I I *Gigiena i Sanitariya* **8** 111 (1977)
68. Belisheva N K et al. *Vestn. Leningr. Univ. Ser. 4* (2) 11 (1994)
69. Lipa B J, Sturrock P A, Rogot F *Nature* **259** 302 (1976)
70. Knox E G, Armstrong E, Lancashire R *Nature* (London) **281** 564 (1979)
71. Benevolenskiĭ V N, Voskresenskiĭ A D *Vestn. Akad. Nauk SSSR* (10) 54 (1980)
72. Malin S R, Srivastava B J *Nature* (London) **277** 646 (1979)
73. Malin S R, Srivastava B J *Nature* (London) **283** 111 (1980)
74. Villoresi G et al. *Abstract in Relations of Biological and Physico-Chemical Processes with Space and Helio-Geophysical Factors* (Pushchino, Russia, 1996) p. 39 (Submitted to *Biofiz.*)
75. Susser M *Am. J. Epidemiol.* **105** 1 (1977)
76. Comba P *J. Exp. Clin. Cancer Res.* **12** 1 (1993)
77. Iucci N et al. *Nuovo Cimento C* **9** 39 (1986)
78. Villoresi G et al., in *Proc. 24th Int. Cosmic Ray Conf.* (*Rome*) **4** 1106 (1995)

79. Villoresi G et al. *Biofiz*. **40** 983 (1995) [*Biophys*. **40** 993 (1995)]
80. Dorman L I et al. *Nucl. Phys. B, Proc. Suppl*. **39A** 136 (1995)
81. Iucci N et al., in *Proc of the "E. Fermi Summer School" — Course "Solarterrestrial relationship and the Earth environment in the last millennia"* (Ed. G Cini Castagnoli) (Amsterdam: North-Holland Phys. Publ., 1988) p. 408
82. Kappenman J G, Albertson V D *IEEE Spectrum* March (1990)
83. Hruska J, Shea M A *Adv. Space Res*. **13** 451 (1993)
84. Dorman L I, Iucci N, Villoresi G *Astroph. and Space Sci*. **208** 55 (1993)
85. Dorman L I *Geophysical and Astrophysical Aspects of Cosmic Rays* (Amsterdam: North-Holland Publ. Co., 1963)
86. Blokh Ya L, Dorman L I, Kaminer N S, in *Proc. 6th Int. Cosmic Ray Conf*. (*Moscow*) **4** 178 (1959)
87. Dorman L I, Freidman G I, in *Proc. Conf. MHD and Plasma Phys*. (Riga, 1959) p. 77
88. Dorman L I, in *Proc. 6th Int. Cosmic Ray Conf*. (*Moscow*) **4** 132 (1959)
89. Dorman L I, Iucci N, Villoresi G, in *Proc. 24th Int. Cosmic Ray Conf*. (*Rome*) **4** 892 (1995)
90. Belov A V et al., in *Proc. 24th Int. Cosmic Ray Conf*. (*Rome*) **4** 888 (1995)
91. McCracken K G, Parsons N R *Phys. Rev*. **112** 1798 (1958)
92. Fenton A G et al. *Can. J. Phys*. **37** 970 (1959)
93. Nagashima K et al. *Nuovo Cimento C* **13** 551 (1990)
94. Nagashima K, Fujimoto K, Sakakibara S *Planet. and Space Sci*. **40** 1109 (1992)
95. Bavassano B et al. *J. Geophys. Res*. **99** 4227 (1994)
96. Dorman L I *Cosmic Rays: Variations and Space Explorations* (Amsterdam: North-Holland, 1974)
97. Belov A V et al. *Adv. Space Res*. **16** 249 (1995)
98. Kozlov V I, Krymskii P F *Fizicheskie Osnovaniya Prognoza Katastroficheskikh Geofizicheskikh Yavleniĭ* (Physical Basis for Catastrophic Geophysical Phenomena Prediction) (Yakutsk, Russian Acad. of Science, 1993)
99. Dorman L I, Libin I Ya *Usp. Fiz. Nauk* **145** 403 (1985) [*Sov. Phys. Usp*. **28** 233 (1985)]
