1.1 Summary

1.1.1 Natural and Human-made sources

Static electric fields occur naturally in the atmosphere. Values of up to 3 kV m-1 can occur under thunderclouds, but otherwise are of order of 100 V m-1 in fair weather. The next most common cause of human exposure is charge separation as a result of friction. For example, charge potentials of several kilovolts can be accumulated while walking on non-conducting carpets, generating local fields of up to 500 kV m-1. Direct current (DC) power transmission can produce static electric fields 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.

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 gas welding. Magnetic flux densities of up to 2 mT have been reported inside electric trains and in developmental magnetic levitation (MagLev) systems. Workers are exposed to larger fields of up to around 60 mT in the electrolytic reduction of alumina, and electric arc welding produces around 5 mT at 1 cm from the welding cables.

The advent of superconductors in the 1970s and 1980s facilitated the use of much larger magnetic fields in medical diagnosis through the development of magnetic resonance imaging (MRI) and spectroscopy (MRS)[1], and nuclear magnetic resonance (NMR), for research. It is estimated that some 200 million MRI scans have been performed worldwide. The static magnetic field of MRI scanners in routine clinical systems is generated by permanent magnets, superconducting magnets and combinations thereof in the range of 0.2 - 3 T. In research applications, higher magnetic fields up to 9.4 T are used for whole body patient scanning. The stray magnetic fields around the magnets for MRI studies are well defined and can be minimized in the shielded magnet versions. In terms of exposure, at the operator's console the magnetic flux density is typically about 0.5 mT, but may be higher. However, occupational exposure up to and exceeding 1 T can occur during the construction and testing of these devices, and during medical procedures carried out in interventional MRI. Various physics research and high-energy technologies also employ superconductors where workers can be exposed regularly and for long periods to fields as high as 1.5 T.

[1] This document refers throughout to MRI; exposures experienced during MRS are essentially similar.

1.1.2 Interaction Mechanisms

The following 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. Ionic currents interact with static magnetic fields as a result of Lorentz forces exerted on moving charge carriers. These effects lead to the induction of electrical (flow) potentials and currents. Flow potentials 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 of aortic blood flow has been estimated to reach about 10% at 15 T.

(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. Forces and torques on both endogenous and exogenous metallic objects are the interaction mechanism of most concern.

(3) Effects on electronic spin states of reaction intermediates. Spin-correlated radical pair chemistry has long been a consideration for magnetic field effects in chemistry and biology. Several classes of organic chemical reactions can be influenced by static magnetic fields in the range of 10 to 100 mT as a result of effects on the electronic spin states of the reaction intermediates. A spin-correlated radical pair may recombine and prevent the formation of a reaction product if two conditions are met: (a) the pair, formed in a triplet state, must be converted into a singlet state by some mechanism and (b) the radicals must physically meet again in order to recombine. Step (a) can be sensitive to magnetic fields. Most research has been on the use of radical pair magnetic field effects as a tool to study enzyme reactions. However, neither physiological effects on cellular functions, nor long-term mutagenic effects from magnetic-field induced changes in free radical concentrations or fluxes appear possible.

Dosimetry

To understand the biological effects of electric and magnetic fields, it is important to consider the fields directly influencing cells in different parts of the body and tissues. A dose can then be defined as an appropriate function of the electric and magnetic fields at the point of interaction. The establishment of a relationship between the external non-perturbed fields and internal fields is the main objective of dosimetry. Computational studies using voxel-based models of humans and animals, and experimental studies of exposure are important aspects of dosimetry.

The interactions of tissue with static magnetic fields are likely to be parametric of physical properties of the field including the magnetic field vector, the gradient of the magnetic field, and/or the product of those quantities, often termed the 'force product'. Some of the larger interactions are characterized by motion through these field quantities, such as body motion or blood flow.

