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Advice on Limiting Exposure to Electromagnetic Fields (0–300 GHz)

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Statement by the National Radiological Protection Board

Advice on Limiting Exposure to Electromagnetic Fields (0–300 GHz)

The Board of NRPB has recommended the adoption in the UK of the guidelines of the International Commission on Non-Ionizing Radiation Protection (ICNIRP) for limiting exposures to electromagnetic fields (EMFs) between 0 and 300 GHz. This follows a thorough review of current scientific knowledge on the effects of EMFs and an extensive consultation exercise. The Board recognises the need to adopt a cautious approach in the interpretation of scientific knowledge and the benefits of common international guidelines.

BOARD STATEMENT

1 Following a review of the relevant scientific data (NRPB, 2004a) and an extensive consultation exercise, NRPB has issued new advice on exposure guidelines for electromagnetic fields (EMFs) (NRPB, 2004b). In establishing quantitative restrictions on exposure to EMFs a range of values are possible, particularly when taking into account uncertainties in the responses of different groups of individuals in the general population. The review of current scientific knowledge by NRPB staff, the adoption of a cautious approach to the interpretation of these data, and a recognition of the benefits of international harmonisation, combine in the Board's recommendation to adopt the ICNIRP exposure guidelines for occupational and public exposure to EMFs between 0 and 300 GHz (ICNIRP, 1998).

2 The detailed scientific analysis by NRPB staff supports the recommendation by ICNIRP that exposure guidelines for members of the public should be more restrictive than for workers. This allows for a greater sensitivity to adverse health effects in the general population than for the working population. Increases in sensitivity may occur in infants and children, individuals being treated with medication, and those in the later years of life. The ICNIRP recommendation of a reduction factor of five in the basic restrictions for members of the public compared with workers is appropriate.

3 In the light of ongoing research, major health risk assessments being carried out by the World Health Organization (WHO), and the possibility of further advice from ICNIRP, the Board considers that guidelines on limiting exposure to EMFs should be kept under review. NRPB staff will continue to monitor the results of research related to the effects of EMFs on health and to make further recommendations when appropriate.

4 The Board recognises that there are concerns that prolonged low level exposure to EMFs across the range 0–300 GHz may be implicated in the development of long-term health effects, in particular cancer. Relevant epidemiological and biological studies have been reviewed in reports by the independent Advisory Group on Non-ionising

Radiation (AGNIR, 2001a,b, 2003). These conclude that there is no firm evidence of such adverse health effects at the levels of EMFs to which people are normally exposed.

5 An association between prolonged exposure to intense power frequency magnetic fields and a small raised risk of childhood leukaemia has, however, been found, the scientific reasons for which are presently uncertain. In the light of these findings and the requirement for additional research, the need for further precautionary measures should be considered by government.

BACKGROUND

6 The National Radiological Protection Board (NRPB) has the responsibility for providing advice on limiting exposure of people to electromagnetic fields (EMFs). These include static, power frequency (50 Hz in the UK), and other extremely low frequency (ELF) electric and magnetic fields, and radiofrequency (RF) fields and radiation. The new advice from NRPB (2004b), supported by a review of the scientific evidence (NRPB, 2004a), updates previous advice on limiting exposure to EMFs (NRPB, 1993, 1999).

7 These revised recommendations have been developed as part of the ongoing review by NRPB of the scientific evidence underlying the exposure guidelines for EMFs. The present review was requested by the Department of Health and has particularly examined the issues of uncertainty in the science and aspects of precaution. The advice on exposure guidelines is based on an assessment of the possible effects of EMFs on human health. It is derived from epidemiological studies of exposed human populations, experimental investigations, results from volunteer studies, and dosimetric information.

8 In developing these recommendations, NRPB has drawn upon advice from individual UK and international scientific experts and from published comprehensive reviews by expert groups. It has additionally sought advice from an ad hoc expert group on weak electric field effects in the body. NRPB organised an open meeting to listen to public concerns about power lines in December 2002 and it was also aware of issues raised at open meetings organised by the Independent Expert Group on Mobile Phones (IEGMP, 2000). A consultation document on the new guidelines was issued in May 2003. Comments received from that consultation have been addressed in completing a review of the science and in formulating the advice.

9 Generally, occupational exposure concerns healthy adults working under controlled conditions. These conditions include the opportunity to apply engineering and administrative measures and, where necessary and practical, to provide personal protection. For members of the public, similar controls do not generally exist, and individuals of varying ages can have wider variability in health status and responses to exposures to EMFs. For these reasons exposure restrictions for the public are lower than those recommended for the working population.

10 Restrictions on exposure to EMFs are designed to prevent adverse health effects and are based on their interactions with body tissues. They are termed *basic restrictions* as they are developed from experimental data relating to thresholds for *direct* and *indirect* health effects, which give rise to the fundamental limits on exposure. Generally, the basic restrictions are not readily measurable.

11 Direct effects are those resulting from the interaction of EMFs with the human body. For exposure to static magnetic fields, the restrictions are intended to avoid the induction of vertigo and nausea. For electric and magnetic fields, up to a frequency of about 100 kHz, the restrictions are intended to avoid adverse effects of induced electric fields and currents on the functions of the central nervous system. For RF fields, above about 100 kHz, which include microwaves, the restrictions are intended to prevent adverse effects due to excessive whole- and partial-body heating.

12 Indirect effects are those resulting from an interaction between EMFs, an external object such as a vehicle or other mechanical structure, and the human body. For these effects, advice on limiting exposure is provided to avoid the shocks and burns that might result. Such effects may be avoided by limiting the external electric field or by other engineering or administrative controls.

13 *Reference* levels are also given; these are conservatively derived levels relating to the electric field, magnetic field, or current for comparison with measurements that can readily be made. Comparison of measurements with the reference levels can be used to assess whether compliance with the basic restrictions has been achieved. If the field to which a person is exposed exceeds the relevant reference level it does not necessarily follow that the basic restriction is exceeded. It is, however, then necessary to investigate compliance with the basic restriction using more detailed methods of exposure assessment. The reference levels may be used to indicate whether there is a need to take appropriate action to prevent shock and burn.

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ADVICE ON LIMITING EXPOSURE TO ELECTROMAGNETIC FIELDS (0–300 GHz)

ABSTRACT

The National Radiological Protection Board (NRPB) has the responsibility for providing advice on exposure guidelines for electromagnetic fields (EMFs). As part of its policy of ongoing evaluation of scientific evidence and health risk assessment, NRPB has reviewed its advice on limiting exposure to EMFs and, at the request of the Department of Health, has particularly addressed the issues of uncertainty in the science and aspects of precaution.

