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INTERACTION MECHANISMS AND BIOLOGICAL EFFECTS OF STATIC MAGNETIC FIELDS

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Abstract

Mechanisms through which static magnetic fields interact with living systems are described and illustrated by selected experimental observations. These mechanisms include electrodynamic interactions with moving ionic charges (blood flow and nerve impulse conduction), magnetomechanical interactions (orientation and translation of molecular structures and magnetic particles), and interactions with electronic spin states in charge transfer reactions (photo-induced electron transfer in photosynthesis). A general summary is also presented of the biological effects of static magnetic fields. There is convincing experimental evidence for magnetoreception mechanisms in several classes of lower organisms, including bacteria and marine organisms. However, in more highly evolved species of animals, there is no evidence that the interactions of static magnetic fields with flux densities up to 2 Tesla (1 Tesla [T] = 10^4 Gauss) produce either behavioral or physiological alterations. These results, based on controlled studies with laboratory animals, are consistent with the outcome of recent epidemiological surveys on human populations exposed occupationally to static magnetic fields.

INTRODUCTION

Research on the possible health and environmental effects of static magnetic fields has increased in recent years as a consequence of the rapidly expanding number of technologies that utilize high-intensity magnetic fields [1]. For example, new technologies being developed for energy production and storage (*e.g.*, thermonuclear fusion reactors and superconducting magnetic energy storage systems) will involve significant exposures of occupational personnel to stray fields. In addition, the rapid development of magnetic resonance imaging as a clinical diagnostic procedure during the past several years has provided a strong rationale for determining the possible biological effects of high-intensity magnetic fields. In this article the primary mechanisms by which static magnetic fields interact with living systems will be described, and a summary will be presented of the current state of knowledge of the biological effects of these fields based on laboratory research and epidemiological surveys of occupationally-exposed personnel. Several reviews of these subjects have recently been published [2-7]. Recent occupational and public exposure guidelines are also discussed.

MECHANISMS OF INTERACTION

Three major classes of static magnetic field interactions with biological processes have been observed in well-controlled laboratory research [2,4,6,7]: (1) electrodynamic interactions with ionic conduction currents that lead to the induction of measurable electrical potentials in the major vessels of the circulatory system; (2) magnetomechanical effects that include the orientation of diamagnetically anisotropic macromolecular structures in strong uniform fields, and the translation of paramagnetic and ferromagnetic materials in strong magnetic field gradients; (3) Zeeman interactions with electronic spin states of radical pair intermediates involved in certain classes of electron transfer reactions, one example being the reduction in triplet state yield when the photo-induced charge transfer reaction in photosynthesis proceeds in the presence of a static magnetic field. Only the first of these three interaction mechanisms has been found to produce biological effects at field strengths to which humans are commonly exposed. Electrodynamic interactions of static magnetic fields have been shown to induce electrical potentials in the aortic vessel that can be detected in large laboratory animals such as dogs and primates at field levels exceeding 0.1 T. Magnetomechanical interactions have been demonstrated *in vitro* to produce orientation of molecular assemblies such as membranes at field levels approaching 1 T, but there is no evidence that this type of interaction influences biological functions in living animals. Similarly, the forces exerted on paramagnetic molecules in a strong magnetic field gradient do not appear to significantly perturb biological processes. Zeeman interactions with electron transfer processes occur only under special laboratory conditions in which the electron acceptor molecules are chemically reduced [8]. Such conditions generally do not exist in nature, and there is presently no evidence that static magnetic fields influence photosynthesis in plants or bacteria in their natural states.

STATIC MAGNETIC FIELD BIOEFFECTS

Several organisms possess unique mechanisms for the detection of weak magnetic fields, as discussed in a later section of this article. In higher organisms, the one well-established biological effect of static magnetic fields is the induction of electrical potentials in the central circulatory system. It is a direct consequence of the Lorentz force exerted on moving ionic currents that blood flowing through a cylindrical vessel of diameter, d, will develop an electrical potential, ψ, given by the equation:

$$\psi = \left|\vec{v}\right| \left|\vec{B}\right| \, d \sin\theta \quad (1)$$

where $\vec{B}$ is the magnetic flux density, $\vec{v}$ is the velocity of blood flow through the vessel, and θ is the angle between the vector quantities $\vec{B}$ and $\vec{v}$. Vertical bars in Eq. 1 denote absolute values of the vector quantities.

