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STATIC MAGNETIC FIELDS: A SUMMARY OF BIOLOGICAL INTERACTIONS, POTENTIAL HEALTH EFFECTS, AND EXPOSURE GUIDELINES

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STATIC MAGNETIC FIELDS: A SUMMARY OF BIOLOGICAL INTERACTIONS, POTENTIAL HEALTH EFFECTS, AND EXPOSURE GUIDELINES

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INTRODUCTION

Interest in the mechanisms of interaction and the biological effects of static magnetic fields has increased significantly during the past two decades as a result of the growing number of applications of these fields in research, industry and medicine (Stuchly, 1986; Tenforde, 1986). A major stimulus for research on the bioeffects of static magnetic fields has been the effort to develop new technologies for energy production and storage that utilize intense magnetic fields (e.g., thermonuclear fusion reactors and superconducting magnet energy storage devices).

Interest in the possible biological interactions and health effects of static magnetic fields has also been increased as a result of recent developments in magnetic levitation as a mode of public transportation. In addition, the rapid emergence of magnetic resonance imaging as a new clinical diagnostic procedure has, in recent years, provided a strong rationale for defining the possible biological effects of magnetic fields with high flux densities (Budinger and Lauterbur, 1986). In this review, the principal interaction mechanisms of static magnetic fields will be described, and a summary will be given of the present state of knowledge of the biological, environmental, and human health effects of these fields. Extensive reviews of these subjects have been published in the last several years (Frankel, 1986; Tenforde, 1985a, 1985b, 1988, 1989a, 1990, 1991; Tenforde and Budinger, 1986; World Health Organization, 1987).

1 INTERACTION MECHANISMS

Three classes of physical interactions of static magnetic fields with biological systems are well established on the basis of experimental data: (1) electrodynamic interactions with ionic conduction currents;

(2) magnetomechanical effects, including the orientation of magnetically anisotropic structures in uniform fields and the translation of paramagnetic and ferromagnetic materials in magnetic field gradients; and (3) effects on electronic spin states of the reaction intermediates in certain types of charge transfer processes. Each of these physical interaction mechanisms, along with relevant experimental data, will be described in the following paragraphs.

1.1 Electrodynamic Interactions

Ionic currents interact with static magnetic fields as a result of the Lorentz forces exerted on moving charge carriers. This electrodynamic interaction gives rise to an induced electric field, $E_i = -v \times B$, where v is the velocity of current flow and B is the magnetic flux density. For ion flows through channels in cell membranes, the interaction of a static magnetic field is extremely weak. It has been estimated, for example, that a static magnetic field in excess of 24 Tesla (T) would be required to produce a Lorentz force on nerve ionic currents equal to one-tenth the force they experience from the local electric field of the nerve membrane (Wikswo and Barach, 1978). The absence of effects of static fields up to 2 T on nerve bioelectric properties has been demonstrated experimentally (Gaffey and Tenforde, 1983).

In the case of bulk flow of an electrically conductive fluid such as blood, significant electrical potentials are induced magnetically at field levels well below 1 T. 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, equal to $|E_i| d = |v| |B| d \sin \phi$, where ϕ is the angle between B and the velocity vector v. It has been demonstrated that an induced electrical potential associated with pulsatile aortic blood flow in the presence of a static magnetic field can be detected in the electrocardiogram (ECG) at the locus of the T-wave signal. As reviewed by Tenforde (1989a, 1991), this feature of aortic blood flow potentials has been demonstrated for rats, rabbits, dogs, baboons and monkeys. Figure 1 shows the three-lead ECG of a 5-kg *Papio* baboon prior to and during exposure to a 1.5-T static magnetic field. The largest superimposed electrical potential occurs at the T-wave locus in the ECG, which corresponds temporally to the opening of the aortic valve during pulsatile ejection of blood from the left ventricular chamber of the heart. The augmentation of the T-wave signal that is observed during magnetic field exposure is completely reversed upon removal of the field.