100. Berezhko E G et al., in *Proc. 20th Int. Cosmic Ray Conf*. (*Moscow*) **4** 99 (1987)
101. Wertheimer N W, Leeper E *Am. J. Epidemiol*. **109** 273 (1979)
102. Modan B *Am. J. Industr. Med*. **13** 625 (1988)
103. Ahlbom A *Scand. J. Work Environ. Health* **14** 337 (1988)
104. Asanova T P, Rakov A M *Gigiena Truda Prof. Zabol*. **10** 50 (1962)
105. Vyalov A M, in *Materialy 2-go Vsesoyuznogo Soveshchaniya po Izucheniyu Vliyaniya MP na Biosistemy* (Proc. of the 2nd USSR General Meeting on the Study of Magnetic Field Influence on Biosystem) (Moscow: 1969) p. 56
106. Vyalov A M *Gigienicheskaya Otsenka Magnitnykh Poleĭ* (Moscow, 1972) p. 7 (Materialy Simpoziuma 22 – 23 May 1972)
107. Korobkova V P et al. *Report on the CIGRE Session No. 23-06* (1972)
108. Perry F S et al. *Health Phys*. **41** 67 (1981)
109. Perry F S, Pearl L *Public Health* **102** 11 (1988)
110. Dawson D et al. *Practitioner* **232** 435 (1988)
111. Cook M R et al. *Bioelectromagnetics* **13** 261 (1992)
112. Baris D et al. *Occup. Environ. Med*. **53** 17 (1996)
113. Baris D, Armstrong B, Deadman J *Occup. Environ. Med*. **53** 25 (1996)
114. Wertheimer N W, Leeper E *Am. J. Epidemiol*. **11** 345 (1982)
115. Tomenius L *Bioelectromagnetics* **7** 191 (1986)
116. Coleman M P et al. *British J. Cancer* **60** 793 (1989)
117. Feychting M, Ahlbom A *Am. J. Epidemiol*. **138** 467 (1993)
118. Juutilainen J, Leera E, Pukkala E *Int. Arch. Occup. Environ. Health* **62** 289 (1996)
119. Demers P A et al. *Am. J. Epidemiol*. **134** 340 (1991)
120. Matanoski G M et al. *Am. J. Epidemiol*. **137** 609 (1993)
121. Savitz D A, Loomis D P *Am. J. Epidemiol*. **141** 123 (1995)
122. Tunes T, Anderson L *Lancet* **336** 8730 (1990)
123. Floderus B, Tornqvist S, Stenlund C *Cancer Causes Control* **5** 189 (1994)
124. Alfredsson L, Hammar N, Karlehagen S *Cancer Causes Control* **7** 377 (1996)
125. Balli-Antunes M, Pfluger D H, Minder C E *Environmetrics* **1** 121 (1990)
126. Pfluger D H, Minder C E *Report No. ISBN 3 9065 1910 2* (University of Berne, Dept. of Social & Preventive Med., 1995)
127. Villoresi G et al., in *2nd World Congress for Electricity and Magnetism in Biology and Medicine, Abstracts* (Bologna, Italy, 1997)
128. Jauchem J R *J. Microwave Power and Electromag. Energy* **30** 165 (1995)
129. Perry F S, Pearl L, Binns R *Public Health* **103** 177 (1989)
130. Bell G B, Marino A A, Chesson A L *Electroencephalogr. Clin. Neurophysiol*. **83** 389 (1992)
131. Lyskov E B et al. *Bioelectromagnetics* **14** 87 (1993)
132. Whittington C J, Podd J V, Rapley B R *Bioelectromagnetics* **17** 131 (1996)
133. Persinger M A, Nolan M *J. Bioelectricity* **4** 2 (1985)
134. Friedman H, Becker R O, Bachman C H *Nature* (London) **213** 949 (1967)
135. Medvedev S V et al. *Fiziologiya Cheloveka* **18** (5) 41 (1992)
136. Graham C et al. *Bioelectromagnetics* **15** 447 (1994)