The induced blood flow potentials within the central circulatory systems of several species of mammals exposed to large static magnetic fields have been characterized from electrocardiogram (ECG) records obtained with surface electrodes [7,9-14]. As demonstrated by the data shown in Fig. 1 for a Macaca monkey exposed to static fields up to 1.5 T, the primary change in the ECG is an augmentation of the signal amplitude at the locus of the T-wave. Based on its temporal sequence in the ECG record, this change in T-wave amplitude has been attributed to the electrical potential that is induced within the aortic vessel during pulsatile blood flow in the presence of a magnetic field. This induced electrical signal is superimposed on the normal T-wave signal, and it is completely reversible upon termination of the magnetic field exposure. In small animal species such as rats, the aortic blood flow potential can be detected in the ECG when the magnetic flux density exceeds 0.3 T [12]. For larger animal species such as dogs, monkeys and baboons, the threshold field level that induces a measurable potential is approximately 0.1 T [13,14]. The linear dependence of the aortic blood flow potential on magnetic field strength and its variation as a function of animal orientation within the field (see Eq. 1) have been confirmed experimentally [12-14]. The occurrence of magnetically-induced blood flow potentials has also been demonstrated in ECG recordings from human subjects exposed to a 2-T static magnetic field [15].

Magnetohydrodynamic effects on the rate of arterial blood flow and intra-arterial blood pressure have also been studied in laboratory animals exposed to high-intensity magnetic fields. The electrodynamic interaction between an applied magnetic field and a flowing electrolyte solution such as blood creates a net volume force within the fluid. The magnetohydrodynamic consequence of this electrical force is a reduction in the axial flow velocity of the fluid [2]. Both arterial blood flow velocity measurements and intra-arterial blood pressure measurements have been carried out in beagle dogs and Macaca monkeys exposed to static magnetic fields with flux densities up to 1.5 T, as illustrated in Fig. 1. In accord with theoretical predictions [2], these experimental results have demonstrated that magnetohydrodynamic interactions in a 1.5-T field do not produce a measurable alteration in blood flow dynamics [7,13].

Based on extensive laboratory studies, many other important biological processes do not appear to be influenced significantly by exposure to static magnetic fields with flux densities up to the range of 1 to 2 T. These processes include: (1) cell growth and morphology, (2) DNA structure and gene expression, (3) reproduction and development (pre- and post-natal), (4) bioelectric properties of isolated neurons, (5) animal behavior, (6) visual response to photic stimulation, (7) cardiovascular dynamics, (8) hematological indices, (9) immune responsiveness, and (10) physiological regulation and circadian rhythms. Laboratory studies on the effects of static magnetic fields on these physiological processes have been described in detail in previous reviews [3-7].

ORGANISMS WITH UNIQUE SENSITIVITY TO STATIC MAGNETIC FIELDS

Three well-known examples of magnetoreception mechanisms in living animals are the following [16]: (1) the electromagnetic detection system of elasmobranch fish (sharks, skates and rays), by means of which these animals derive directional cues from the weak voltages that are induced in sensory organs as they swim through the