As a result of this review, NRPB recommends the adoption of the guidelines of the International Commission on Non-Ionizing Radiation Protection (ICNIRP) for limiting exposure to EMFs.

In its review of the science, NRPB has drawn upon advice from individual UK and international scientific experts and from published comprehensive reviews by expert groups. It sought advice from an ad hoc expert group on weak electric field effects in the body and gave careful consideration to the views expressed in response to a consultation document on its proposed guidelines issued in May 2003. NRPB has listened to the concerns raised at a public open meeting on power lines held in December 2002 and is also aware of issues raised at the open meetings held around the country by the Independent Expert Group on Mobile Phones (IEGMP).

Uncertainties, particularly in relation to the responses of different groups of individuals, result in a range of possible values for restrictions on exposure. The review of the science, the need to adopt a cautious approach, and recognition of the benefits of international harmonisation combine in the recommendation to adopt the ICNIRP EMF exposure guidelines. These guidelines incorporate two tiers of protection: one set of values for occupational exposure and another, more restrictive, set for general public exposure.

NRPB is committed to monitoring the results of further research related to effects of EMFs on health and to revising its advice when appropriate.

There remain concerns about possible effects of exposure to EMFs and, in particular, power frequency magnetic fields. The view of NRPB is that government should consider the possible need for further precautionary measures.

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This advice from NRPB reflects understanding and evaluation of the current scientific evidence as presented and referenced in this document.

INTRODUCTION

1 The National Radiological Protection Board (NRPB) has the responsibility for providing advice on exposure guidelines for electromagnetic fields (EMFs) in the frequency range 0–300 GHz. In 1993, NRPB published a comprehensive review of epidemiological and experimental data relevant to the assessment of health effects from exposure to EMFs and provided advice on limiting exposure (NRPB, 1993). This advice gave similar exposure guideline values for workers and members of the public. NRPB subsequently reviewed its advice (NRPB, 1999) following publication of exposure guidelines by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) with restriction values for workers broadly similar to those of NRPB but which also included more restrictive values for members of the public (ICNIRP, 1998). At the time, NRPB saw no scientific evidence for changing its previous advice.

2 In May 2000, an Independent Expert Group on Mobile Phones (IEGMP) published a report on mobile phones and health (IEGMP, 2000). This report contained a recommendation to government to adopt, 'as a precautionary approach', the general public exposure guidelines of ICNIRP for mobile telephony. The government responded positively to this recommendation and the Board of NRPB supported the government's response (NRPB, 2000). The Board noted that it had foreseen in its statement of 1999 that, in the absence of direct scientific evidence, government may take other factors into account in establishing generally accepted exposure guidelines for the public. Moreover, in issuing the supportive statement, it was recognised that the Board's advice would be further developed following detailed consideration of the IEGMP recommendation, taken together with other relevant information.

3 The recommendation by IEGMP to adopt the ICNIRP exposure guidelines was put forward as 'a precautionary approach' to reflect some uncertainties in knowledge about possible biological effects of exposures to radiofrequency (RF) fields. A recommendation to adopt the ICNIRP guidelines for RF exposure had already been made by the Select Committee on Science and Technology (SCST, 1999) and supported by the Scottish Parliament Transport and the Environment Committee (SPTEC, 2000) in their respective reports on mobile telecommunications. Support for the IEGMP recommendation has also been expressed by various other UK bodies in connection with planning issues and the development of telecommunications masts. These included the (then) Department of the Environment, Transport and the Regions, the Welsh Assembly Government, the Scottish Executive, and the Department of the Environment for Northern Ireland.

4 The ICNIRP guidelines also provided the basis for a Council of the European Union (CEU) Recommendation on limiting exposure of the general public to EMFs (CEU, 1999), which the UK supported. This Recommendation covers the EMF spectrum up to 300 GHz, encompassing static fields and power frequencies (50 Hz in the UK), in addition to RF fields.

5 As part of its policy of ongoing evaluation of scientific evidence and health risk assessment, NRPB has reviewed its advice on limiting exposure to EMFs and, at the request of the Department of Health, has particularly addressed the issues of uncertainty in the science and aspects of precaution*.

* In this document the terms 'precaution' and 'precautionary' are used strictly in relation to possible additional measures that might be considered in the light of the uncertainties associated with the evidence of long-term adverse effects of exposure.

6 In developing this document, NRPB drew upon advice from individual UK and international scientific experts and upon published comprehensive reviews from expert groups. These groups included the independent Advisory Group on Non-ionising Radiation (AGNIR), IEGMP, ICNIRP and the World Health Organization (WHO).

7 NRPB also identified the need for additional specific scientific advice on weak electric field effects in the body and invited an ad hoc scientific expert group to provide this. The conclusions of these experts are in the associated scientific review document (NRPB, 2004). A further input was an ICNIRP/WHO international workshop on the topic organised by NRPB (ICNIRP/WHO, 2003).

8 In order to provide as wide an input to the scientific review and recommendations as possible, a consultation document was developed. This document was published on the NRPB website on 1 May 2003 and, over three months of consultation, around 50 sets of comments were received from individual scientific experts, government departments, industry, individual citizens and special interest groups. NRPB has carefully considered all of these comments in formulating the recommendations for limiting exposure to EMFs set out in this document.

9 NRPB also listened to the concerns raised at a public open meeting on power lines it organised in December 2002 and was aware of issues raised at the open meetings held around the country by IEGMP.

DEVELOPMENT OF EXPOSURE GUIDELINES

Role of science

10 National and international guidelines for limiting exposure to EMFs have the objective of preventing adverse effects on health.

11 They are based on thorough reviews of the science – an approach that necessitates caution and judgement both in assessing individual studies and their significance in identifying possible adverse effects on human health, and in addressing the uncertainties in the science. Caution* has been exercised in arriving at judgements on exposure levels for preventing health effects that are supported by the totality of the scientific evidence. An important aspect of this approach is the need to highlight where data are sparse and/or inconclusive and to identify where further relevant research is appropriate.

12 The interaction of EMFs with the human body leads to *direct effects*, while *indirect effects* result from the interaction between EMFs and another object, such as a vehicle or other mechanical structure, with which the body comes into contact.

13 Epidemiological and biological data, together with dosimetric information, underpin the basic framework for exposure restrictions on EMFs and the derivation of external field strength levels used in assessing compliance with the guidelines.

* In this document the terms 'caution' and 'cautious' are used strictly to describe the approach taken in evaluating scientific data and in particular the uncertainties associated with these data and in making judgements as to their relevance to exposure restrictions.