Appropriate dosimetric parameters depend on the physical mechanism for the safety concern. Clearly, ferromagnetic objects must be restricted from the vicinity of the magnet. Screening for such objects and for implants that may move either due to forces or torques is imperative. Measures of peak magnetic induction vector and peak magnetic force product are appropriate. Field maps may be used to estimate these at various locations near the magnets where workers may be exposed, but personal dosimetry may be more useful.

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 occasionally magnetic phosphenes experienced by patients, volunteers and workers during movement in the field.

There are many sources of exposure and one of the most prolific is that of magnetic resonance imaging (MRI) equipment. In the past decade, there has been a concerted effort to enable MRI to operate at very high field strengths. The most common system in current clinical use has a 1.5 T central field. However, 3.0 T systems are now accepted for routine clinical work and more than 100 systems were operational worldwide by 2004. Research systems from 4 - 9.4 T are now being developed for clinical imaging. As the field strength of the MRI system increases, so does the potential for a variety of types of tissue/field interactions. Understanding the interactions between the electromagnetic fields generated by MRI systems and the human body has become more significant with this push to high field strengths.

1.1.3 In vitro studies

The results of *in vitro* studies are useful for elucidating interaction mechanisms, and for indicating the sorts of effects that might be investigated *in vivo*. However, they are not sufficient to identify health effects without corroborating evidence from *in vivo* studies.

A number of different biological effects of static magnetic fields have been explored *in vitro*. Different levels of organization have been investigated, including cell free systems (employing isolated membranes, enzymes or biochemical reactions) and various cell models (using both bacteria and mammalian cells). Endpoints studied included cell orientation, cell metabolic activity, cell membrane physiology, gene expression, cell growth and genotoxicity.

Positive and negative findings have been reported for all these endpoints. However, most data were not replicated. The observed effects are rather diverse and were found after exposure to a wide range of magnetic flux densities. There is evidence that static magnetic fields can affect several endpoints at intensities lower than 1 T, in the mT range. Thresholds for some of the effects were reported, but other studies indicated non-linear responses without clear threshold values.

Effects of static magnetic fields on cell orientation have been consistently found above 1 T, but their *in vivo* relevance is questionable. A few studies suggested that combined effects of static magnetic field with other agents such as genotoxic chemicals seem to produce synergistic, both protective and stimulating, effects. The current information is inadequate and needs to be confirmed before any firm conclusions on human health can be drawn.

Besides possible complicated dependence on physical parameters such as intensity, duration, recurrence and gradients of exposure, biological variables appear to be important for the effects of static magnetic fields. Variables such as cell type, cell activation, and other physiological conditions during exposure have been shown to affect the outcome of the experiments. The mechanisms for these effects are not known, but effects on radicals and ions may be involved. *In vitro* studies provide some evidence for this.

If the very few studies employing MRI signals or other combined fields show any biological effects, they do not show any that are different from those of static magnetic fields alone.

Taken together, the *in vitro* experiments do not present a clear picture of specific effects of static magnetic fields, and they consequently also do not indicate possible adverse health effects.

1.1.4 Animal studies

Few animal studies on the effects of static electric fields have been carried out. No evidence of adverse health effects have been noted, other than those associated with the perception of the surface electric charge.

A large number of animal studies on the effects of static magnetic fields have been carried out. Most of those considered relevant to human health have examined the effects of fields considerably larger than the natural geomagnetic field. A number of studies have been carried out of fields in the millitesla region, comparable to relatively high industrial exposures. More recently, with the advent of superconducting magnet technology and MRI, studies of behavioural, physiological and reproductive effects have been carried out at flux densities around, or exceeding, 1 T. Few studies, however, have examined possible chronic effects of exposure, particularly in relation to carcinogenesis.

The most consistent responses seen in neurobehavioural studies suggest that the movement of laboratory rodents in static magnetic fields equal to or greater than 4 T may be unpleasant, inducing aversive responses and conditioned avoidance. Such effects are thought to be consistent with magnetohydrodynamic effects on the endolymph of the vestibular apparatus. The data are otherwise variable.