In large animal species such as baboons, monkeys and dogs, the aortic blood flow potential can be detected in the ECG at field levels above approximately 0.1 T, and is a linear function of field strength up to 1.0 T (Tenforde et al., 1983, 1985). At higher field levels, the total electrical potential at the T-wave locus in the ECG increases more rapidly as a function of magnetic field strength, possibly as a result of the superposition of additional, weaker flow potentials which cannot be detected at field strengths below 1.0 T. Based on the timing of valve displacements during the cardiac cycle (see Figure 1), the magnetically induced flow potential associated with pulsatile ejection of blood into the pulmonary artery may also contribute to the total ECG signal at the locus of the T-wave during exposure to very large magnetic fields. It is also evident from the ECG recordings shown in Figure 1 that other magnetically induced flow potentials can be detected during exposure to strong magnetic fields. The temporal sequence of these flow potentials relative to cardiac valve displacements indicates that they may be associated with rapid movements of blood during the filling and emptying phases of the heart cycle. A similar conclusion has been drawn from studies with *Macaca* monkeys and beagle dogs, in which a combination of phonocardiography and echocardiography were used to study the temporal sequence of cardiac valve displacements in relation to the timing of signals recorded in the ECG during magnetic field exposure (Tenforde, 1989a).

The electrodynamic interaction between an applied magnetic field and a flowing electrolyte solution such as blood also creates a net volume force within the fluid. This force is equal to $J \times B$, where $J = -\sigma v \times B$ is the ionic conduction current density resulting from the induced electric field within the flowing solution, and σ is the electrical conductivity. For a moving fluid within a static magnetic field, the magnetohydrodynamic consequence of this electrical force is a reduction in the flow velocity of the fluid. As an experimental test of the strength of magnetohydrodynamic interactions within the circulatory system, a combination of arterial blood flow velocity measurements and intra-arterial blood pressure measurements were carried out in beagle dogs and *Macaca* monkeys exposed to static magnetic fields with flux densities up to 1.5 T (Tenforde. 1989a). In accord with theoretical

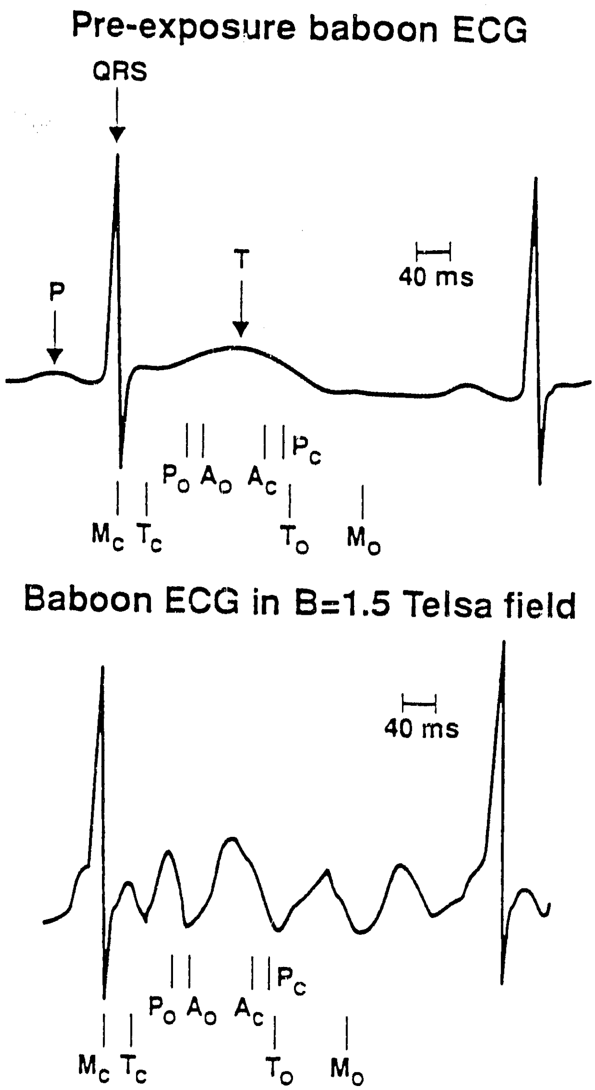

Figure 1. Electrocardiograms are shown for a female *Papio* baboon immediately prior to and during exposure to a 1.5-T static magnetic field. The estimated times of opening (subscript "o") and closing (subscript "c") of the mitral (M), tricuspid (T), pulmonary (P) and aortic (A) valves are denoted by vertical bars. (From Tenforde et al., 1985, Figure 1)

predictions (Tenforde, 1985a), these experimental results demonstrated that magnetohydrodynamic interactions in a 1.5-T field do not produce a measurable alteration in blood flow dynamics.