14 Of greatest importance to the development of exposure guidelines are well-controlled human laboratory and epidemiological studies. They most closely relate to the exposure of people to EMFs and the physiological and/or adverse health effects that might result from, or correlate with, such exposures.

15 Animal studies are also important, but with caveats as to the conclusions that might be drawn from them with respect to effects on human health.

16 Cellular (or *in vitro*) studies can provide data that increase knowledge about possible mechanisms of biological interaction at the cellular and subcellular level in living systems.

17 Computational dosimetry provides both knowledge of the nature of the physical interactions of EMFs with living matter (people, animals and *in vitro* preparations), and knowledge linking the strengths of external fields to which people may be exposed with those of fields induced in their bodies.

18 Guidelines for limiting exposure of people to EMFs are intended to provide a framework for a system of protection by recommending limits on exposure, generally termed *basic restrictions*, to avoid the adverse health consequences of exposure. Generally the basic restrictions are not readily measurable.

19 Another set of levels, generally termed *reference levels* (or *investigation levels*), is also provided in exposure guidelines. These are expressed as measurable field and electric current quantities in order to assist the assessment of compliance with the basic restrictions for particular exposure situations. NRPB advice has not been prescriptive with regard to setting field limits, in order to allow the health and safety professional to use the most up-to-date measurement and computational techniques in assessing compliance with the basic restrictions. This system, first developed by NRPB (1993), has proved effective in practice and has been adopted by other expert advisory bodies including ICNIRP (1998).

Epidemiology

20 Epidemiology can be defined as the study of the distribution of disease in populations and of the factors that influence this distribution. In contrast to clinical medicine where the emphasis is on treating the individual, epidemiology is concerned with evaluating patterns of disease among groups of individuals. Consequently the conclusions drawn from epidemiological studies are applicable generally, rather than to specific individuals.

21 Epidemiology has proved to be of great value in studying the effects of various agents on human health and, particularly for cancer, in quantifying risks (Doll, 1998). Epidemiological studies of people exposed to EMFs have the advantage over animal studies of providing direct information on the health of people subject to such exposures. However, a number of caveats must be borne in mind when attempting to interpret epidemiological results (NRPB, 2004).

22 The observational nature of epidemiology makes it difficult to infer causal relationships based on epidemiological studies alone, and such inferences are possible only when the evidence is strong. Difficulties of low statistical power and multiple hypothesis testing may also affect the interpretation of studies. Nevertheless, in combination with information from other sources (such as experimental studies), epidemiological studies can assist in testing for causality – for example, using the guidelines suggested by Bradford Hill (1965).

23 Therefore, epidemiological results can provide an input to guidelines for limiting exposure, although the importance of information from other sources should be recognised (NRPB, 2004). Furthermore, the strengths and weaknesses of both epidemiological and experimental findings require critical review and informed judgement.

Biology

24 Biological studies include laboratory experiments with volunteers, with various animal species including rats and mice, and with cells in culture. Exposure may last from a few minutes in the case of volunteer studies, to several years in the case of lifetime animal studies. The main objective of these studies is to determine the biological responses that occur as a result of exposure to EMFs, and to evaluate any uncertainties concerning the reliability with which these responses can be defined. Studies are evaluated for the rigour with which they are conducted, their consistency with other experimental results, their biological plausibility and their coherence, or compatibility with current scientific understanding (NRPB, 2004).

25 Experimental studies using volunteers, including those exposed to EMFs, are restricted for ethical reasons to the investigation of transient physiological phenomena which, in the controlled conditions of a laboratory, can be determined to be harmless. The advantage of volunteer experiments is that they indicate the likely response of other people exposed under similar conditions. Disadvantages of volunteer studies include the innocuous nature of the effects able to be investigated, the often short duration of investigation, and the small number of subjects usually examined. Such experiments are subject to ethical constraints; the subjects are usually adults screened for medical fitness and therefore may not reflect the responses of potentially more susceptible members of society. Within this limited context, however, volunteer studies can give valuable insight into the physiological effects of exposure to an agent.

26 Animal studies are frequently based on experiments using inbred strains of mice or rats. The advantage of such studies compared with studies using cells (*in vitro* studies) is that they provide information concerning the interaction of EMFs with living systems which display the full repertoire of body functions, such as immune responses, cardiovascular changes and behaviour, in a way that cannot always be achieved with cellular studies. Individual animals in inbred strains are genetically identical, thus ensuring a relative consistency of response to the agent in question. Transgenic or gene knockout animal models of certain diseases have further increased the value of animal studies to reveal potential adverse health effects. Animal studies are usually a more powerful experimental tool than cellular studies in this context, but typically are more expensive and time-consuming. Extrapolation of this information to humans cannot, however, be expected *a priori* to be straightforward since there are obvious differences in physiology and metabolism between species as well as differences in life expectancy, the proliferative capacity of different tissues, DNA repair capacity, and many other variables. However, at a molecular level, there are many similarities between processes in animals and humans. For example, animal studies have been valuable in helping to unravel the sequence of genetic events in the development of a number of human cancers and in identifying agents that cause cancer.

27 Studies carried out at the cellular level are usually used to investigate mechanisms of interaction with EMFs but are not generally taken alone as evidence of effects *in vivo* (in animals or people). There are a number of reasons for this. Cells in culture are removed from the normal constraints of growth *in vivo*, the culture medium usually contains biological supplements to enable the cells to grow, and quite often the cell lines used are derived from various types of cancer because of their ability to grow for long periods in culture.

28 The interpretation of biological evidence is crucial to making judgements of harm. It is therefore necessary at the outset to identify criteria for assessing the strength of the experimental evidence to be discussed. The more important criteria in this context are the adequacy of experimental design, statistical analysis of the data, and the avoidance of possible confounding that might otherwise result in a misleading or erroneous conclusion (Repacholi and Cardis, 1997). It is a fundamental principle of scientific investigation that effects described in one laboratory can be repeated in the same and in other laboratories, providing the correct procedures and protocols are followed. Replication of an effect by an independent laboratory considerably strengthens the view that any effect represents a true response.

29 Extrapolating from biological effects to possible adverse human health effects is not straightforward. Biological effects can be defined as any detectable changes in a biological system in response, for example, to EMFs – but not all effects will necessarily result in harm. For example, eating food causes substantial changes in the levels of circulating nutrients, biochemicals and hormones in the body but these biological effects are not adverse health effects. WHO defines health as the state of complete physical, mental and social well-being, and not merely the absence of disease or infirmity (WHO, 1946). Deciding whether biological changes have adverse health consequences depends on whether they affect the mental, physical or general well-being of exposed people, in either the short- or the long-term. Permanent damage to organs and tissues is clearly harmful, but transient functional changes are more difficult to categorise. In this regard, the context of the exposure might be important. For example, a transient but marked perception of the field may be entirely inconsequential in most cases, but could be expected to reduce the effectiveness of a worker performing a cognitively demanding task, and be stressful to people chronically exposed.