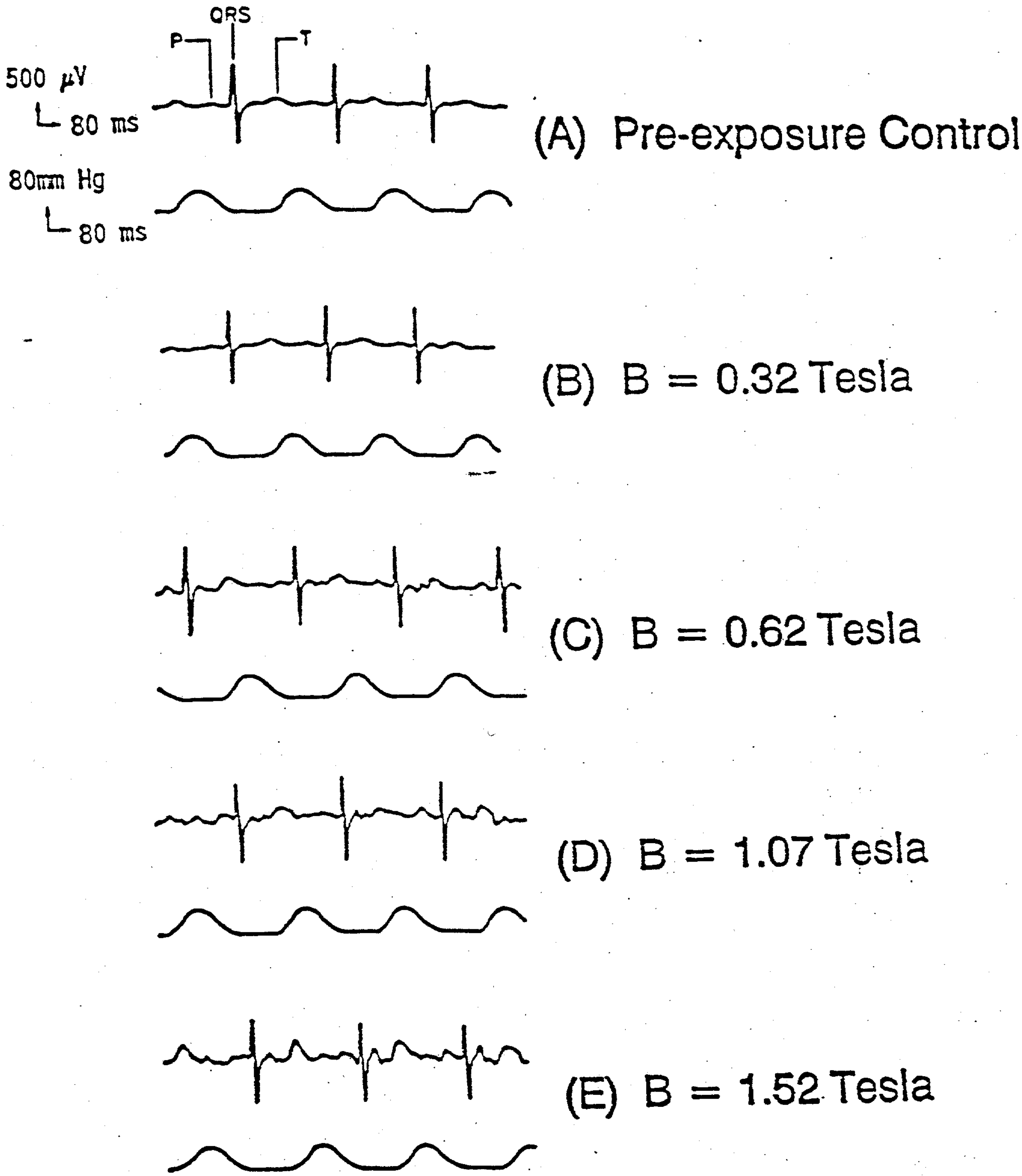

Figure 1. Electrocardiogram and intra-arterial blood pressure records are shown for a Macaca monkey exposed to uniform static magnetic fields up to 1.5 T. The ECG clearly demonstrates the increase in signal amplitude at the locus of the T-wave during magnetic field exposure. No measurable change occurred in the intra-arterial blood pressure at field levels up to 1.5 T.

lines of flux of the geomagnetic field; (2) the orientation of magnetotactic bacteria within the geomagnetic field; and (3) the effects of weak magnetic fields, including the geomagnetic field, on the migratory patterns of birds. Each of these examples of magnetoreception will be discussed briefly in this article.