1.2 Magnetomechanical Interactions

There are two basic mechanisms through which static magnetic fields exert mechanical forces and torques on objects. In the first type of magnetomechanical interaction, rotational motion of a substance occurs in a uniform field until it achieves a minimum energy state. The second mechanism involves the translational force exerted on a paramagnetic or ferromagnetic substance placed in a magnetic field gradient. These two types of interaction will be discussed separately.

Macromolecules and structurally ordered molecular assemblies with a high degree of magnetic anisotropy will experience a torque in a uniform magnetic field and rotate until they reach an equilibrium orientation that represents a minimum energy state. Macromolecules such as DNA that exhibit this property generally have a cylindrical symmetry, and magneto-orientation occurs as a result of the anisotropy of the diamagnetic susceptibility tensor along the axial and radial coordinates. The extent to which these molecules orient is a function of their magnetic interaction energy, U, relative to the Boltzmann thermal energy, kT, where k is the Boltzmann constant (1.382×10^{-23} J/K) and T is the Kelvin temperature. The interaction energy depends upon the product of B^2, the molecular volume, and the difference in magnetic susceptibility along directions parallel and perpendicular to the applied field. The ratio U/kT is referred to as the "order parameter," and reflects the extent of molecular orientation in an applied magnetic field.

For individual macromolecules, the order parameter is much less than unity at field levels that can be easily achieved in the laboratory, and the extent of orientation of individual molecules in strong magnetic fields is very small. for example, optical birefringence measurements on calf thymus DNA in solution have demonstrated that a field of 13 T is required to produce 1% orientation of the molecules (Maret et al., 1975). In contrast, there are several examples of molecular assemblies that can be completely oriented by fields on the order of 1 T (Tenforde, 1985b). These assemblies behave as structurally coupled units in which the summed magnetic anisotropy is large, thus giving rise to a large magnetic interaction energy. Examples of molecular aggregates that exhibit magneto-orientation include retinal rod outer segments, muscle fibers, photosynthetic systems (chloroplast grana and *Chlorella* cells), purple membranes of *Halobacteria*, and filamentous virus particles. An example of an intact cell that can be oriented magnetically is the deoxygenated sickled erythrocyte. It has been shown that these cells, in which the deoxygenated hemoglobin is paramagnetic, will align in a 0.35-T static field with the long axis of the sickled cell oriented perpendicular to the magnetic flux lines (Murayama, 1965). This equilibrium orientation results from the stacking of the planar haem moieties parallel to the long axis of the sickled erythrocyte, with the net magnetic moment oriented perpendicular to the long axis.

Despite the fact that magneto-orientation of biologically important structures such as retinal rod outer segments can be demonstrated by optical techniques when these units are suspended in an aqueous medium (Becker et al., 1978), extensive electrophysicological studies have failed to reveal any influence of this effect on visual functions *in vivo*. A series of electroretinogram (ERG) recordings were made from a *Macaca* monkey before, during and after exposure to static magnetic fields with flux densities up to 1.5 T. Neither the A-wave (receptor field potential) or the B-wave (postsynaptic potential) elicited by flashes of white light were altered during magnetic field exposure. Similar results were obtained in ERG studies on three monkeys and six cats (Tenforde, 1989a; Tenforde et al., 1985). These data indicate that magneto-orientational forces exerted by static magnetic fields with flux densities up to 1.5 T have no significant influence on visual phototransduction processes *in vivo*. The most likely reason for this lack of effect is the motional restriction imposed on retinal photoreceptors by virtue of being embedded in a rigid structural matrix within the intact retina.

