9 HEALTH RISK ASSESSMENT

In this chapter, the possible impact on human health from exposure to static electric or static magnetic fields is assessed from the reviews of the epidemiological and biological data, along with the information on exposure indicated in the preceding chapters.

9.1 Static electric field effects

Static electric fields occur naturally in the atmosphere. Values of up to 3 kV m-1 can occur under thunderclouds, but in fair weather they generally are of order of 100 V m^{-1}. The most common cause of human exposure is charge separation as a result of friction. For example, , charge potentials of several kilovolts can be accumulated when walking on non-conducting carpets, generating local fields of up to 500 kV m^{-1}. Direct current (DC) power transmission can produce static electric field strengths of up to 20 kV m^{-1}, rail systems using DC can generate fields of up to 300 V m^{-1} inside the train, and VDUs create electric fields of around 10 - 20 kV m^{-1} at a distance of 30 cm.

Static electric fields do not penetrate electrically conductive objects such as the human body. The field induces a surface electric charge and is always perpendicular to the body surface. A sufficiently large surface charge density may be perceived through its interaction with body hair and by other effects such as spark discharges (microshocks). The perception threshold in people depends on various factors and can range between 10 - 45 kV m^{-1}. Thresholds for annoyance from such sensations are probably equally variable, but have not been systematically studied. Painful microshocks can be expected when a person who is well insulated from the ground touches a grounded object, or when a grounded person touches a conductive object that is well insulated from ground. However, the threshold static electric field values will vary depending on the degree of insulation and other factors.

Few animal studies of static electric field effects have been carried out. The overall results do not suggest that exposure is associated with adverse health effects.

There are no studies on exposure to static electric fields from which to make any conclusion on chronic or delayed effects. IARC (2002) noted that there was insufficient evidence to determine the carcinogenicity of static electric fields.

9.2 Static magnetic field effects

The geomagnetic field varies over the Earth's surface between about 35 - 70 μT and is implicated in the orientation and migratory behaviour of certain animal species. Man-made static magnetic fields are generated wherever DC currents are used, such as in some transportation systems powered by electricity, industrial processes such as aluminium production, and in arc welding. Magnetic flux densities of up to 2 mT have been reported inside electric trains and in modern magnetic levitation (MagLev) systems. Workers are exposed to larger fields in arc welding, where fields of around 5 mT are present close to the welding cables, and in the electrolytic reduction of alumina where fields of up to around 60 mT are encountered.

The advent of superconductors in the 1970's and 80's facilitated the use of much larger magnetic fields in medical diagnosis through the development of magnetic resonance imaging (MRI) and spectroscopy (MRS). It is estimated that some 200 million MRI scans have been performed worldwide. Most scanners operate at 1 to 3 T, and MRI exposures include pulsed magnetic and radiofrequency fields. Typically, static magnetic flux density is only 0.5 mT at the operator's console, but it may be higher. However, occupational exposure > 1 T can occur during the construction, testing and maintenance of these devices, as well as during certain medical procedures carried out in MRI. Machines of 7 - 8 T are being installed at a few sites and the first 9.4 T MRI system was installed in 2003. Both are associated with higher exposures. Various research and high energy technologies also employ superconductors where workers can be repeatedly exposed to fields as high as 2 T for periods of up to a few hours per day.

A major difficulty in the assessment of the effects of exposure to static magnetic fields is the paucity of relevant data. There have been few studies of possible long-term health effects in exposed people, particularly in fields of ~ 1 T and above. The likelihood of there being such effects can be assessed, in the first instance, from a consideration of physical interaction mechanisms. Three broad categories of effects can be recognized; namely, a) electrodynamic interactions with ionic conduction currents; b) magnetomechanical effects, including the orientation of magnetically anisotropic structures in a uniform field and the translation of paramagnetic and ferromagnetic materials in magnetic field gradients; and c) effects on the electron spin states of radical pair intermediates in certain types of metabolic reactions. The second effect represents generally weak interactions because the magnetic susceptibility of most biological material is very small and therefore significant mostly at flux densities greater than 1 T.

Ionic currents interact with static magnetic fields as a result of the Lorentz forces exerted on moving charge carriers, giving rise to an induced electric field and exerting a force opposing the motion. Examples of such processes are the ionic currents associated with the flow of blood, and the movement of ions through channels in cell membranes. Thresholds for significant interactions with the movement of ions in ion channels are thought to be around 24 T. However, measurable flow potentials are generated in major blood vessels around the heart in fields above ~ 0.1 T and their possible physiological consequences are discussed below. The magnetohydrodynamic forces opposing the blood flow could become increasingly physiologically significant at much higher flux densities.

Movement of the whole or part of the body, e.g. eyes and head, in a static magnetic field gradient will also induce an electric field and current during the period of movement. Dosimetric calculation suggests that such induced electric fields will be substantial during normal movement around or within fields > 2 - 3 T, and may account for the numerous anecdotal reports of vertigo and occasional magnetic phosphenes experienced by patients, volunteers and workers during movement in the field. These effects are discussed in greater detail below.

