BIOLOGICAL EFFECTS OF MAGNETIC FIELDS

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Abstract
The use of devices generating high magnetic fields in industrial processes, energy production and storage, medical diagnostics, new transport vehicles and large scale research facilities is expected to expand significantly in the near future. Scientific and public interest has focused recently on the biological effects and the potential health risks associated with the exposure to magnetic fields. Over the last twenty years several laboratory studies and epidemiological surveys have been carried out in this field but no definite conclusions concerning the related risks for personnel or general public have been drawn. The aim of this article is to provide an overview of these investigations together with an analysis of the well-established effects of the interaction between static or ELF magnetic fields and living matter. The international guidelines and standards for exposure to magnetic fields are also reported and discussed.

1. INTRODUCTION

Magnetic fields are produced by electrical appliances, power lines, electromagnets and everything that carries electric current. The level of magnetic fields at which humans may be exposed has considerably increased over this last century. The exposure level is normally limited for practical reasons. To work in places with appreciable magnetic fields would be nearly unrealisable nowadays: computer disks may be erased, monitors would be distorted, magnetic light objects may experience rotational or translational forces. A much more important question regards the possible health risks associated to static and ELF magnetic field exposure. The potential health effects of biomagnetic interactions have been under discussion over the last twenty years and the debate is still open.

This article is a review of the known biological effects caused by the interaction between magnetic fields and living matter together with a survey of the laboratory and epidemiological studies described in the scientific literature. We focus our attention on static and Extremely Low Frequency (below 3 kHz) magnetic fields. In the ELF range ionising effects (when the energy carried by the field is so large that it can damage internal organs and biologic molecules like DNA) do not play a role; usually also the thermal effects (due to induced electric currents in the tissues) are negligible if we consider the typical magnetic field strengths associated to common electrical equipment. Nevertheless, there are other ways in which magnetic fields may interact with biological matter to produce biological changes. Whether these changes can lead to health risks, in the long term, is still an open question. The initiatives to establish guidelines and official standards for occupational or public exposure to static and ELF magnetic fields will be described and discussed.

2. THE MAGNETIC FIELD

A magnetic field is a region of space that results from the motion of electric charges, it is always associated with everything that carries electric current. The field may be pictured as lines of force, also called flux lines: the direction of the field at any point is given by the direction of the line in that point and its magnitude is proportional to the density of lines near the point. Unlike electrostatic field lines, the flux lines are continuous without beginning and end (this means that isolated magnetic poles do not exist). The magnetic field is described by two vector quantities: the magnetic field strength $\vec{H}$ and the magnetic flux density $\vec{B}$**.** These two quantities are related by the relation $\vec{B} = \mu \cdot \vec{H}$. The constant of proportionality μ, the magnetic permeability, depends on the medium and in the case of biological tissues is assumed to be equal to the value of the permeability of free space $\mu_0 = 4\pi \times 10^{-7}$ (T•m/A^{-1}).

The magnetic flux density $\vec{B}$ may be defined in terms of the Lorentz force $\vec{F}$ acting on a charge q that moves in a magnetic field with a velocity $\vec{v}$ [1]:

$$\vec{F} = q \cdot (\vec{v} \times \vec{B}) \qquad (1)$$

The unit of the magnetic field, in the SI system, is the *tesla* (T) while in the cgs system it is the *gauss* (G) with 1 G = 10^{-4} T. The strength of the magnetic field decreases with the distance from the source. In the approximation of a long wire carrying an electric current (valid for small distances r compared to the straight portion of the wire) the magnitude of the field varies as:

$$B = \frac{\mu_0 I}{2\pi r} \qquad (2)$$

In the case of a dipole approximation (valid for example for field calculation at large distances from coils carrying electric current) the field amplitude decays more rapidly as:

$$B(r,\theta) = \frac{\mu_0}{4\pi}\frac{m}{r^3}\left(1 + 3\cos^2\theta\right)^{\frac{1}{2}} \qquad (3)$$

where m is the dipole magnetic moment of the coil and θ the angle with respect to the dipole axis.

3. THE EARTHíS MAGNETIC FIELD

The geomagnetic field of the Earth is dipolar (the magnetic poles are not coincident with the geographic poles) and varies at the surface from 26 μT near the equator to about 60 μT near the poles. In the last centuries the dipole moment is continually decreasing and it is assumed that it reverses every ≈ 200,000 y ears. The magnetic field is maintained by the so called geodynamo: the interaction of the already existing Earthís field with the molten iron of the outer core, that flows around the solid inner core, induces an electric current just as in a metallic wire that moves across a magnet. Once the electric current is established it generates a self-perpetuating magnetic field that sustains the Earthís field. The forces driving the conducting fluid arise from both the rotation of the Earth and heat.