A second major type of magnetomechanical interaction is the translation of paramagnetic and ferromagnetic substances in static magnetic field spatial gradients. Denoting the magnetic susceptibility of an object as χ and the volume as V, the force, F(z), experienced in a linear magnetic field gradient, dB/dz, is equal to the product of the net magnetic moment and the field gradient: $F(z) = (\chi VB/\mu_0)(dB/dz)$, where μ_0 is the magnetic permeability of free space ($4\pi \times 10^{-7}$ H/m). The forces exerted on paramagnetic and ferromagnetic substances by strong static magnetic field gradients provide the physical basis for a number of useful biological and biochemical processes (Frankel, 1986; Tenforde, 1991). Examples of the application of magnetic forces include the targeting of drugs encapsulated in magnetic microcarriers, the separation of deoxygenated erythrocytes from whole blood, and the separation of antibody-secreting cells from a suspension of bone marrow cells.

In contrast to their useful applications in biology, the forces exerted by strong magnetic field gradients can pose a significant physical hazard in the workplace and in magnetic resonance imaging facilities. There is a risk of large tools and other metallic objects becoming projectiles in the proximity of a high-field magnet. In addition, significant magnetic forces are exerted on many types of implanted medical devices, including aneurysm clips, dental amalgam, prostheses, and pacemaker cases (Tenforde and Budinger, 1986).

1.3 Magnetic Field Effects on Electronic Spin States

Several classes of organic chemical reactions can be influenced by static magnetic fields greater than approximately 1 mT as a result of effects on the electronic spin states of the reaction intermediates (Schulten, 1982). One example of such reactions that has been studied extensively is the photo-induced charge transfer reaction in bacterial photosynthesis (Hoff, 1981). This reaction involves a radical pair intermediate state through which electron transfer occurs to the ultimate acceptor molecule, a ubiquinone-iron complex. Under natural conditions the electron transfer occurs within 200 ps following flash excitation of the bacteriochlorophyll. However, chemical reduction of the acceptor molecules extends the lifetime of the intermediate state to about 10 ns. With an extended lifetime, the singlet state of the radical pair intermediate evolves into a triplet state via the hyperfine interaction mechanism. In the presence of an external magnetic field greater than approximately 10 mT, however, the triplet channels are completely blocked and the resulting yield of triplet product is expected to decrease by two thirds. This predicted blocking of triplet channels by a weak magnetic field has been confirmed experimentally using laser pulse excitation and optical absorption measurements (Michel-Beyerle et al., 1979).

It should be emphasized that the magnetic field effect on the photo-induced electron transfer in photosynthesis occurs only when the photosynthetic system is placed in an abnormal state by chemical reduction of the electron acceptor molecules. The possibility cannot be excluded, however, that similar magnetic field effects may occur in other radical-mediated biological processes under naturally occurring conditions. For example, it has been proposed that an anisotropic Zeeman interaction with a radical-mediated reaction system could provide a basis for geomagnetic direction finding (Schulten et al., 1978). Several types of enzymatic reactions also involve radical intermediate states that may exhibit sensitivity to static magnetic fields (Tenforde, 1985b).

2 ORGANISMS WITH UNIQUE SENSITIVITY TO MAGNETIC FIELDS

Various types of organisms have been demonstrated to possess sensitivity to extremely weak magnetic fields, comparable in strength to the geomagnetic field. In several instances, there is direct experimental evidence indicating that this magnetic sensitivity is linked to direction-finding ability. The two basic mechanisms of magnetoreception are (1) magnetic induction of weak electrical signals in specialized sensory receptors, and (2) magnetomechanical interactions with localized deposits of single-domain magnetite crystals (Tenforde, 1989b). These two mechanisms of geomagnetic field detection are described in the following paragraphs.

2.1 Elasmobranch Fish

A well-known example of electrodynamic interactions involving weak magnetic fields is the electromagnetic guidance system of elasmobranch fish, a class of marine animals that includes sharks, skates and rays. 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 (Kalmijn, 1982). 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.