Dosimetry

30 Computational dosimetry provides a link between external non-perturbed EMFs and the fields induced within living matter. It is a useful tool for planning and carrying out experimental studies in cells and animals and in providing a pointer to the choice of reference levels as measurable quantities in relation to basic restrictions for the exposure of people (NRPB, 2004).

31 The approach to deriving reference levels is to solve Maxwell's equations numerically in fine resolution, anatomically realistic models of the body. These models are usually derived from medical imaging data and are referred to as voxel (volume pixel) phantoms. The phantom structure is a three-dimensional array of voxels, each of which has an identifying tag denoting the discrete tissue type or the surrounding air.

32 Computational techniques may also be used to relate specific energy absorption rate (SAR*) to temperature rises within the body, thereby helping to indicate basic restrictions on SAR which will avoid adverse effects due to heating.

33 Experimental dosimetry plays an important complementary role with computational dosimetry, but more with regard to the measurement of exposures and compliance testing than with the development of exposure guidelines.

Scientific uncertainty

34 Like all scientific investigation, studies on the effects of EMFs are subject to uncertainties. Further, uncertainties arise when the results of animal studies are extrapolated to possible effects in people because of the inter-species and inter-strain differences that exist. Even the results from well-designed and well-conducted experimental and epidemiological studies have uncertainties that can be statistically quantified, but may not always be explained. In addition, not all studies are equally well designed and executed, and this should be taken into account when assessing the available information.

35 To ensure that exposure guidelines provide general community protection, the health risk assessment includes recommendations based on the above criteria (NRPB, 2004). An intrinsic part of the EMF risk assessment process is the exercise of caution. The degree to which caution is applied in the interpretation of the scientific evidence is a matter of judgement and should be consistent.

36 In recommending values for exposure restrictions, judgements have been made as to the degree of uncertainty in the scientific data on the adverse effects on which such restrictions are based and how this indicates the choice of the restriction values. The basic restrictions on exposure recommended in this document for preventing direct adverse health effects of exposure to EMFs and other recommendations for limiting the occurrence of indirect effects (eg shock and burn) include such considerations and overall they reflect a cautious approach.

37 Generally, occupational exposure concerns healthy adults working under controlled conditions. These conditions include the opportunity to apply engineering and administrative measures and, where necessary and practical, provide personal protection. For members of the public, similar controls do not generally exist, and individuals of varying ages can have wider variability in health status and responses to exposures to EMFs.

38 Judgements have also been made concerning the degree to which exposure should be further restricted where increased susceptibility is expected on scientific grounds, but where, because there is a lack of specific scientific data, the degree of susceptibility has not been quantitatively determined. These judgements form the basis of recommendations for more restrictive exposure values for members of the public compared with those for workers, again reflecting a cautious approach (NRPB, 2004).

* Specific energy absorption rate (SAR) is the rate of absorption of electromagnetic energy per unit mass, measured in watts per kilogram ($W\ kg^{-1}$).

39 The cautious interpretation of scientific data in order to develop appropriate guidance on exposure is seen as a necessary measure, pending clarification through further research. A number of recommendations are made which are specifically aimed at developing guidance through research in key areas where continuing uncertainty limits the rigour with which appropriate restrictions on exposure can be formulated.

SUMMARY OF SCIENTIFIC EVIDENCE

40 A review of the scientific evidence underpinning the advice given in this document has been carried out (NRPB, 2004). The following summarises the main conclusions of that review in the context of the development of exposure guidelines.

Static electric and magnetic fields

41 Static electric fields interact directly with the body by inducing a surface electric charge. Indirect effects can also occur when a person is in contact with a charged conducting object, eg a vehicle exposed to a static field. At sufficiently high voltage the air will ionise and become capable of conducting an electric current between the charged object and a person in good electrical contact with the ground. A charged insulated person touching a grounded object would receive a microshock (spark discharge). Very few laboratory studies have investigated the effects of exposure to static electric fields.

42 Cutaneous perception is the most robust biological consequence of exposure to static electric fields. A threshold for perception has been reported around 20 kV m^{-1} and annoying sensations were induced above about 25 kV m^{-1}. Painful spark discharges 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 the ground. However, threshold static electric field values for spark discharges will vary depending on the degree of insulation and other factors. Skin diseases do not appear to be caused by EMFs from visual display units (VDUs), although existing skin conditions may be aggravated.

43 The interactions of static magnetic fields with biological materials include magnetomechanical effects, effects on electronic spin states in certain types of charge transfer processes, and electrodynamic interactions with ionic conduction currents. 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. An example of such a process is the induction of electric potentials as a result of blood flow in the presence of a static magnetic field.

44 Very low frequency electric fields are induced in the body whenever movement of electrically conductive biological materials, such as blood, occurs in a static magnetic field. Vertigo, nausea, a metallic taste and phosphenes can be induced during movement of the head in static magnetic fields larger than about 2 T. In addition, flow potentials induced by the flow of blood in a magnetic field of this value have been calculated to generate electric fields of about 200 mV m^{-1} near the sino-atrial (pacemaker) node of the heart during the relative refractory period of the cardiac cycle, when cardiac excitability is relatively low.

45 Studies of workers exposed to static magnetic fields up to several tens of mT do not overall demonstrate raised health risks. However, the number of studies, their size, and the information on exposure levels are generally limited.

46 The effects of static magnetic fields have been investigated using a wide variety of animal models and exposure conditions. Apart from possible field-dependent changes on localised blood flow in the skin, and on neuroendocrine effects associated with migratory behaviour in some animal species, no consistent effects have been reported using fields below 2 T, although the possibility of biological effects increases with exposure to fields of 5–8 T and above. There is little information regarding possible effects of chronic exposure.

47 There is little evidence suggesting that static magnetic fields up to about 1 T are genotoxic, and while some *in vitro* data suggest that static magnetic fields are not carcinogenic, few *in vivo* studies have been carried out. Very few laboratory studies have investigated the effects of exposure to static electric fields.

48 Overall, the available data remain insufficient to draw any firm conclusions regarding long-term health effects due to chronic exposure to static electric and magnetic fields.