4. ARTIFICIAL MAGNETIC FIELDS

The Earthís static magnetic field has roughly not exceeded 100 μT over the last 80 million years. The natural magnetic field consists also of time-varying components, associated mainly with solar activity and thunderstorms, whose intensities vary from about 0.1 μT to 0.1 fT in the ELF range. Prolonged exposure to higher static and ELF fields is nowadays an ordinary situation as shown in Table 1.

Table 1
Typical values of static and ELF magnetic flux densities associated with different sources in homes, workplaces and public areas.

Field source	**Frequency** (Hz)	**Magnetic flux density**
Offices, homes		
Background	50/60	0.05–0.4 μT
Household appliances	50/60	0.01–0.5 μT at 1 m 0.1–30 μT at 0.3 m
Video displays	30–3,000	0.02–0.6 μT at 0.3 m
Research facilities (personnel areas)		
Linear accelerator	0	0.1–5 mT
Bubble chamber	0	> 50 mT
MHD and fusion plants	0	1–50 mT
NMR	0	1–60 mT
Industries		
Electrolytic processes	0, 50/60	1–10 mT
Aluminium production	0	1–10 mT / 60 mT
Electric and induction furnaces	1–10,000	1–50 mT
Welding machines	0, 50/60	0.2–10 mT
Security systems	0.1–10,000	up to 1 mT
Average exposure of workers	50/60	1 μT, electrical 0.17 μT, non electrical
Power systems		
380 kV transmission lines	50/60	1–20 μT
15 kV distribution lines	50/60	0.05-0.4 μT
20 MWh S/C Magn. energy storage (SMES)	0	0.5 T (max. accessible field) 10 mT at 300 m
Transportation		
Magnetically-levitated trains (MAGLEV)	0	2–6 mT (head level) 20–50 mT (floor level)

Subway	50/60	0.7–1 mT
Medicine		
Magnetic resonance imaging (MRI)	0	0.5–2 mT (operator) 2 T (patient)
Therapeutic devices	12–75	1–10 mT

Static fields of significant intensity are encountered mainly in industrial processes and in large scale scientific facilities but may be experienced by the public in medical equipment for diagnostic or therapeutic purposes and in new emerging technologies like magnetically-levitated trains.

Exposure to ELF magnetic fields, essentially from 50/60 Hz sources, is an ordinary situation. The magnetic field background level in homes (away from appliances and averaged over time) ranges from 0.05 μT to 0.4 μT (based on a EPRI study of nearly 1000 homes) and higher localised magnetic fields are present near household appliances. People living in the proximity of power transmission lines, or workers in some industrial sites, may be exposed all the time to magnetic fields higher than 1 μT. Levels of tens of μT can occur for short periods in certain working situations.

In the case of both static and ELF fields, ionising and thermal effects are negligible but other mechanisms play a role. Scientists are investigating the effects of these magnetic environments on humans. The well-established effects of the interaction between static or ELF magnetic fields and living organisms may be divided into three main categories: electrodynamical, magnetomechanical and induction of electric currents. The last one is effective only for exposure to ELF magnetic fields or in the case of rapid motion in high static fields.

5. INTERACTION MECHANISMS BETWEEN MAGNETIC FIELDS AND BIOLOGIC SYSTEMS

5.1 Electrodynamic effects

A well-recognised effect of the interaction of magnetic fields with the cardiovascular system is the change in electrocardiograms (ECG). Moving ionic charge carriers (electrolytes) in the blood, when exposed to a magnetic field, are subjected to the Lorentz force, reported in Eq. (1), that induces an electric potential ϕ given by:

$$\phi = v \cdot B \cdot d \cdot \sin\varphi \tag{4}$$

where v is the velocity, d is the diameter of the artery and φ is the angle between the direction of the blood flow and the magnetic field. This phenomenon is the basis of the Hall effect in solid-state materials and magnetohydrodynamic (MHD) power generation. For example, in a man with a blood flow rate of 0.6 m/s and an aortic diameter of 0.025 m, the expected induced potential is 15 mV/T [2]. These induced electric potentials have been observed by ECG on mammalians exposed to magnetic field [3]. Clear typical modifications in the ECG signal are visible in the T-wave region delimiting the opening and closing times of the aortic valve.