137. Maresh C M et al. *Aviat. Space Environment. Med*. **59** 1139 (1988)
138. Graham C et al., in *Interaction of Biological Systems with Static and ELF Electric and Magnetic Fields* (Eds L Anderson, R Weigel, B Kelman) (Washington: NTIS, 23rd Annual Hanford Life Sciences Symp, 1984) p. 471
139. Graham C, Sastre A, Cook M R, in *2nd World Congress for Electricity and Magnetism in Biology and Medicine, Abstracts* (Bologna, Italy, 1997)
140. Kavaliers M, Eckel L A, Ossenkopp K P *J. Compt. Physiol. A* **173** 241 (1993)
141. Jentsch A et al. *Neurosci. Let*. **1** 79 (1993)
142. Lovely R H et al., in *16th Annual Meeting of Bioelectromagnetic Society, Abstracts* (1994)
143. Silney J, in *Proc. Symposium on Biological Effects of Static and ELF Magnetic Fields* (Ed. J Berhardt) (Munich: BGA-Schrifteinreibe, MMv Medizin Verlag, 1985)
144. Tenforde T S, Kaune W T *Health Phys*. **53** 585 (1987)
145. Reilly J P *Med. Biol. Eng. Comp*. **27** 101 (1989)
146. Tenforde T S *Ann. Rev. Publ. Health* **13** 173 (1992)
147. Reille A *J. Physiol*. (*Paris*) **30** 85 (1968)
148. Ramon C, Powell M R *Bioelectromagnetics* **13** 303 (1992)
149. Artishenko B A et al., in *Problemy Kosmicheskoĭ Biologii* **43** 139 (1982)
150. Bellossi A, Desplaces A, Morin R, in *8th Annual Meeting of Bioelectromagnetics Society, Abstracts* (Frederick, MD, 1986) p. 51b
151. Beniashvili D S, Bilanishvili V G, Menabde M Z *Cancer Let*. **61** 75 (1991)
152. McLean J R N et al., in *13th Annual Meeting of Bioelectromagnetics Society, Abstracts* (Salt Lake City, USA, 1991)
153. Cleary S F A *Am. Ind. Hyg. Assoc. J*. **54** 178 (1993)
154. Wilson B W, Reiter R J, Pilla A A, in *Electricity and Magnetism in Biology and Medicine* (Ed. M Blank) (San Francisco: Press Inc., 1993) p. 251
155. Adey W R, in *Biological Coherence and Response to External Stimuli* (Ed. H Frohlih) (Heidelberg: Springer-Verlag, 1988) p. 148
156. Leal J et al. *J. Boielectricity* **7** 141 (1989)
157. Makeev V B, Temur'yants N *Problemy Kosmicheskoĭ Biologii* **43** 116 (1982)
158. Gavalas-Medici R, Day-Magdaleno S *Nature* **261** 256 (1976)
159. Bawin S M et al. *Bioelectromagnetics* **17** 386 (1996)
160. Lebedeva I, Vekhov A, Bazhenova S, in *Problemy Élektromagnitnoĭ Neĭrobiologii* (Problems of Electromagnetic Neurobiology) (Moscow: Nauka, 1988) p. 85
161. Kavet R I, in *Future Epidemiologic Studies of Health Effects of Electric and Magnetic Fields* (Palo Alto, CA: Electric Power research Institute, EPRI report TR-101175, 1992) p. A47
162. Reiter R J, in *Annual Review of Research on Biological Effects of 50 and 60 Hz Electric and Magnetic Fields* (Denver, CO.: DOE, A-30, 1990)
163. Lerchl A et al. *Biochem. Biophys. Res. Commun*. **169** 102 (1990)
164. Frazer-Smith A C, Coates D B *Radio Sci*. **13** 661 (1978)