Electromagnetic fields of frequencies below 100 kHz

49 The main physical effect of high levels of exposure to EMFs of frequencies less than about 100 kHz is the induction of electric fields and currents in body tissues. These can cause adverse health effects and provide the basis for exposure guidelines. However, there remains concern that power frequency (50/60 Hz) fields are implicated in the development of cancer, and in particular childhood leukaemia. AGNIR and a number of other expert groups have addressed this issue.

Epidemiology

50 There is some epidemiological evidence that time-weighted average exposure to power frequency magnetic fields above 0.4 μT is associated with a small increase in the absolute risk of leukaemia in children, from about 1 in 20 000 to 1 in 10 000 per year. On a relative scale, this corresponds to a doubling of the risk. Such exposures are seldom encountered by the general public in the UK, and the raised risk – if it were real – would correspond roughly to an additional two cases of childhood leukaemia per year in the UK, compared with an annual total of around 500 cases.

51 AGNIR has concluded that the epidemiological evidence is currently not strong enough to justify a firm conclusion that such fields cause leukaemia in children as other factors may be involved. However, the possibility remains that intense and prolonged exposures to magnetic fields can increase the risk of leukaemia in children, unless further research indicates that the finding is due to chance or some currently unrecognised artefact (AGNIR, 2001a).

52 The ICNIRP Standing Committee on Epidemiology reached a similar conclusion. It took the view that, among all the outcomes evaluated in epidemiological research of EMFs, childhood leukaemia in relation to postnatal exposures above 0.4 μT is the one for which there is most evidence of an association. This result is unlikely to be due to chance but may be, in part, due to bias, and is difficult to interpret in the absence of a known mechanism or reproducible experimental support (Ahlbom et al, 2001). In practice, background levels of exposure to magnetic fields in most UK homes are in the range 0.01–0.1 μT.

53 The International Agency for Research on Cancer (IARC, 2002) judged that this finding provided limited evidence for an excess risk in humans exposed at these levels, and it evaluated extremely low frequency (ELF) magnetic fields as being 'possibly carcinogenic to humans' (Classification 2B). IARC also concluded that for the vast majority of children, who are exposed to residential magnetic fields less than 0.4 μT, there is little evidence of any increased risk of leukaemia. Furthermore, IARC considered the evidence for excess cancer risks of all other kinds, in children and adults, as a result of exposure to ELF electric and magnetic fields to be inadequate.

54 In the view of NRPB, the epidemiological evidence that time-weighted average exposure to power frequency magnetic fields above 0.4 μT is associated with a small absolute raised risk of leukaemia in children is, at present, an observation for which there is no sound scientific explanation. There is no clear evidence of a carcinogenic effect of ELF EMFs in adults and no plausible biological explanation of the association can be obtained from experiments with animals or from cellular and molecular studies. Alternative explanations for this epidemiological association are possible: for example, potential bias in the selection of control children with whom leukaemia cases were compared in some studies and chance variations resulting from small numbers of individuals affected. Thus any judgements developed on the assumption that the association is causal would be subject to a very high level of uncertainty.

55 Studies of occupational exposure to ELF EMFs do not provide strong evidence of associations with neurodegenerative diseases. The only possible exception concerns people employed in electrical occupations who appear to have an increased risk of developing amyotrophic lateral sclerosis; however, this may be due to effects of electric shocks rather than any effect of long-term exposure to the fields *per se* (AGNIR, 2001b).

56 Studies of suicide and depressive illness have given inconsistent results in relation to ELF EMF exposure, and evidence for a link with cardiovascular disease is weak.

57 The overall evidence from studies of maternal exposure to ELF EMFs in the workplace does not indicate an association with adverse pregnancy outcomes, while studies of maternal exposure in the home are difficult to interpret.

58 Results from studies of male fertility and of birth outcome and childhood cancer in relation to parental occupational exposure to ELF EMFs have been inconsistent and unconvincing.

59 All these conclusions are consistent with those of AGNIR (2001).

60 NRPB concludes that the results of epidemiological studies, taken individually or as collectively reviewed by expert groups, cannot currently be used as a basis for restrictions on exposure to EMFs.

Biology

61 With regard to effects of surface charge induced by exposure to low frequency electric fields, exposure to fields less than 5 $kV\,m^{-1}$ will have a low risk of painful discharge from a person to ground. Thresholds for the discharge from an object through a grounded person depend on the size of the object and therefore require specific assessment. In environments where appropriate control is possible, the risk of painful discharge can be minimised by engineering or administrative means (including training).

62 The primary means by which electric fields and currents induced in the body by exposure to external fields interact with biological tissue is through voltage-gated ion channels situated in cell membranes. The effect is to alter the flux of certain ions and the electric potential difference across the cell membrane leading to subsequent biological responses. The most sensitive tissues are those comprising interacting networks of electrically excitable tissue, such as the central, autonomic and enteric nervous systems. The heart, other muscle tissue, and 'non-excitable' tissues with voltage-sensitive ion channels are expected to show a lower sensitivity.

63 An ad hoc expert group on weak electric field effects in the body (NRPB, 2004) has concluded that electrical stimulation of the retina can be used to assess the potential for effects on the nervous system in general. The group considered threshold internal electric field strengths of around 100 mV m^{-1}, possibly as low as 50 mV m^{-1}, would be sufficient to protect normal adults against the potentially adverse effects on the function of the central, autonomic and enteric nervous systems. However, there is considerable uncertainty associated with these values, which cannot be resolved without further research.

64 The group considered restricting the induced electric field to less than 20 mV m^{-1} adequate to protect people who are at increased risk from induced electric fields. These include people with epilepsy, a family history of seizure, or those using tricyclic anti-depressants, neuroleptic agents and other drugs that lower seizure threshold. In addition, this value is considered adequate to protect the developing nervous system *in utero*, and in neonates and young children. However, given the uncertainties associated with this value, the appropriate threshold may be as low as 10 mV m^{-1}.

65 Although the frequency response of these effects is not known, the group considered threshold values can be conservatively applied over a broad frequency range (approximately 10 Hz – 1 kHz) and to a minimum of 1000 interacting cells, which would occupy approximately 1 mm^3 in tissue of the central nervous system (CNS).

66 In addition, a number of studies suggest that ELF EMFs, particularly magnetic fields in excess of about 100 μT, may induce a variety of subtle responses in biological systems, as well as those attributable to the effects of either surface charge or the induced electric field. However, the pattern of reported responses is diffuse and inconsistent. Furthermore, many tend to be small in magnitude and often fail to be replicated. Overall, none is considered sufficient to provide a coherent framework on which to base restrictions for human exposures.