The experimental investigations confirmed that:

a) the magnetically induced alteration in the flow potential is generally well observed above 0.1 T – 0.3 T (depending on body size);
b) the amplitude of the T-wave increases linearly with the field;
c) no changes in the arterial pressure are observed;
d) the effect is completely reversible without adverse effects and disappears instantly at the end of the exposure.

The last consideration is important to underline that an observed change in a biologic system, during field exposure, is not necessarily an evidence for adverse human health effects.

5.2 Magnetomechanical effects

5.2.1 Magnetic orientation

In a uniform magnetic field, both diamagnetic and magnetic substances, are subjected to a torque that will tend to orientate them. In biological systems, there are several examples of orientation in strong static fields. Diamagnetic macromolecules undergo a magneto-orientation owing to the anisotropy in their magnetic susceptibility along the different axes of rotational symmetry. These molecules, generally with a rod-like shape, will tend to rotate in order to achieve a minimum energy configuration. The degree of alignment β is usually very small; however for stacked assemblies of N macromolecular with parallel rotational axes, β is increased of a factor N, giving rise to large effects. Observed examples, by in-vitro studies, of nearly complete magnetic alignment in static fields of 0.5 T – 2 T, are the outer segments of retinal rods [4] and cells containing chloroplasts [5]. Also sickled red blood cells have been observed to orient perpendicular to magnetic fields of 0.2 T to 0.5 T [5, 6]. Both these effects happen at field strengths used in MR imaging systems and may be important for safety considerations. However, the magnitude of the response is small and probably does not result in any detectable clinical consequences in humans.

Also some gel-like tissues, such as the vitreous fluid of the eye and the synovial fluid of the skeletal joints, may be affected by exposure to magnetic fields. The gelation temperature of aqueous 1.4 % agarose solutions, similar to these biologic fluids, showed an increase as a function of the magnetic field strength [7].

There are some interesting cases of orientations of living organisms that synthesise organic chain structures, containing magnetite (Fe_3O_4) crystals with a net permanent magnetic moment, called magnetosomes. It was discovered that these magnetosomes influence the direction of motion of magnetotactic bacteria. They align themselves with the Earthís magnetic field lines and swim toward the north and downward (due to the vertical component of the geomagnetic field) in the northern hemisphere and to the south and downward in the southern hemisphere. This motion allows them to survive in the oxygen-poor mud of their aquatic environments.

There is also experimental evidence that the Earthís magnetic field influences the geomagnetic orientation and navigation of some migratory (such as some species of salmons) and elasmobranch (such as sharks, skates and rays) fish, migratory bird species, homing pigeons, monarch butterflies and honeybees (during their waggle dances) [8, 9].

5.2.2 Magnetic translation

Ferromagnetic and paramagnetic materials exposed to a magnetic field gradient are subjected to a magnetomechanical force (that tends to move them along the gradient direction) given by:

$$F = V \cdot \frac{\lambda}{\mu_0} \cdot B \cdot \frac{dB}{dx} \qquad (5)$$

where V is the volume of the magnetic substance and λ the magnetic susceptibility. Owing to the limited amount of magnetic substances in most living beings, the influence of this effect on biological functions is negligible.

Important safety considerations concern the possible displacement of metal implants and prosthesis that may experience significant forces and torques in strong magnetic field gradients.

5.3 Electric currents induction

Time-varying magnetic fields induce electric currents in biological systems that may be evaluated by the Faraday law of induction. In the case of sinusoidal fields with amplitude B_o and frequency f, the magnitude of the induced current density is given by:

$$J = \pi \cdot r \cdot f \cdot \sigma \cdot B_o \qquad (4)$$

The proportionality of the induced currents on loop radius r and tissue electrical conductivity σ has important consequences for biological systems. A fixed time-varying field may induce notable currents at the macroscopic level but much smaller ones at the cellular level. These currents are usually smaller than those naturally produced by the brain, nerves and heart.

5.3.1 Magnetophospenes

A well known biological effect of ELF magnetic field is the induction of visual sensations (flickering white light in the eyes), called magnetophosphenes, when exposed to fields having frequency in the range 10–100 Hz and amplitude above 10–100 mT [3]. Magnetophosphenes have been found to occur also in strong magnetic field during movement of the head and in transient fields during energising or deenergising of high-field magnets. This effect was first described by díArsonval in 1896 [10] and the possible explanation was reported by Lövsund [11]. The maximum sensitivity is at 20 Hz where the flashes are synchronised with the field.