Magnetomechanical interactions in a magnetic field exert a torque on macromolecules and structurally ordered molecular assemblies that exhibit magnetic anisotropy, causing them to tend to rotate. Such effects can be seen *in vitro* at fields > 1 T and may play a role in orientation of magnetotactic bacteria and other organisms sensitive to the geomagnetic field. The significance of this, if any, to human health is unclear. A second major type of magnetomechanical interaction is the translation of paramagnetic and ferromagnetic substances in static magnetic field spatial gradients. However, most biological materials are only weakly diamagnetic. A few, for example de-oxygenated red blood cells, are weakly paramagnetic, but the force exerted on them even at 4 T is very small compared to gravity. The forces exerted on ferromagnetic objects such as metal tools pose dangers due to their acceleration in strong magnetic field gradients. Of particular concern in MRI, are electromagnetic interference (EMI) with the normal functioning of pacemakers and other implantable medical devices, and the physical forces on these and other implanted metal objects (such as aneurysm clips).

Several classes of organic chemical reactions can be influenced by static magnetic fields in the range from 10 to 100 mT as a result of effects on the electron spin states of the reaction intermediates. Studies carried out *in vitro* have shown that some metabolic reactions of this type can be affected. It is considered that it is unlikely that there will be major effects of physiological consequence, or even long-term mutagenic effects, arising from magnetic field induced changes in free radical concentration or fluxes.

9.2.1 Physiological responses

Mechanistic considerations and volunteer studies of acute effects from short-term exposure to static fields in the tesla range and field gradients point to the following effects: the induction of electrical potentials (flow potentials) around the major blood vessels close to and within the heart, and an increase in the resistance to blood flow in these vessels; and the induction of electrical potentials and eddy currents in the body caused by physical movement within an high static field gradient, resulting for example in vertigo and nausea during head movement. These latter effects have also been attributed to magnetohydrodynamic effects on the vestibular organs of the inner ear.

9.2.1.1 Flow potentials and reduced blood flow

Flow potentials result from Lorentz forces acting on moving charges and are generally associated with ventricular contraction and the ejection of blood into the aorta in animals and humans. The Lorentz interaction also results in a ‘magnetohydrodynamic’ force opposing the flow of blood. The reduction in aortic blood flow predicted at 5, 10 and 15 T is about 1%, 5% and 10%, respectively.

Theoretical considerations indicate that flow potentials generated by blood flow in coronary arteries may be of greater physiological significance than those generated in the aorta. The consequences of flow potentials for health are less clear. Three possibilities have been considered: changing the rate of excitation of the heart by acting on the sinoatrial pacemaker tissues, inducing the ectopic initiation of activity at sites that are not normally endogenously active, and altering the pattern of action potential propagation through the ventricular myocardium, which could be potentially arrhythmogenic. Calculations on healthy hearts suggest that the first two effects have thresholds in excess of 8 T. It is more difficult to assess the threshold for initiating potentially lethal re-entrant arrhythmias by disturbing the pattern of action potential propagation. It is important to note that these calculations have not been validated by experimental investigation, although the paper of Chakares (2005) contains some information on this.

Changes in blood pressure and heart rate were observed in some studies of healthy volunteers, but not in others. The observed changes were within the range of normal physiology. The methodological limitations of the available studies are such, however, that it is not generally possible to draw conclusions about the effects of static magnetic fields on these endpoints.

Mammalian studies do not provide strong evidence for or against effects on the cardiovascular system when exposed to static magnetic fields up to 8 T.

9.2.1.2 Movement-induced electric potentials and related effects

Physical movement within a static field gradient, such as that occurring at the entrance to an MRI scanner and head movement within the scanner, has been reported to induce transient sensations of vertigo and nausea, and sometimes phosphenes and a metallic taste in the mouth.

Occurrence of these effects is likely to be dependent on the gradient of the field and the movement of the subject. Such effects have been reported in volunteers, workers and patients exposed to static fields in excess of about 2-4 T. Such effects are also consistent with the results of animal studies in which aversive behaviour and conditioned avoidance was induced in laboratory rodents following exposure to static fields of 4 T and above.

It is conceivable that such effects, although only transient, may adversely affect people within such magnetic fields and field gradients. The available studies do not indicate that there are effects of static magnetic field exposure on neurophysiological responses and cognitive functions in stationary volunteers, nor can they rule out such effects. One study suggested that eye-hand coordination and near visual contrast sensitivity are reduced in fields adjacent to a 1.5 T MRI unit. The potential of such effects affecting the optimal performance of workers carrying out delicate procedures (e.g. surgeons) must be highlighted. Steps taken to mitigate these effects include moving slowly in and around magnets. However, the electric fields and currents induced in people working in such fields have not been clearly defined.

9.2.1.3 Other physiological responses

With regard to effects on the circulatory system, a number of researchers have reported that exposure of laboratory animals to fields up to several tesla (but sometimes as weak as the geomagnetic field of 35 - 70 μT) variously affect skin blood flow, arterial blood pressure and other cardiovascular parameters. However, these endpoints are rather labile, a situation which may have been complicated by pharmacological manipulation (including anaesthesia in some cases) and immobilisation.