Dosimetry

67 Computational dosimetry enables the calculation of the link between external non-perturbed fields and the fields induced within the body. Sources of uncertainty in calculations include the reliability of numerical methods, different anatomies and postures, and resolution and variation in dielectric parameters as a function of age.

Electromagnetic fields of frequencies above 100 kHz

68 The main physical effect of exposure to EMFs at frequencies above 100 kHz is heating of tissues. Adverse health effects may occur as a result of such heating. There have also been concerns that other adverse health effects may occur, including the induction of cancer and changes to cognitive function.

Epidemiology

69 Epidemiological studies of groups exposed to radiofrequency (RF) fields have been variable in quality. Some studies have been limited by low statistical power or a lack of exposure measurements, while others may have been affected by bias.

70 The overall evidence from the more methodologically sound studies, including those conducted recently of mobile phone users, does not indicate that RF exposures increase the risk of cancer. However, the evidence is not conclusive. In particular, these studies have generally provided little information on whether risks might be raised many years after exposure, or on some specific types of exposure, eg from the use of digital mobile phones. One recent large study reported a raised risk of brain tumours some years after using an analogue mobile phone, but this finding may be due – at least in part – to bias in the recall of phone use.

71 Studies of occupational RF exposures do not indicate raised risks of non-cancer mortality or adverse pregnancy outcome, although it is not possible to exclude the possibility of a small risk.

72 Mortality, mainly from cardiovascular disease, has been shown to be raised in populations exposed to high or low temperatures, and there are indications that maternal hyperthermia may lead to CNS defects in offspring. However, for several methodological reasons, it is difficult to use these studies to quantify effects on mortality and prenatal development associated with internal heating from RF exposures.

Biology

73 Studies indicate that heat-related disorders should not occur in the majority of healthy adults provided core body temperature does not rise above 38°C. This is also likely to prevent adverse effects on the performance of all but the most demanding cognitive tasks. High rates of physical activity and/or warm, humid environments will reduce the additional RF heat loads that most adults can tolerate without exceeding 38°C. An RF heat load of 0.4 $W\,kg^{-1}$ averaged over the whole body should be sufficiently low that these other factors can be ignored.

74 Individual susceptibility to heat-related disorders varies considerably in the general population. Infants, children and those in the later years of life may be considered particularly susceptible. In addition, adults taking certain drugs and other chemicals that have direct effects on the control of body temperature, or on metabolism or heat production of the body, may also be considered at greater risk. An RF heat load of 0.1 $W\,kg^{-1}$ averaged over the whole body should be physiologically trivial in this context.

75 Exposure of pregnant women to an average whole-body SAR of 0.1 $W\,kg^{-1}$ should not result in adverse effects on the development of the embryo and fetus *in utero*. The fetus itself is thought to be in general about 0.5°C above maternal body temperature (the embryo less so) and is to some extent limited in its ability to dissipate heat to the mother by heat exchange within the umbilical blood vessels. In view of the uncertainty regarding possible effects of raising fetal temperatures directly through the absorption of RF fields, a rise in embryo and fetal temperature to less than 38°C should also not result in adverse developmental effects. The development of some tissues, such as the CNS, continues during infancy and early childhood, suggesting that some potential increased susceptibility may continue during these periods.

76 With regard to localised heating and the susceptibility of individual tissues to heat, the CNS, the testis and the lens of the eye seem particularly sensitive, the last more

through a limited ability to dissipate heat than a greater sensitivity to heat *per se*. Other tissues, such as liver, kidney and muscle, seem marginally less susceptible, but nevertheless can also be adversely affected by elevated temperature. Temperature rises in the CNS (ie the brain, retina and spinal cord) to above 38°C, of the other tissues of the neck and trunk (with the exception of the testes) to above 39°C and of the tissues of the limbs to above 40°C may result in localised heat-induced damage. The testes are particularly sensitive to the effects of heat; adverse effects should not occur in this tissue provided temperature increases are less than 1°C.

77 The ability to dissipate heat from locally heated tissues or regions of the body will depend on their temperature in relation to their surroundings and rate of blood flow through the tissue. Both may to some extent be compromised by significant whole-body heating when the increase in skin blood flow is greater than the corresponding increase in cardiac output. In addition, people with cardiovascular disease, such as peripheral vascular disease or heart failure, which will reduce the circulation of blood through tissues, may be at increased susceptibility to localised heating of tissues by RF EMFs compared with people with normal cardiovascular responses.

78 A number of studies suggest that low level RF fields may induce a variety of subtle biological responses. Of particular note are possible effects of pulsed fields on brain function and on changes in heat shock protein expression. Further work is needed to examine these and other possibilities, especially to consider if local heating effects may explain these results. Overall, none of these possible effects is considered sufficient to provide a coherent framework on which to base restrictions for human exposures.

Dosimetry

79 Computational dosimetry enables the calculation of the link between external non-perturbed fields and the fields induced within the body. Sources of uncertainty in calculations include the reliability of numerical methods, different anatomies and postures, and resolution and variation in dielectric and thermal parameters as a function of age.

80 There are still relatively few dosimetric studies linking localised temperature increases and SAR in most parts of the body. However, with respect to exposure of the head from the use of mobile phones, there is a growing body of computational work available. These studies provide insight on the relationship between temperature rise and SAR in this case. The results indicate a range of localised temperature increases of 0.05 to 0.12°C in the brain from a localised SAR of 1 W kg^{-1}. The highest of this range of values indicates that, in order to limit the temperature in all parts of the brain to 38°C (corresponding to a temperature rise of 1°C above baseline) the SAR in the head, averaged over any 10 g cube, should not exceed about 8 W kg^{-1}.

81 Studies of heating in the eye suggest that an SAR of 1 W kg^{-1} averaged over the eye may lead to a temperature rise of up to 0.25°C in the region of the lens. Therefore, these studies indicate that in order to limit the temperature in the eye to 39°C, the SAR averaged over 10 g should be limited to about 8 W kg^{-1}.

82 There are contradictory reports as to whether there are significant differences in the SAR produced in the heads of adults and children.

CONCLUSIONS AND RECOMMENDATIONS

The review of current scientific knowledge, the adoption of a cautious approach to the interpretation of these data, and a recognition of the benefits of international harmonisation, combine in a recommendation to adopt the ICNIRP exposure guidelines for occupational and general public exposure to electromagnetic fields between 0 and 300 GHz.

83 Scientific evidence related to biological effects of electromagnetic fields (EMFs) and possible consequential adverse effects on human health has been reviewed (NRPB, 2004) and summarised in this document. In evaluating the basis for providing guidance on limiting exposure and possible risks from exposure to EMFs, consideration has been given to uncertainties in scientific data and a cautious approach has been adopted in their interpretation.