Other biological effects of circulating currents in the body are: bone healing, nerve stimulation, electroshock anaesthesia (therapy) and heart fibrillation. They may be classified on the basis of threshold values of the induced current densities [12] as shown in Table 2.

Table 2

Threshold values of ELF induced current densities for producing biological effects

Induced current density (mA/m^2)	**Effects**
< 1	Same order of naturally flowing biocurrents, no effects.
1–10	Minor biological effects.
10–100	Magnetophospenes, bone fracture healing, possible nervous system effects.
100–1000	Influence on neuron excitability; stimulation threshold for sensory receptors, nerve and muscle cells with possible health hazards.
> 1000	Possibility of ventricular fibrillation, continuous muscle contraction; definite health hazards.

Owing to differences in biologic matter conductivities and unknown current loops, the calculation of induced currents is rather complicated. However, using cautious assumptions, an estimation of the threshold magnetic field values for the different effects may be made as reported in Ref. [12]. These estimated values give an idea of the ELF magnetic fields that should not produce biological effects but may not be used as safe limit values.

6. LABORATORY STUDIES

Several kinds of biological effects have been reported in studies of exposure to magnetic fields by animal experimentation and by work with cell cultures, trying also to find biological evidence of adverse health effects. It is not possible to report here on the extensive literature existing on this topic [13]. Some of the results (change in functions of cells and tissues, decrease in the hormone melatonin, alterations of immune system, accelerated tumour growth, changes in brain activity and heart rate) were obtained with field levels that are orders of magnitude larger than fields involved in ordinary cases. Some effects on cell cultures due to ELF low fields of a few μT and less than 100 μT were also reported [14].

Laboratory studies confirmed, as shown above, no biological effects for induced currents lower than 10 mA/m^2. In the case of exposure to static fields, the reported studies for fields lower than 2 T seem to indicate the absence of irreversible effects on the main biological functions.

These results should be treated, in any case, with great attention because the human organism has many compensating mechanisms that may modify the effects observed in cell cultures.

Some researchers also reported data on biodetection of high static magnetic fields or gradients. In one experiment [15], rats avoided systematically to enter into regions where the field strength was 4 T and the gradient was up to 13 T/m. These findings were not observed at 1.5 T.

7. EPIDEMIOLOGICAL STUDIES

Although animal experiments, cell culture studies and computer models provide useful data, most researchers agree that potentially adverse health effects of static or ELF magnetic fields may be provided by studies of human population that are ordinary exposed to magnetic fields in residential or working areas. These observational studies, called epidemiologic, may show associations that could point out an increased risk of disease associated with some environmental factors. They already allowed the important risk factors for cancer to be identified as cigarette smoke (relative risk of 10 for lung cancer) and benzene. In several cases, scientists cannot be sure whether the association is one of cause and effect or if the increased risk may be related to other factors.

This methodology requires carefully consideration because a positive association between a disease and exposure is not necessarily a definite proof especially when the risk is small. To judge if the increased incidence of risk is real other correlation criteria must be considered such as consistency with other studies involving different methods and population, dose-response relationships (increasing exposure levels should correspond to higher disease rates), plausible biological explanation supported by laboratory results, reliability of information.

Several epidemiologic surveys on the possible health risks associated with static and ELF magnetic field exposure have been carried out over the last 20 years, principally on 50/60 Hz fields, but none of them has definitively convinced the legislators.

Table 3 reports a review of epidemiological studies of occupational and residential exposure to static and ELF magnetic fields. These studies examined mainly electrical workers that are ordinarily more exposed to ELF magnetic (mean exposure of about 1 μT against 0.2 μT of workers in other job categories). The doses of field exposure in the first surveys were based only on job titles and not on actual measurements fields.

Some epidemiologic residential and occupational studies have suggested a weak relation with a few types of cancer in humans, particularly leukaemia in children as well as brain and breast cancer in adults, while others reported no consistent evidence of relations between magnetic field exposure and any type of cancer. Moreover, the studies reporting a positive association are not quite concordant and do not agree upon the forms of cancer. Considering three recent studies we may observe in fact some controversial conclusions. The first one, conducted by the Swedish National Institute of Working Life, one of the largest studies involving a broad range of industries and occupations [24], found an association with chronic lymphocytic leukaemia and an increased risk for brain cancer for men exposed to an average field of more than 0.2 μT. The second one, conducted by Canadian and French researchers on 223,292 electric utility workers, between 1979 and 1989, found a relative risk of 3 to contract acute myeloid leukaemia [17]. The last study, the most recent one, conducted in North Carolina, and involving 139,000 US utility workers found no association with both types of leukaemia but supported an association with brain cancer [23].