There is some evidence that several vertebrate and invertebrate species are able to use static magnetic fields, at levels as low as geomagnetic field strengths, for orientation. However, these responses are not thought to have any significance for health.

There is good evidence that exposure to fields greater than about 1 T (0.1 T in larger animals) will induce flow potentials around the heart and major blood vessels, but the physiological consequences of this remain unclear. Several hours of exposure to very high flux densities of up to 8 T in the heart region did not result in any cardiovascular effects in pigs. In rabbits, short and long exposures to fields ranging from geomagnetic levels to the millitesla range have been reported to affect the cardiovascular system, although the evidence is not strong.

The results from one group suggest that the static magnetic fields of mT intensities may suppress early blood pressure elevation via hormonal regulatory system. The same group has reported that low-intensity static magnetic fields of up to 0.2 T may induce local effects on blood flow that may lead to improvement of microcirculation. In addition, another group reported that high static magnetic field flux densities of up to 10 T may lead to reduced skin blood flow and temperature. In all these cases, however, the endpoints are rather labile, a situation that may have been complicated by pharmacological manipulation, including anaesthesia in some cases, and immobilisation. In general, it is difficult to reach any firm conclusion without some independent replication.

Several studies described possible effects of magnetic field exposure on blood cells and the haemopoietic system. However, the results are equivocal, limiting the conclusions that can be drawn. The available evidence regarding effects of static magnetic field exposure on enzymatic and ionic constituents in serum comes primarily from one laboratory. These findings need to be confirmed by independent laboratories before conclusions can be drawn.

In terms of effects on the endocrine system, several studies from one laboratory suggest that static magnetic field exposure can affect pineal synthesis and melatonin content. However, some studies performed at other laboratories have been unable to demonstrate an effect. The finding of a suppressive effect of static magnetic field exposure on melatonin production needs to be confirmed in further research before firm conclusions can be drawn. On the whole, few studies have investigated static magnetic field effects on endocrine systems other than the pineal. No consistent effects have emerged.

Reproduction and development are very important issues in MRI exposure of both patients and clinical staff. In this respect, only a few good studies of static magnetic fields are available at field values above 1 T. MRI studies *per se* are uninformative because the effect of the static field cannot be distinguished from the possible general effects of the radiofrequency and pulsed gradient fields. Further examination is urgently needed to assess the health risk.

In general, so few animal studies have been carried out with regard to genotoxicity and cancer that it is not possible to draw any firm conclusions.

1.1.5 Laboratory studies on humans

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}. Annoying sensation thresholds 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.

Endpoints investigated in human experimental studies have included peripheral nerve function, brain activity, neurobehavioural and cognitive function, sensory perception, cardiac function, blood pressure, heart rate, serum proteins and hormone levels, body and skin temperature, and therapeutic effects. Exposure levels up to 8 T have been investigated, and both pure static fields and MRI imaging have been studied. The exposure duration ranged from a few seconds up to nine hours, but was usually less than one hour. The data available are limited for several reasons, including the facts that generally convenience samples of patients or healthy volunteers have been studied and the numbers of subjects have usually been small.

The results 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. A dose-dependent induction of vertigo and nausea was found in workers, patients and volunteers during movement in static fields greater than about 2 T. One study suggested that eye-hand coordination and near visual contrast sensitivity are reduced in fields adjacent to a 1.5 T MRI unit. Occurrence of these effects is likely to be dependent on the gradient of the field and the movement of the subject. A small change in blood pressure and heart rate was observed in some studies, but were in the range of normal physiological variability. There is no evidence of effects of static magnetic fields on other aspects of cardiovascular physiology, or on serum proteins and hormones. Exposure to static magnetic fields of up to 8 T does not appear to induce temperature changes in humans.