2.2 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 (Blakemore, 1975). 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 (Frankel et al., 1979). Magnetite crystals are synthesized within the magnetotactic bacterium ("biogenic magnetite"), and they are arranged as a chain of approximately 20 to 30 single domain crystals encapsulated in a membrane structure (Gorby et al., 1988). 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 (Blakemore et al., 1980; Kirschvink, 1980). Magnetotactic bacteria that have been found at the geomagnetic equator are nearly equal mixtures of south-seeking and north-seeking organisms (Frankel et al., 1981). 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 (Blakemore et al., 1980). In support of this hypothesis it has been shown that the population density of magnetotactic bacteria decreases abruptly as the vertical component of the magnetic field at the mud/water interface approaches zero (Chang and Kirschvink, 1989).

2.3 Avian Navigation

The effects of the static geomagnetic field on the navigation of avians have been studied extensively (Tenforde, 1991). In early experiments by Keeton (1971), measurements were made of orientation and homing ability in groups of pigeons to which small bar magnets were attached to the back at the base of the neck, producing a static field of about 45 μT at the head. Nonmagnetic brass bars of comparable weight were attached to the control group of birds. The results of these experiments illustrated a significant disorientation of birds wearing the bar magnets compared to controls when they were released under overcast skies.

A remarkable recent finding by Moore (1988) 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, he 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 both the accuracy and consistency of pigeon orientation were observed in response to an altered magnetic field environment produced by an attached bar magnet. Moore (1988) concluded 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 proposed by Moore 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 under overcast skies.

2.4 Magnetite and Magnetoreception in Animals

It was first observed by Lowenstam (1962) that the teeth of mollusks contain a high concentration of iron in the form of magnetite. Evidence has subsequently been obtained that the interaction of the geomagnetic field with these iron-containing crystals may influence the kinetic movements of mollusks (Ratner, 1976; Kirschvink and Lowenstam, 1979). The important role of magnetite deposits in geomagnetic field detection has now been shown for a large variety of biological organisms, including the magnetotactic bacteria discussed above (Kirschvink et al., 1985). Following the demonstration of biogenic magnetite in bacteria, sensitive magnetometer measurements have detected the presence of localized magnetite domains in a variety of animal species, including pigeons, bees, dolphins, tuna, salmon, turtles, and humans (Tenforde, 1991). In several of these species, there is an apparent sensitivity to the geomagnetic field, which confers direction-finding ability. Baker (1980) has claimed that humans can also use the geomagnetic field for orientation and direction-finding. However, tests of this hypothesis have let to negative results (Gould and Able, 1981; Fildes et al., 1984).

The possible influence of ambient magnetic fields on the direction-finding ability of bees is also an unresolved issue. Experimental evidence obtained by Lindauer and Martin (1968) indicated that the directional information conveyed in the bee's waggle dance is influenced by the geomagnetic field. This finding, and other evidence (Kirschvink, 1981), have raised the possibility that bees use the earth's magnetic field as a secondary directional cue when the sun is not visible. However, experiments by Dyer and Gould (1981) on bee navigational patterns indicated that these animals possess a "memory" of the sun's position at different times of the day, which serves as a back-up orientational cue when the sky is overcast. The results of these experiments suggest that magnetic field sensitivity may play only a minor role in direction-finding by bees. In contrast, recent behavioral experiments by Walker and Bitterman (1985, 1989) have demonstrated that the foraging behavior of honeybees can be influenced by ambient magnetic fields. This finding has been confirmed and initial evidence for a ferromagnetic transduction mechanism was recently reported (Kirschvink and Kobayashi-Kirschvink, 1991). Currently available evidence suggest that bees can sense weak magnetic fields, but do not necessarily use this information as a directional cue.

3 LABORATORY STUDIES ON STATIC MAGNETIC FIELD EFFECTS

As discussed in the preceding section, several species of marine animals and various other species possess an inherent sensitivity to static magnetic fields with flux densities as low as that of the geomagnetic field. In higher organisms, however, the only effect that is well established at the present time is the magnetic induction of electrical potentials in the central circulatory system. There are also numerous instances in which contradictory results have been reported in the literature.