A noteworthy survey has been conducted in Sweden on people living near high-voltage transmission lines [25]. This study, highly exposed in the media and government circles, suggested for the first time a dose/response relationship, although it was based on a small number of cases. The risk to contract childlike leukaemia was found to be 2.7 times higher for magnetic fields exposure of 0.2 μT and 3.8 times for fields above 0.3 μT. There were no

Table 3
Epidemiological studies of occupational and
residential exposure to static and ELF magnetic fields

Human population	Average exposure	Reported risks
Static magnetic fields		
Soviet workers in permanent magnet production (645 exposed people)	2–5 mT at hands 0.3–0.5 mT at head	Subjective and minor physiological effects [16]
US workers in aluminium plants	No field values reported	Increased risk of all classes of leukaemia [17]
High-energy accelerator labs, bubble chambers, high-field magnet facilities (792 controls)	Up to 2 T	No increased risk for 19 common diseases including cancers [18]
50/60 Hz magnetic fields		
US workers 438,000 death records	Field exposures based on job title	Increased risk of acute myeloid leukaemia [19]
US workers death data from 16 States	Field exposures based on job title	Higher incidence of brain cancer, but not leukaemia [20]
US electric utility workers (36,000 people)	Field exposures estimated on measurements in the workplace	No detection of risks for any type of cancer [21]
Canadian and French electric utility workers (223,292 people)	Field exposures estimated on measurements in the workplace	Relative risk of acute myeloid leukaemia among workers with higher cumulative exposure [22]
US electric utility workers (138,000 people)	Field exposures estimated on measurements in the workplace	No association between occupational exposure and leukaemia but link to brain cancer [23]
1015 different workplaces in Sweden involving 169 occupations	Field exposures estimated on measurements in the workplace	Increased risk for chronic lymphocytic leukaemia. Increase risk for brain tumours for age under 40 and average field above 2 μT [24].
Swedish report on people living near high voltage transmission lines	Field exposures estimated on measurements in the residential areas.	Childlike leukaemia risk 2.7 times higher for exposure of 0.2 μT and 3.8 above 0.3 μT [25].

elevated risks for other types of cancer. The relative risk values are closer to the border line of statistical significance and the value of 0.2 μT distinguishing exposed and unexposed people may not provide, from current knowledge, a sufficient basis for setting threshold exposure limits of such low intensity.

On the contrary, a recent survey on 36,000 electric utility workers reported no strong consistent evidence of association between magnetic fields and any type of cancer [23].

As already mentioned above, different studies disagree in important ways both on the value of excess risk associated with magnetic exposure and on the type of disease.

So far there is no laboratory evidence for health effects at the field values considered in these studies. If some effects occur, they are likely to be so weak that the body is almost able to compensate, making them very hard to study.

8. STATIC AND ELF MAGNETIC FIELD EXPOSURE GUIDELINES AND PROTECTIVE MEASURES

Currently available information has not confirmed evident and reproducible adverse health effects in order to clearly indicate safe limit values and durations for magnetic field exposure. There are several initiatives to establish official standards for occupational and public exposure to static and ELF magnetic fields. Some governments, being unable to determine standards with the support of the scientific knowledge, defined limit values based on what is technologically achievable and not on medical or epidemiological studies.

Most of the guidelines reported in Table 4 have not been issued by authoritative laws but have been defined by international institutions as recommended limit values.

Table 4

Limit values for occupational and public exposure to static and ELF magnetic fields.
(These reference values are not intended as a threshold to a dangerous level.)

Static magnetic fields				
	SLAC	**CERN**	**CENELEC TC 111**	**ACGIH**
Working day/whole body	20 mT	200 mT	200 mT	60 mT
Working day/limbs	200 mT			600 mT
Short/whole body	200 mT	2 T	2 T	
Short/limbs	2 T	5 T	5 T	2 T
General public/whole body		10 mT	40 mT	
General public/limbs			100 mT	
Persons with pace-maker (or large metal implants)		0.5 mT	0.5 mT	0.5 mT
Average Earth's field	50 μT			

ELF magnetic fields					
	CENELEC TC 111	**ACGIH**	**ICNIRP (50/60 Hz)**	**Regulations for transmission lines** (50/60 Hz)	
Day/whole body	80/f 1.6 mT at 50 Hz	60/f 1.2 mT at 50 Hz	0.5 mT 5 mT (short)	Italy	100 μT 1 mT (short)
Day/limbs	1250/f	300/f	25 mT	Florida	15 μT