A few studies in rats indicated a possible temporary or weak dysfunction of the blood brain barrier following a short clinical MRI procedure. At present, there is inadequate data to evaluate risks to human health.

Some laboratories have looked for effects of static magnetic fields on hormones, mostly the production and release of melatonin from the pineal gland. Several studies from one laboratory suggested that the inversion of the horizontal component of the geomagnetic field can affect pineal melatonin synthesis and content.

It is difficult to reach any firm conclusion without independent replication of these studies.

9.2.2 Reproduction and development

The available evidence from epidemiological studies is not sufficient to draw any conclusions about potential reproductive and developmental effects of exposure to static magnetic fields encountered in occupational environments, including MRI. The few studies that were available had severe methodological limitations.

Studies of possible reproductive and developmental effects on mammalian species are most relevant to humans. No adverse effects have been demonstrated in such studies, but few have been carried out, especially in excess of 1 T. The MRI studies, taken as a whole, were inconclusive. The animal numbers were small, the data variable and the effect, if any, impossible to disentangle from the effects of pulsed gradient magnetic or RF fields, or other potential stressors.

9.2.3 Cancer and genotoxicity

The few epidemiological studies published to date concerning the possibility of increased cancer risk from exposure to static magnetic fields leave a number of unresolved issues. Assessment of exposure has been poor, and the numbers of participants in these studies have been very small. Most of the studies were conducted in aluminium and other smelter plants. Inability of these studies to provide useful information is supported by lack of clear evidence for other, more established, carcinogenic factors present in some of the work environments. The evidence from animal studies concerning carcinogenesis is inconclusive, since too few studies have been carried out.

From the limited number of animal studies that have been published, there is no evidence that static fields of less than 1 T are genotoxic. However, while one study reported an increased frequency of micronuclei following exposure at fields of 3 or 4.7 T, there has been no replication of this work.

No genotoxic effects have been seen in *in vitro* studies following static magnetic field exposures of up to 7 T. Investigations of the combined action of static magnetic field exposure and known mutagens have shown variable results. Conclusions about synergistic effects on genotoxicity cannot be made without confirmation in mammalian studies.

9.3 Conclusions

9.3.1 Chronic and delayed effects

Electric fields

There are no studies of exposure to static electric fields from which to make any conclusion on chronic or delayed effects. IARC (2002) noted that there was insufficient evidence to determine the carcinogenicity of static electric fields.

Magnetic fields

With regard to static magnetic fields, the available evidence from epidemiological and laboratory studies is not sufficient to draw any conclusions about chronic and delayed effects. IARC (2002) concluded that there was inadequate evidence in humans for the carcinogenicity of static magnetic fields, and no relevant data available from experimental animals. They are therefore not at present classifiable as to their carcinogenicity to humans.

9.3.2 Acute effects

Electric fields

Few studies of static electric field effects have been carried out. On the whole, the results suggest that the only adverse acute health effect is associated with direct perception of fields and discomfort from microshocks.

Magnetic fields

Short-term exposure to static magnetic fields in the tesla range and associated field gradients revealed a number of acute effects.

Cardiovascular responses, such as changes in blood pressure and heart rate, have been occasionally observed in human volunteer and animal studies. However, these were within the range of normal physiology for exposure to static magnetic fields up to 8 T.

Although not experimentally verified, it is important to note that calculations suggest three possible effects of induced flow potentials: minor changes in the rate of heart beat (which may be considered to have no health consequences), the induction of ectopic heart beats (which may be more physiologically significant), and an increase in the likelihood of re-entrant arrhythmia (possibly leading to ventricular fibrillation). The first two effects are thought to have thresholds in excess of 8 T, while threshold values for the third are difficult to assess at present because of modelling complexity. Some 5 - 10 per 10,000 people are particularly susceptible to re-entrant arrhythmia, and the risk to such people may be increased by exposure to static magnetic fields and gradient fields.

The limitations of the available data are such, however, that it is not possible to draw firm conclusions about the effects of static magnetic fields on the endpoints considered above.

Physical movement within a static field gradient is reported to induce sensations of vertigo and nausea, and sometimes phosphenes and a metallic taste in the mouth, for static fields in excess of about 2 - 4 T. Although only transient, such effects may adversely affect people. Together with possible effects on eye-hand coordination, the optimal performance of workers executing delicate procedures (e.g. surgeons) could be reduced, along with a concomitant reduction in safety.

Effects on other physiological responses have been reported, but it is difficult to reach any firm conclusion without independent replication.

This risk assessment for static fields has been conducted with all the scientific information available. This has involved identifying whatever health risks can be determined and quantified. Nonetheless, the severe lack of information has meant that it has not been possible to properly characterise the risks from static field exposure. There are indications, from modelling studies and/or some observations in people, of field levels that could elicit acute effects. However, the information on long-term and delayed effects is insufficient to characterize risk, only general statements can be made, and these rely on very few well-conducted studies. Having identified large gaps in knowledge, research recommendations have been made in Chapter 1.