During the past decade, a large number of studies have been conducted in which the biological effects of static magnetic fields were examined under well-controlled laboratory conditions, including the use of precise dosimetry, large numbers of experimental subjects, quantitative biochemical and physiological end points, and careful control of ambient environmental conditions that could influence the experimental results. Based on laboratory studies involving field levels of 1 T or higher, the following important biological processes appear not to be altered by exposure to static magnetic fields at high flux densities (Tenforde, 1985b, 1988): (1) cell growth and morphology, (2) DNA structure and gene expression, (3) reproduction and development (pre- and postnatal), (4) visual functions, (5) nerve bioelectric activity, (6) cardiovascular dynamics, (7) hematological indices, (8) immune responsiveness, (9) physiological regulation and circadian rhythms, and (10) animal behavior.

Although the majority of published studies have not shown significant behavioral or physiological effects of strong magnetic fields, occasional reports have appeared in the literature on the response of various organ and tissue systems to relatively weak magnetic fields. For example, it has been reported that the electrical activity of rodent and avian pineal cells can be altered by artificial changes in the strength and direction of the local geomagnetic field (Semm, 1983). In addition, evidence has been obtained that pineal melatonin content and serotonin-N-acetyltransferase activity in rodents can be modified by changes in the ambient magnetic field strength (Welker et al., 1983; Lerchl et al., 1990). Weak magnetic fields have also been reported to abolish the circadian rhythmicity of Purkinje cell responses to pineal melatonin in pigeons (Demaine and Semm, 1986). Other studies have indicated that circadian variations may exist in the sensitivity of turtle retinal cells to static magnetic fields with flux densities as low as 2 to 3 mT (Raybourn, 1983). In these and other observations of apparent biological effects of weak magnetic fields, the types of interaction mechanisms involved have not as yet been elucidated. Further research will be required to verify the existence and the nature of these interactions, and to determine their potential implications for human health.

4 HUMAN HEALTH EFFECTS

Several epidemiological studies in the United States and Europe have shown no adverse health effects associated with occupational exposure to static magnetic fields at National Laboratories (Budinger et al., 1984), and in chemical separation plants that use electrolytic cells operated with large DC currents (Marsh et al., 1982; Barregård, 1985). Two studies on workers in aluminum plants, where large static magnetic fields are present near prebake anode cells (Tenforde, 1986), have demonstrated an increased mortality from leukemia and various other types of cancer in comparison with the general population (Milham, 1979; Rockette and Arena, 1983). 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 (Mur et al., 1987).

Another important aspect of potential human health effects is the influence of static magnetic fields on the operation of medical electronic devices (Tenforde and Budinger, 1986). Of particular concern is the fact that static magnetic fields exceeding 1.7 mT can produce closure of a reed relay switch used in modern cardiac pacemakers, thereby causing the pacemaker to revert to an asynchronous mode of operation (Pavlicek et al., 1983). As a consequence, persons wearing pacemakers should not enter areas where the static magnetic field levels exceed 1 mT.

5 MAGNETIC FIELD EXPOSURE GUIDELINES

Several sets of guidelines limiting human exposure to static magnetic fields in the workplace have been proposed during the past two decades. Until recently, the most widely used guidelines have been those established at the Stanford Linear Accelerator in California in 1970. 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 was also adopted in the United Kingdom (National Radiological Protection Board, 1986).

A less conservative set of exposure guidelines for static magnetic fields was implemented in 1985 at the Lawrence Livermore National Laboratory in California. These guidelines limit whole-body exposure to a time-weighted-average field strength of 60 mT measured at the torso or 0.6 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 (Miller, 1987). From earlier research with experimental animals described in this paper, it was concluded that magnetically induced potentials of this magnitude 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 magnetic field level exceeds 1 mT. This field strength 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 can be exposed was set at 2 T. The American Conference of Governmental Industrial Hygienists (ACGIH) recently adopted a set of occupational exposure guidelines for static magnetic fields that are identical to those used at the Lawrence Livermore National Laboratory (ACGIH, 1991). The International Radiation Protection Association is in an advanced stage of development of new guidelines for exposure of workers and the general public to static magnetic fields (Repacholi, 1991).

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