84 The review has covered epidemiological studies as well as experimental biology, volunteer studies and dosimetry. These play important individual and collective roles in identifying possible adverse effects on health and in providing information on the need for, and appropriate levels of, protection.

85 Based on the review, this section summarises the NRPB conclusions and recommendations including:

(a) the basis for providing restrictions on exposure of people to EMFs,
(b) basic restrictions on exposure to EMFs to avoid direct effects,
(c) reference levels, which are measurable quantities for assessing compliance with basic restrictions or for assessing the possibility of indirect effects of exposure (shock and burn),
(d) the possible need for further precautionary measures in relation to EMF exposure and health.

86 The recommendations are not concerned with exposures of patients carried out under medical supervision or with possible electrical interference with implantable medical devices such as pacemakers. They do not address detailed aspects of applying the guidelines to specific exposure situations.

87 A number of recommendations are made which are specifically aimed at developing guidance through research in key areas where continuing uncertainty limits the rigour with which appropriate restrictions on exposure can be formulated.

88 NRPB is committed to continued monitoring of the results of scientific studies on EMFs and health and to revising its advice when appropriate.

General conclusions on the science

89 It is concluded that there are scientific data indicating the need for appropriate values for restrictions on exposure. These data derive from experimental studies related to effects of EMFs on the central nervous system (CNS) and effects of heating on the body. The nature of such effects and the mechanisms underlying them have been reviewed (NRPB, 2004). The restrictions on exposure and recommendations for further investigation, where relevant, are derived from data on these effects.

90 Evidence of other possible effects associated with EMF exposure derives principally from epidemiological studies and from some experimental studies. The main, but not sole, subject of such studies has been cancer. These studies have been reviewed

extensively by expert groups, including AGNIR, and are summarised in the associated review of the science (NRPB, 2004). It is concluded that currently the results of these studies on EMFs and health, taken individually or as collectively reviewed by expert groups, are insufficient either to make a conclusive judgement on causality or to quantify appropriate exposure restrictions. This conclusion is in accord with the manner in which other expert bodies – for example, ICNIRP (1998) – have developed EMF exposure guidelines.

91 However, such studies taken together with people's concerns provide a basis for considering the possible need for further precautionary measures in addition to the application of quantitative restrictions on exposure to EMFs.

Exposure circumstances

92 The basic restrictions on exposure to EMFs recommended in this document distinguish between occupational and general public exposure situations. This is a departure from previous NRPB advice and is supported by the associated review of the science (NRPB, 2004).

93 It is noted that exposure in occupational situations will generally be to healthy adults working under controlled conditions. These conditions include the opportunity to apply engineering and administrative measures and, where necessary and practical, provide personal protection. It is also noted that the general public includes people of all ages and widely varying health status and exposure is likely to occur under uncontrolled conditions.

Static electric and magnetic fields

94 Where direct perception of static electric fields causes annoyance, or indirect effects of electrostatic discharge cause pain, it is important to reduce the possibility of occurrence of these effects. The threshold for perception of static electric fields is around 20 kV m^{-1}, and sensations become annoying above about 25 kV m^{-1}.

95 For static magnetic fields, vertigo, nausea, a metallic taste and phosphenes can be induced during movement in fields larger than about 2 T.

96 It is concluded that acute adverse responses will not occur for exposure to static magnetic fields of less than 2 T.

97 There is insufficient evidence from animal and cellular studies to determine long-term health effects due to chronic exposure to static magnetic fields.

Occupational exposure

98 On the basis of the evidence on acute effects, and the uncertainty concerning long-term effects, a cautious approach to restricting exposure to static magnetic fields is merited.

99 It is concluded that restricting whole-body time-weighted average exposure to a magnetic flux density of 200 mT is appropriate for occupational exposure to static magnetic fields with an instantaneous ceiling of 2 T. For exposure of the limbs, a ceiling of 5 T is appropriate.

General public exposure

100 It is concluded that restricting time-weighted average magnetic flux density of 40 mT for whole-body exposure is appropriate for the general public.

101 Exposures in excess of 40 mT are appropriate for occasional access to special facilities under controlled conditions provided that the occupational exposure restrictions are not exceeded.

Recommendation

102 The ICNIRP exposure guidelines should be used for restricting occupational and general public exposure to static magnetic fields (see the appendix).

Electric and magnetic fields of frequencies below 100 kHz

103 The most plausible and coherent set of data from which guidance can be developed concerns weak electric field interactions in the CNS and certain other electrically excitable tissues. A cautious approach has been used to indicate thresholds for adverse health effects that are scientifically plausible. There is a need for key uncertainties in these data to be addressed through further research and scientific discussion. Data on other possible health effects examined lack plausibility, coherence and consistency.

104 Threshold internal electric field strengths of around 100 mV m^{-1}, possibly as low as 10 mV m^{-1}, have been identified for effects in the nervous system in general spanning the range for most adults and for potentially susceptible individuals. However, it is recognised that there is considerable uncertainty associated with these values. It is considered appropriate to apply these threshold values over the frequency range from 10 Hz to 1 kHz and to 1 mm^3 in most nerve tissue.

105 Precise comparison of basic restrictions expressed in terms of induced electric field strength with those expressed in terms of induced current density requires computational modelling employing tissue- and frequency-dependent values of electrical conductivity. At present, simple comparisons can be made with existing guidelines assuming a fixed chosen value of electrical conductivity.

106 When an ungrounded person is in an electric field and comes into contact with a grounded object there is the possibility of occurrence of a spark discharge at the point of contact between the person and the object. For fields external to the body greater than about 5 kV m^{-1}, there is the likelihood of such discharges being painful. The extent to which this is a problem in practice is unclear and further investigation is merited.

107 When a person is in an electric field and comes into contact with an ungrounded object there is the possibility of occurrence of a spark discharge at the point of contact between the object and the person. For such situations, the probability and the magnitude of the effect depend on the field strength and the size of the ungrounded object.

Occupational exposure

108 It is concluded that a restriction of the induced electric field in the central, autonomic and enteric nervous systems to less than 100 mV m^{-1} is adequate to protect most adult members of the population.

109 The value of 100 mV m^{-1} was derived primarily from a consideration of weak electric field effects in the CNS and corresponds approximately to the existing ICNIRP basic restriction on current density of 10 mA m^{-2}, assuming an electrical conductivity of CNS tissue of 0.1 S m^{-1}.

110 NRPB concludes that 10 mA m^{-2} is an appropriate basic restriction on induced current density in the CNS for occupational exposure.