Elasmobranch Fish. The heads of these fish contain long jelly-filled canals with a high electrical conductivity, known as the ampullae of Lorenzini. As an elasmobranch swims through the lines of flux of the geomagnetic field, small voltage gradients are induced in its ampullary canals. These induced electric fields can be detected at levels as low as 0.5 μV/m by the sensory epithelia that line the terminal ampullary region [17]. The polarity of the induced field in an ampullary canal depends upon the relative orientation of the geomagnetic field and the compass direction along which the fish is swimming. As a consequence, the weak electric fields induced in the ampullae of Lorenzini provide a sensitive directional cue for the elasmobranch fish.

Magnetotactic Bacteria. An example of a cellular structure in which significant magnetic orientational effects occur in response to the geomagnetic field is the magnetotactic bacterium originally discovered by Blakemore [18]. Approximately 2% of the dry mass of these aquatic organisms is iron, which has been shown by Mössbauer spectroscopy to be predominantly in the form of magnetite: Fe_3O_4 [19]. The magnetite crystals are arranged as chains of approximately 20-30 single domain crystals. The orientation of the net magnetic moment is such that magnetotactic bacteria in the Northern Hemisphere migrate towards the North Pole of the geomagnetic field, whereas strains of these bacteria that grow in the Southern Hemisphere move towards the South Magnetic Pole [20]. Magnetotactic bacteria that have been found at the geomagnetic equator are nearly equal mixtures of south-seeking and north-seeking organisms [21]. The polarity of the microbial magnets can be reversed by applying a strong pulsed magnetic field that reverses the direction of the net magnetic moment [22]. As a result, the swimming direction of the bacteria within the geomagnetic field is reversed.

Because of the polarities of their magnetic moments, the magnetotactic bacteria in both the Northern and Southern Hemispheres migrate downwards in response to the vertical component of the geomagnetic field. It has been proposed that this downward-directed motion, which carries the bacteria into the bottom sediments of their aquatic environment, may be essential for the survival of these microaerophilic organisms [18,20]. Recent studies indicate that fossil bacterial magnetite may be responsible for the natural remanent magnetization in deep-sea sediments [23,24].

Avian Navigation. The effects of the static geomagnetic field on the navigation of avians have been studied extensively [25-28]. As discussed by Yorke [29], the discovery of magnetite crystals in the head and neck region of birds may provide a mechanism for sensing the geomagnetic field [30,31]. Jungerman and Rosenblum [32] have proposed an alternative detection mechanism for the geomagnetic field involving the induction of weak voltages in an electroreceptor organ during flight. Their theoretical calculations indicated that the receptor would have to be several millimeters in size, and they discussed the labyrinth of the inner ear as a candidate organ for magnetoreception.

A surprising observation by Moore [33] has challenged the widely-accepted view that the geomagnetic field influences avian navigation. In an evaluation of unpublished data collected by the late W.T. Keeton during the period 1971-1979, Moore [33] found no evidence for statistically significant effects of bar magnets attached to the backs of pigeons on either the consistency or the accuracy of their initial orientation during flight under overcast skies. These findings are in direct contrast to the results of Keeton's earlier studies conducted in 1969 and 1970, in which statistically significant decreases in the accuracy and consistency of pigeon orientation were observed in response to an altered magnetic field environment produced by an attached bar magnet. Moore [33] concludes that it is conceivable that pigeons can detect magnetic fields, but that some unknown factor masked or blocked the effect in Keeton's later studies. An alternative explanation is that the difference in results between the two sets of experiments may indicate that pigeons do not detect magnetic fields, and that the positive outcome of the earlier studies by Keeton resulted from some unknown source of bias or as a result of random chance alone. Regardless of the explanation, the remarkable divergence between the results of Keeton's 1971-1979 experiments and his earlier studies raises a severe challenge to the concept that the geomagnetic field provides a back-up compass for avians under overcast skies.

Magnetite and Magnetoreception in Animals. Subsequent to the demonstration of biogenic magnetite in bacteria, sensitive magnetometer measurements have demonstrated the presence of localized magnetite deposits in a variety of animal species [34]. Animals in which deposits of magnetite have been found include bees, dolphins, mice, mollusks, pigeons, salmon, tuna and turtles. A recent finding of particular interest is the demonstration of magnetite crystals in the human brain [35]. In many of these species, there is an apparent sensitivity to the geomagnetic field, which confers direction-finding ability [36-40]. Baker has claimed that humans also can use the geomagnetic field for orientation and direction finding [41]. However, further tests of this hypothesis have led to negative results [42,43].