Note, however, that most of the studies were very small, were based on convenience samples, and often included non-comparable groups. Thus, it is not possible to draw any conclusions regarding the wide variety of end-points examined in this report.

1.1.6 Epidemiological studies

Epidemiological studies have been carried out almost exclusively on workers exposed to static magnetic fields generated by equipment using large DC currents. Most workers were exposed to moderate static magnetic fields of up to several 10’s mT either as welders, aluminium smelters, or workers in various industrial plants using large electrolytic cells in chemical separation processes. However, such work is also likely to have involved exposure to a variety of potentially hazardous fumes and aerosols, thus confounding interpretation. Health endpoints studied in these workers include cancer, haematological changes and related outcomes, chromosome aberration frequency, reproductive outcomes, and musculoskeletal disorders. In addition, a few studies examined fertility and pregnancy outcome in female MRI operators, where the potential to have been exposed to relatively large static fields of up to ~ 1 T may have existed. Two studies examined pregnancy outcome in healthy volunteers exposed to MRI examinations during pregnancy.

Increased risks of various cancers, e.g. lung cancer, pancreatic cancer, and haematological malignancies, were reported, but results were not consistent across studies. The few epidemiological studies published to date leave a number of unresolved issues concerning the possibility of increased cancer risk from exposure to static magnetic fields. Assessment of exposure has been poor, the number of participants in some of the studies has been very small, and these studies are thus able to detect only very large risks for such rare diseases. The inability of these studies to provide useful information is confirmed by the lack of clear evidence for other, more established carcinogenic factors present in some of the work environments. Other non-cancerous health effects have been considered even more sporadically. Most of these studies are based on very small numbers and have numerous methodological limitations. Other environments with a potential for high fields have not been adequately evaluated, e.g. those for MRI operators. At present, there is inadequate data for a health evaluation.

1.1.7 Health risk assessment

Static electric fields

There are no studies on exposure to static electric fields from which any conclusions on chronic or delayed effects can be made. IARC (IARC, 2002) noted there was insufficient evidence to determine the carcinogenicity of static electric fields.

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

Static magnetic fields

The available evidence from epidemiological and laboratory studies is not sufficient to draw any conclusions with regard to chronic and delayed effects. IARC (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. Their carcinogenicity to humans is therefore not at present classifiable.

Short-term exposure to static magnetic fields in the tesla range and associated field gradients induce 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. These include minor changes in heartbeat (which may be considered to have no health consequences), the induction of ectopic heartbeats (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, and 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 put them all together to draw firm conclusions about the effects of static magnetic fields on the endpoints considered above.

Physical movement within a static field gradient induced 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, with a concomitant impact on safety.

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

1.1.8 Recommendations for national authorities

National authorities are recommended to implement programs that protect both the public and workers from any untoward effects of static fields. However, given that the main effect of static electric fields is discomfort from electric discharge to tissues of the body, the protective program could merely be to provide information on situations that could lead to exposure to large electric fields and how to avoid them. A program is needed to protect against established acute effects of static magnetic fields. Because sufficient information on possible long-term or delayed effects of exposure is currently unavailable, cost-effective precautionary measures such as those being developed by WHO (www.who.int/emf) may be needed to limit the exposures of workers and the public.

National authorities should adopt standards based on sound science that limit the exposure of people to static magnetic fields. Implementation of health-based standards provides the primary protective measure for workers and the public. International standards exist for static magnetic fields (ICNIRP, 1994) and are described in Appendix 1. However, WHO recommends that these be reviewed in light of more recent evidence from the scientific literature.

National authorities should establish or complement existing programs that protect against possible effects of exposure to static magnetic fields. Protective measures for the industrial and scientific use of magnetic fields can be categorized as engineering design controls, the use of separation distance, and administrative controls. Protective measures against ancillary hazards from magnetic interference with emergency or medical electronic equipment, and for surgical and dental implants, are a special area of concern regarding possible adverse health effects of static magnetic fields. Precautions must be taken because of the mechanical forces imparted to ferromagnetic implants and loose objects in high-field facilities.