	25 mT at 50 Hz	6 mT at 50 Hz			
General public/ whole body	32/f 0.64 mT at 50 Hz		0.1 mT 1 mT (short)	New York	20 µT
General public/ limbs	500/f 10 mT at 50 Hz				
People with pacemaker		0.1 mT			
Background field	0.1 µT				

In Europe, a prestandard was approved in late 1994 by the Technical Committee CENELEC TC111 ìElectromagnetic fields in the human environmentî. This prestandard, whose validity is limited initially to three years, is divided into two parts dedicated respectively to occupational and public exposure to low frequency (0–10 kHz) and high frequency (10 kHz – 300 Ghz) electromagnetic fields [26]. It was issued for provisional application and may be modified, before conversion to a standard, on the basis of new scientific findings and experience gained during its application.

Presently there are no federal standards in the United States but the Federal Energy Policy Act established in 1994 a five-year program, known as EMF RAPID program (Electric and Magnetic Fields Research and Public Information Dissemination), managed by DoE and the National Institute of Environmental Health Sciences. This program should explore the potential relevance of EMF exposure for possible health effects.

Among the most important international organisations that developed exposure guidelines should be mentioned: the International Commission on Non-Ionising Radiation Protection (ICNIRP) [27], the European Organisation for Nuclear Research (CERN) [28] and the American Conference of Governmental Industrial Hygienists (ACGIH) [29]. The first widely used guidelines for researchers working with high magnetic fields were formulated by the Stanford Linear Accelerator Laboratory (SLAC).

Some studies [24, 25] reported possible long-term effects on health associated with magnetic field strengths lower than those specified in Table 4. However, as already mentioned above, they do not prove indisputably that harmful risks exist and are not supported by evident scientific confirmations. Consequently there are no sufficient bases for setting threshold exposure limits of such low intensities.

The American Physical Society (APS) issued a bulletin in 1995 on this subject reporting that both the scientific literature and reviews by other panels show no consistent and significant links between cancer and ordinary ELF magnetic fields.

On the basis of extensive laboratory studies, various other significant biological processes do not seem to be influenced significantly by static magnetic fields up to 1–2 T. These processes include: cell growth and morphology, DNA structure, reproduction, physiological regulation and circadian rhythms [30].

8.1 Pacemakers and implanted metal objects

Low intensity magnetic fields may be considered to be safe from the biological point of view but may cause problems to people with pacemakers. The majority of pacemakers implanted today are synchronous and are activated only when the heart rate, continuously monitored, falls below a preset level. Incorporated in the pacemaker is usually a reed relay that activates fixed-frequency pulses and is helpful for the physician to test the correct working of the apparatus. It was found that certain types of cardiac pacemakers in the presence of static fields, above 0.5–1.5 mT, may reverse into this fixed-rate mode (called asynchronous mode). This circumstance is potentially hazardous and may lead to fibrillation owing to the competitive pacing between the natural heart rate and the rate stimulated by the pacemakers [31]. Also time-varying magnetic fields, in excess of 0.1–0.4 mT, may alter the pacemaker functioning, by inducing voltages that may be recognised as cardiac signals.

Since magnetic fields decrease as the distance from the source increases, the best protective measure, when the magnetic field is higher than these limit values, is a separation distance. In any case warning signs for people with cardiac pacemakers or metal implants and prosthesis (that may experience significant forces and torques) must be displayed in accessible places where magnetic fields are above 0.5 mT.

9. CONCLUSIONS

There is controversy on the possible health effects of static and ELF magnetic fields on humans [32]. It is difficult to prove indisputably whether harmful risks exist or not. Although the potentially exposed population is large, the risks, if any, appear to be small and limited to specific situations. But, in any case, it is better to keep the public exposure well below the limit values. A valuable support may come from the new technologies that, if duly stimulated, may solve problems in ways that are compatible with the environment. There are already examples, in other sectors, pointing out how high-technology companies are able to find alternatives in a short time to comply with new regulations.

Most of the public attention is now focused on ELF fields, associated to high voltage transmission lines but studies on the effects of static fields are also expanding after the large diffusion of magnetic resonance imaging (MRI) systems employing static magnetic fields up to 2 T. Static fields are expected to attract much more attention when high magnetic field technologies, based mostly on superconductors, like superconducting magnetic energy storage plants (SMES), thermonuclear fusion reactors and magnetically levitated trains (MAGLEV), begin to spread.

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