HUMAN HEALTH EFFECTS

One of the earliest studies of the possible effects of exposure to static magnetic fields on human health was conducted in the Soviet Union by Vyalov [44]. The exposure group consisted of 645 workers whose hands were routinely exposed to static fields of 2 to 5 mT, and whose chest and head were in fields of 0.3 to 0.5 mT under normal working conditions. It was estimated that the magnetic field exposure levels were 10 to 50 times larger than the typical values during 10 to 15% of the workday. The control group in this study consisted of 138 supervisors in a machine-building plant who were not in contact with magnets. A number of subjective symptoms were reported among the exposed group, including headache, fatigue, dizziness, unclear vision, noise in the ears, and itching and sweating on the palms of the hands. Edema and desquamation on the palms of the hands were also reported. In addition, minor physiological effects including decreased blood pressure and changes in hematological parameters were noted in the exposed group. These studies were qualitative in nature and statistical analysis was not performed on the clinical data. There was also no attempt to assess the possible effects of stressful environmental factors such as high ambient temperature, airborne metallic particles, or the chemical agents used for degreasing and other procedures.

In contrast to the Soviet study, three recent epidemiological surveys in the United States and Europe failed to reveal any significant health effects associated with chronic exposure to static magnetic fields. Marsh and coworkers [45] conducted a study on the health data of 320 workers in plants using large electrolytic cells for chemical separation processes. The average static field level in the work environment was 7.6 mT and the maximum field was 14.6 mT. The study included a control group of 186 unexposed workers. Among the exposed group, slight decreases were found in the blood leukocyte count and the percent of monocytes, while a small increase occurred in the lymphocyte percentage. However, the mean value of the white cell count for the exposed group remained within the normal range. There was also a slight tendency for elevated systolic and diastolic blood pressure levels among the black workers in the study. None of the observed changes in blood pressure or hematologic parameters was considered indicative of a significant adverse effect associated with magnetic field exposure.

A similar finding of no adverse health effects was reported by Barregård and coworkers [46] for employees during the period 1951-1983 in a chloralkali plant in Sweden, where a direct current of 100 kA is used in the production of chlorine by electrolysis. The exposed group consisted of 157 men who worked in static magnetic fields with flux densities ranging from 4 to 29 mT. As compared with the Swedish male population, these workers had no excess cancer incidence and the mortality rate from all causes was similar to that of the general population. Another study characterized the prevalence of disease among 792 workers who were exposed occupationally to static magnetic fields in National Laboratories in the United States [47]. The control group consisted of 792 unexposed workers matched for age, race and socioeconomic status. The range of magnetic field exposures was from 0.5 mT for long durations to 2 T for periods of several hours. No significant increase or decrease in the prevalence of 19 categories of disease was observed in the exposed group relative to the controls. Of the 792 exposed subjects, 198 had experienced exposures of 0.3 T or higher for periods of 1 hr or longer. No difference in the prevalence of disease was found between this subgroup and the remainder of the exposed population or the matched controls. No trends were observed in the health data suggestive of a dose-response relationship.

Two studies on workers in aluminum plants, who are exposed to significant static magnetic fields generated by DC currents in the prebake cells [1], have demonstrated an increased mortality from leukemia and various other types of cancer in comparison with the general population [48,49]. However, the possible influence of potentially carcinogenic factors other than magnetic fields was not adequately addressed in these studies. In addition, a large study on French aluminum workers showed their cancer mortality and mortality from all causes not to differ significantly from that observed for the general male population of France [50].