165. Dietrich F M, Feero W E, Jacobs W L *Final Report of Electric Research and Management* (Inc to National Transportation Systems Center, September 8, 1997)

166. Paul H U et al., in *Interference of Monitors by Magnetic Fields of Power Frequency Installations and Traction Lines* (Paris, France: CIGRE, 1990) p.36
167. Minder C E, Pfluger D H *Radiation Protection Dosimetry* **48** 351 (1993)
168. Anger G, Berglund A, Hansson Mild K *Magnetic Fields in Electric Locomotives, SSI Report 97.04 ISS No 282-4434* (Swedish Radiation Protection Institute, Stocholm, Sweden, 1997)
169. Ptitsyna N G et al. *Report FIZ-97-1* (St. Petersburg: SPbFIZMIR-AN, 1997)
170. Jackson J D *Classical Electrodynamics* (New York: Wiley & Sons, 1975)
171. Neurath P W, in *Biological Effects of Magnetic Fields* Vol. 1 (Ed. M F Barnothy) (New York: Plenum Press, 1964) p. 25
172. Frankel R B, in *CRC Handbook of Biological Effects of Electromagnetic Fields* (Eds C Polk, E Postow) (Boca Raton, Fla: CRC Press, 1986) p. 180
173. Kirshvink J L, Kobayashi-Kirshvink A, Woodford B *Proc. Nat. Acad. Sci. USA* **89** 7683 (1992)
174. Kirshvink J L *EOS Trans. Am. Geophys. Union* **75** (15) (1994)
175. Beason R C, Nichols J E *Nature* (London) **309** 151 (1984)
176. Towne W F, Gould J L, in *Magnetic Biomineralization and Magnetoreception in Organisms* (Eds J L Kirschvink, D S Jones, B J MacFadden) (New York: Plenum Press, 1985) p. 385
177. Korchevskiĭ E M, Marochnik L S *Biofiz.* **10** 371 (1965) [*Biophys.* **10** 411 (1965)]
178. Vardanyan V A *Biofiz.* **18** 491 (1973) [*Biophys.* **18** 515 (1973)]
179. Hilemann B *Chem. Eng. News* **71** 15 (1993)
180. Adair R K *Phys. Rev. A* **43** 1039 (1991)
181. Polk C *Bioelectromagnetics* **15** 261 (1994)
182. Engstroem S *Bioelectromagnetics* **17** 58 (1996)
183. Adey W R *Physiol. Rev.* **61** 435 (1981)
184. Taylor L S *Bioelectromagnetics* **2** 259 (1981)
185. McLeod B R, Liboff A R *Bioelectromagnetics* **7** 177 (1986)
186. Liboff A R et al. *J. Bioelectricity* **6** 13 (1987)
187. Ross S M *Bioelectromagnetics* **11** 27 (1990)
188. Liboff A R *J. Biol. Phys.* **13** 99 (1985)
189. Chiabrera A et al., in *Interaction Between Electromagnetic Field and Cells* (Eds A Chiabrera, C Nicolini, H P Schwan) (London: Plenum Press, 1985) p. 253
190. Lednev V V *Bioelectromagnetics* **12** 71 (1991)
191. Podgoretskiĭ M I, Khrustalev O A *Usp. Fiz. Nauk* **81** 217 (1963) [*Sov. Phys. Usp.* **6** 682 (1964); *Fortschr. Phys.* **12** 235 (1964)]
192. Aleksandrov E B et al. *Zh. Eksp. Teor. Fiz.* **45** 503 (1963) [*Sov. Phys. JETP* **18** 346 (1964)]
193. Halle B *Bioelectromagnetics* **9** 381 (1988)
194. Sandweiss J *Bioelectromagnetics* **11** 203 (1990)
195. Adair R K *Bioelectromagnetics* **13** 231 (1992)
196. Adair R K *Bioelectromagnetics* **17** 242 (1996)
197. Lovely R H *Microwave News* (May/June) 5 (1993)
198. Morgan M G, Nair I *Bioelectromagnetics* **13** 335 (1992)