National authorities should consider licensing MRI units in order to ensure that protective measures are implemented. This would also allow additional requirements for MRI units with strengths in excess of local national standards or 2 T to be complied with. Such requirements relate to provision of information on patients, workers and any incidents or injuries resulting from the strong magnetic fields.

National authorities should fund research to fill the large gaps in knowledge that pertain to the safety of people exposed to static magnetic fields. Recommendations for further research form part of this document (see below) and are posted on the WHO web site: www.who.int/emf. Researchers should be funded to conduct studies recommended in this WHO research agenda.

National authorities should fund MRI units to collect information on worker exposure to static magnetic fields and patient exposure to MRI. These should be available for future epidemiological studies. They should also fund databases collecting information on exposures to workers where high long-term exposures occur, such as those involved in the manufacture of MRI or similarly high strength magnets and new technologies such as MagLev trains.

1.2 Recommendations for further study

Identifying gaps in our knowledge of the possible health effects of static field exposure is an essential part of this health risk assessment. The following recommendations for further research have been made.

1.2.1 Static electric fields

There appears to be little benefit in continuing research into the effects that static electric fields have on health. None of the studies conducted to date suggest any untoward health effects, except for possible stress resulting from prolonged exposure to microshocks. Thus, there are no recommendations for further research concerning biological effects from exposure to static electric fields. In addition, there is only limited opportunity for significant exposure to these fields in the workplace or living environment and this therefore does not warrant any epidemiological studies.

1.2.2 Static magnetic fields

In general terms, research carried out to date has not been systematic and has often been performed without appropriate methodology and exposure information. Coordinated research programs are recommended as an aid to a more systematic approach. There is also a need to investigate the importance of physical parameters such as intensity, duration and gradient on biological outcome.

Following a discussion of the limitations of existing studies, further research is recommended covering epidemiology, volunteer studies, animal and *in vitro* biology, studies into mechanisms of interaction, and theoretical and computational investigations. These recommendations are summarized in Table 1.

1.2.2.1 Theoretical and computational studies

Computational dosimetry provides the link between an external static magnetic field and the internal electric fields and induced currents caused by movement of living tissues in the field. Such theoretical techniques allow the fields to be characterised in specific tissues and organs. There are 4 fine resolution, anatomically realistic, voxel phantoms of adult men available, and these have been widely used in studies with time-varying electromagnetic fields. However, very little work has been done with static fields, and further work is considered necessary using these models. In particular, the use of different sized phantoms, and the use of female phantoms, is considered important, as is the use of pregnant phantoms with fetuses of differing ages. Similar studies could be performed with phantoms of pregnant animals to aid interpretation of the results of developmental studies with these models. (**Medium priority**)

A very fine resolution head-and-shoulder phantom should be developed and used to investigate the electric fields and currents associated with visual phosphenes and vertigo. This model could also be used to investigate the fields and currents generated by head and eye movements in a static magnetic field. The latter is considered of particular relevance to interventional MRI procedures where reduced head movements of surgeons and other clinical staff may necessitate increased movement of the eyes. Gross body movement by staff around the interventional system should also be simulated. (**High priority**)

Computations using a detailed model of the heart and modelling of common cardiac pathologies are considered important. This model should include the micro-architecture of the heart as well as the smaller blood vessels within the heart that might produce fields and currents that could have some influence on pacemaker rhythm generation and the propagation of depolarisation. In addition, calculations are necessary to estimate the magnitude and spatial distribution of currents that are induced in the heart as a consequence of field and field gradient exposure. Multiple orientations to the field should be studied. These would allow comparison with the currents that have been calculated to induce cardiac effects. Supportive experimental and laboratory studies are recommended. (**High priority**)

Although there is a reluctance to use high field MRI on pregnant women at the moment, it is acknowledged that this situation may change. It would therefore be advisable to carry out modelling studies investigating the currents induced in a fetus by maternal or intrinsic fetal movement in a high field. These calculations (and similar studies with gradient and radiofrequency fields) would allow an estimate to be made of the likelihood of possible effects on the fetus. (**High priority**)

1.2.2.2 In vitro studies

Static magnetic fields may interact with biological systems in a number of ways, although the most likely means of causing health effects are via field-induced effects on charged molecules and alterations in the rate of biochemical reactions.