An important aspect of occupational exposure to strong magnetic fields is the physical hazard posed by the interaction of these fields with medical devices. Two well-studied types of physical hazards that are associated with exposure to static magnetic fields are [5]: (1) forces and torques exerted on implanted medical devices such as prostheses, aneurysm clips, dental amalgam and cardiac pacemakers [51], and (2) interference with the operation of implanted electronic devices such as cardiac pacemakers [52-54]. Based on tests with pacemakers from six major manufacturers, it was found that fields of 1.7 to 4.7 mT produced closure of the reed switch, thereby causing the pacemakers to revert to an asynchronous mode of operation that is potentially hazardous because of competition with the heart's intrinsic pacing rate [52]. More recent studies on pacemaker sensitivity to static magnetic fields have indicated that a small fraction of the commercially available models exhibit reversion to an asynchronous pacing mode when exposed to fields less than 1 mT [53,54]. The minimum interference level observed for any model of pacemaker was 0.3 mT, and 1.7% of the pacemakers tested exhibited reversion to a fixed pacing rate in fields of 0.3 to 0.5 mT [53].

STATIC MAGNETIC FIELD EXPOSURE GUIDELINES

Several sets of guidelines limiting human exposure to static magnetic fields in the workplace have been proposed in the United States and elsewhere during the past two decades. The most widely used guidelines have been those proposed at the Stanford Linear Accelerator in California [55]. These guidelines limit whole-body or head exposure to 20 mT during the entire workday, and to 0.2 T for short intervals of several minutes duration. The limits for exposure of the arms and hands are 10 times greater than those for the whole body or head. An occupational limit of 20 mT for whole-body exposure to static magnetic fields has also been adopted in West Germany and the United Kingdom [56,57].

A less conservative set of exposure guidelines for static magnetic fields was recently implemented at the Lawrence Livermore National Laboratory in California [58]. These guidelines limit whole-body exposure to a time-weighted average field strength of 60 mT measured at the torso or 0.6 T measured at the extremities. The rationale for the whole-body limit of 60 mT was based on a calculation of the field level that would induce a maximum electrical potential in the aortic vessel of 1 mV in a large worker with a high rate of blood flow [59]. From research with experimental animals described in an earlier section of this paper, it was concluded that magnetically-induced potentials with magnitudes up to 1 mV should not produce adverse effects on cardiac performance or hemodynamic parameters. The Lawrence Livermore National Laboratory guidelines prohibit individuals with cardiac pacemakers from entering areas where the static magnetic field level exceeds 1 mT. This recommendation was made on the basis of early studies on pacemaker interference in static magnetic fields [52]. A field strength of 1 mT was also set as a cautionary warning level for individuals with aneurysm clips or other implanted prosthetic devices. The maximum field level to which any worker may be exposed was set at 2 T, based again upon available information from laboratory studies. The American Conference of Governmental Industrial Hygienists has adopted a set of occupational exposure guidelines for static magnetic fields that are identical to those used at the Lawrence Livermore National Laboratory, except that individuals with cardiac pacemakers or other implanted medical electronic devices are excluded from areas where the field level exceeds 0.5 mT [60].

A limit of 200 mT for the time-weighted average daily exposure of workers was recently recommended by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) of the International Radiation Protection Association [61]. This limit was based on the maximum current density induced in body tissues as a result of low-frequency movements within a static magnetic field. For a 200 mT flux density, the maximum induced current density was calculated to lie in the range of 10 to 100 mA/m^2, which is below a level that would produce acute neural or neuromuscular effects. The maximum current density induced in the aorta as a result of electrodynamic interactions with blood flow was calculated to be 44 mA/m^2 at a field level of 200 mT, and this current density is considerably below a level that would be expected to exert cardiovascular effects. The ceiling value of 2T recommended by ACGIH was also adopted by ICNIRP for acute whole-body exposures of workers, and this value was raised to 5T for acute exposures of the arms and legs. In view of the most recent information on cardiac pacemaker vulnerability to weak magnetic fields, ICNIRP recommended that workers wearing pacemakers or other electrically-activated medical devices should not be permitted to enter fields with flux densities exceeding 0.5 mT. The same limit was imposed for workers with implanted ferromagnetic devices. For the general public, a whole-body continuous exposure limit of 40 mT was recommended. This limit introduces a safety factor of 5 relative to occupational exposures, and is consistent with the difference in the maximum possible exposure duration in a public versus an occupational setting when averaged over a one-week interval.

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