Further studies are needed on possible mechanisms and targets for biological effects of static magnetic fields. It is recommended to investigate the effects of static magnetic fields of 0.01 - 10 T on interaction of ions (e.g. Ca^{2+} or Mg^{2+}) with enzymes and radical pair formation. Although it is considered difficult to do, there is merit in searching for more enzymatic reactions that proceed through radical pair mechanisms in model systems that are relevant for human health. Another suggestion is to concentrate on toxic radical species, such as the superoxide, which are known to be damaging and are produced by free radical mechanisms. (**Medium priority**)

Reports of a co-mutagenic effect in various cells are of particular interest concerning the carcinogenic potential of static magnetic fields. This type of study should be performed using human primary cells and extended to include transformation and genetically-modified systems. (**High priority**)

Static magnetic fields might affect gene expression and relevant functions in human and mammalian cells under specific conditions of exposure, but there is only little information available on this. Studies with techniques such as proteomics and genomics should be performed with primary human cells to search for possible molecular markers for effects of static magnetic fields relevant to human health issues. (**Low priority**)

1.2.2.3 Animal experimental studies

The effects of long-term exposure to static magnetic fields can be addressed using animal models. In the absence of specific information regarding the carcinogenic potential of static magnetic fields, long-term (including life-time) studies are recommended. Both normal and genetically-modified animals could be used. For example, if an amplification of free radicals was considered a possible route whereby cancer risk may be increased, a mouse model with deletion of the superoxide dismutase gene could be used. The susceptibility to tumours and other free radical related diseases is greatly enhanced in this model. The use of microarray techniques allows the effects of many different exposure parameters to be readily assessed and quantified on the genome and proteome. (**High priority**)

The possibility of increased risk of developmental abnormalities and teratological effects needs to be addressed in a systematic fashion. The developing brain may be particularly susceptible to the effects of movement-induced currents since orientation effects are very important for guiding the normal growth of neuronal dendrites. It is also possible that long-lasting changes could be induced by relatively short exposures. The study of neurobehavioural parameters can provide a rapid and sensitive assay to explore the effects of exposure on developing brain function, and such studies are recommended. Studies to chart the subtle morphological changes that occur during development of specific regions of the brain, such as the cortex or hippocampus, are also of value. The use of appropriate transgenic models should be considered. (**High priority**)

Although there are data indicating that exposure of animals (and human) to fields of around 2 T does not cause electrophysiological effects, it would be useful to know the effects of higher fields. Thus the effects of exposure up to and above 10 T could usefully be explored in animals. (**Medium priority**)

A variety of other endpoints have been investigated in animals that have so far provided only limited information. While a series of single studies for each of those endpoints might not be cost-effective, a broad animal study to cover different endpoints might be worthwhile. (**Low priority**)

1.2.2.4 Human experimental studies

The cognitive and behavioural effects of static magnetic fields should be investigated further. However, the available data do not suggest particular risks to specific aspects of cognition nor do they suggest which parameters should be tested in the laboratory. In the absence of a clear direction, a possible approach would be to investigate the effects of exposure on the performance of a battery of cognitive tasks that encompass standard tests of attention, reaction time and memory, if only to act as an initial screen pending more focused work. The initial work could be done with volunteers as part of experimental studies. (**Medium priority**)

With a wider utilization of MRI studies where support staff are in close proximity to patients within a magnet, such as in MRI interventional procedures, additional studies are needed of head and eye coordination, cognitive performance and behaviour in a gradient field. Further investigation of mechanisms and intensity of field-induced vestibular dysfunction including vertigo is considered of special interest because of the increasing likelihood that medical staff will be performing complicated tasks for extended periods of time within a magnetic field. (**High priority**)

Similarly, additional studies on cardiac function would be useful and could investigate effects on the cardiovascular system. These studies may also need to be performed at higher than 3 T to evaluate potential risks beyond those in the routine clinical environment. (**Low priority**)

1.2.2.5 Epidemiological studies

There are a number of categories of workers with elevated exposures to static magnetic fields, including MRI technicians, workers at aluminium smelting plants, and certain transportation workers (those on subways, MagLev trains, commuter trains, and light rail). For rare chronic diseases such as cancer, feasibility studies are needed to identify the highly exposed occupational groups that could be assessed for participation in epidemiological studies. Feasibility studies also need to determine which other exposures are present in these occupations. If sufficient numbers of workers can be identified, then a nested case-control approach is probably the most appropriate, since detailed information about the exposure and important confounding variables, such as ionizing radiation, needs to be obtained. International collaborative studies will probably be necessary to obtain sufficient numbers of exposed subjects. (**High priority**)

For other more common health outcomes with short latency periods, specific highly exposed occupational groups (for example, workers in industries where MRI systems are manufactured) can be identified and followed over time. Information about different health outcomes may already be available from routinely performed health examinations of these workers, but this can only be used if similar information is also available for a comparable unexposed group. A health survey of surgeons, nurses and other workers using interventional MRI would provide useful information as to levels, durations and frequency of exposures of workers to static fields in these systems. Similarly, patient records may exist in some hospitals from which it might be possible to obtain data on people who were exposed, but whose condition was subsequently found to be benign. (**High priority**)

There is also merit in performing a prospective study of pregnancy risks associated with occupational static magnetic field exposure, as well as follow-up studies of pregnancy outcomes of pregnant women who had to undergo MRI examinations. (**High priority**)

Experience with other frequencies has shown that obtaining reliable estimates of exposure to electromagnetic fields for use in epidemiological studies can be very difficult, and surrogate measures of exposure, such as job title or distance from a particular source, may not always provide sufficiently accurate assessments. The use of specific instruments is thus required to measure exposure. Relatively small personal dosimeters have proved very useful in research on ELF fields. Personal dosimeters would therefore greatly improve exposure assessment in epidemiological studies. Numerical and experimental validation of the dosimeters should be performed. Magnetic field strength, magnetic field gradients, exposure durations and, ideally, the rate of change of the magnetic due to motion should be recorded. (**High priority**)

Table 1. Recommendations for research

Interaction mechanisms	
	Chemistry of radical pair reactions (0.1 - 10 T)
	Co-mutagenic effects using human cells
Theoretical and computational studies	
	Dosimetric studies with male/female/pregnant voxel phantoms
	Induced currents in the eye
	Flow potentials in the heart
***In vitro* studies**	
	Interaction mechanisms: radical pair reactions and enzymatic activity
	Influence of physical parameters (intensity, duration, recurrence, SMF gradients)
	Mutagenicity and transformation in primary human cells
	Gene expression in primary human cells
Experimental studies with animals	
	Cancer
	Developmental/neurobehavioural effects
	Cardiac function (~20 T)
Experimental studies with volunteers	
	Vestibular function, head and eye coordination
	Cognitive performance and behaviour
	Cardiovascular effects
Epidemiological studies	
	Feasibility study of exposure sources, confounding factors, no. exposed
	Nested case-control study of chronic disease, e.g. cancer (if feasible)
	Pregnancy outcomes in relation to occupational exposure and MRI examinations
	Cohort study of short-term effects in highly exposed occupations