General public exposure

111 In respect of general public exposure, those exposed might include people potentially at increased risk from induced electric field effects, ie people with epilepsy, a family history of seizure, or using tricyclic anti-depressants, neuroleptic agents and other drugs that lower seizure threshold. It should be noted that some workers may have these conditions, and that seizure is a phenomenon of the CNS alone. The ad hoc expert group (NRPB, 2004) considered that such sensitive people should be adequately protected at lower induced electric field strengths, possibly about a factor of five lower than for normal adults. In addition, the group considered that this reduction factor would be adequate to protect the developing nervous system *in utero*, and in neonates and young children. It is concluded that a restriction of the induced electric field in the tissue of the CNS to less than 20 mV m^{-1} is adequate to protect these members of the population.

112 The value of 20 mV m^{-1} was derived from a consideration of weak electric field effects in the CNS and corresponds approximately to the existing ICNIRP basic restriction on current density of 2 mA m^{-2}, assuming an electrical conductivity of CNS tissue of 0.1 S m^{-1}.

113 It is concluded that 2 mA m^{-2} is an appropriate basic restriction on induced current density in the CNS for general public exposure.

Reference levels

114 Calculations have been carried out by NRPB, to judge the appropriateness of the ICNIRP reference levels for occupational and general public exposure to electric and magnetic fields of frequencies less than 100 kHz (see Figures 1 and 2). These calculations indicate that the reference levels are appropriate for use at the initial stage of assessing compliance with the relevant basic restrictions on induced current density.

Recommendations

115 The ICNIRP basic restrictions on induced current density should be used for restricting occupational and general public exposure to electric and magnetic fields of frequencies less than 100 kHz (see the appendix).

116 The ICNIRP reference levels should be used at the initial stage of assessing compliance with basic restrictions on exposure.

117 Further investigations of compliance, that are indicated by exceeding these reference levels, should use the most up to date dosimetry methods.

Time-varying EMFs of frequencies above 100 kHz

118 The most plausible and coherent set of data from which guidance can be developed concerns raised temperatures and the physiological stress induced by increased heat loads. A cautious approach has been used to derive thresholds for adverse health effects that are scientifically plausible. There is a need for key uncertainties in these data to be addressed through further research. In particular, the distribution of increased sensitivity to the effects of heat in members of the population is not well defined at present. Other studies reviewed lack plausibility, coherence and consistency.

119 The exposure metric for restricting exposure to fields of frequencies between 100 kHz and 10 GHz is specific energy absorption rate (SAR), unit W kg^{-1}. For frequencies between 10 and 300 GHz, because of diminishing penetration into the body, the exposure metric is incident power density, unit W m^{-2}.

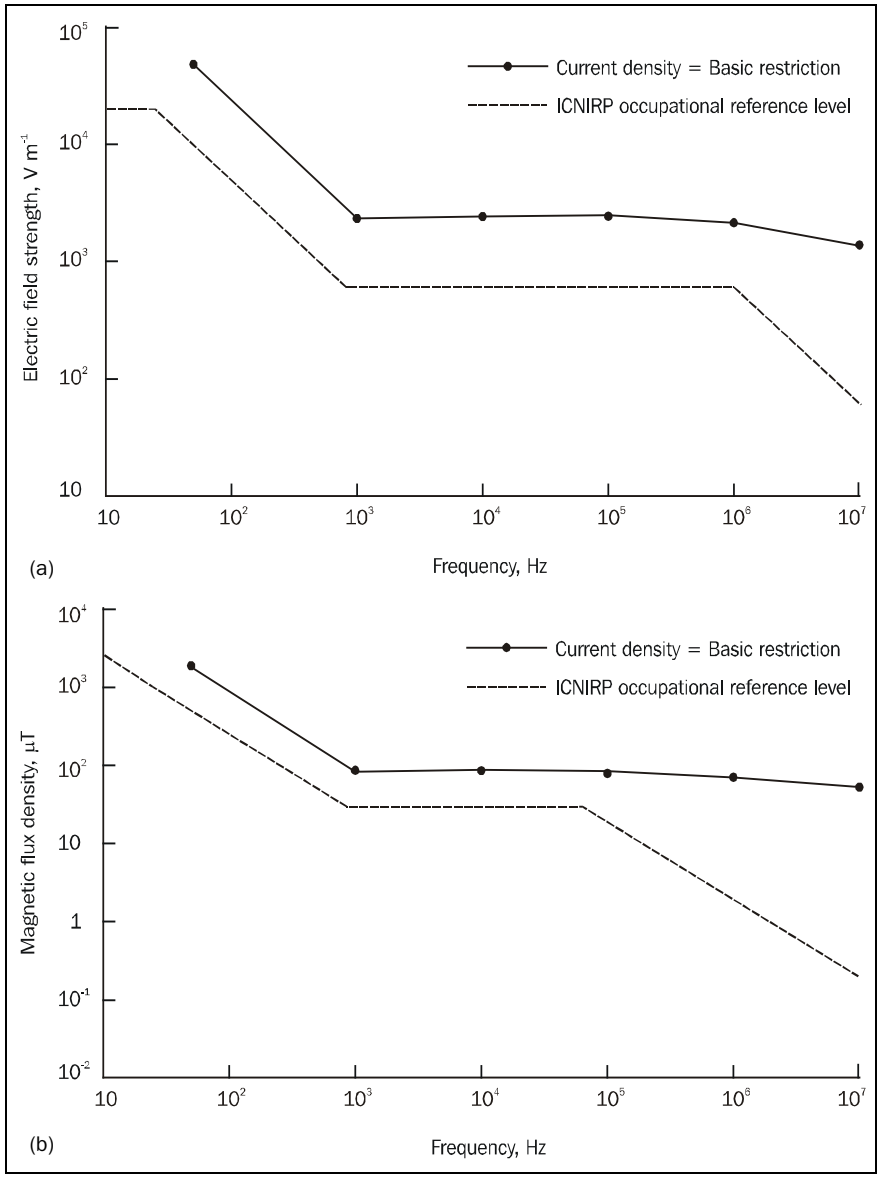


FIGURE 1

(a) *Comparison of the ICNIRP occupational reference level and NRPB quasistatic calculations of the electric field strength required to produce a current density equal to the ICNIRP basic restriction on induced current density with averaging over 1 cm^2 in the brain, spinal cord and retina*

(b) *Comparison of the ICNIRP occupational reference level and NRPB quasistatic calculations of the magnetic flux density required to produce a current density equal to the ICNIRP basic restriction on induced current density with averaging over 1 cm^2 in the brain, spinal cord and retina*

Occupational exposure

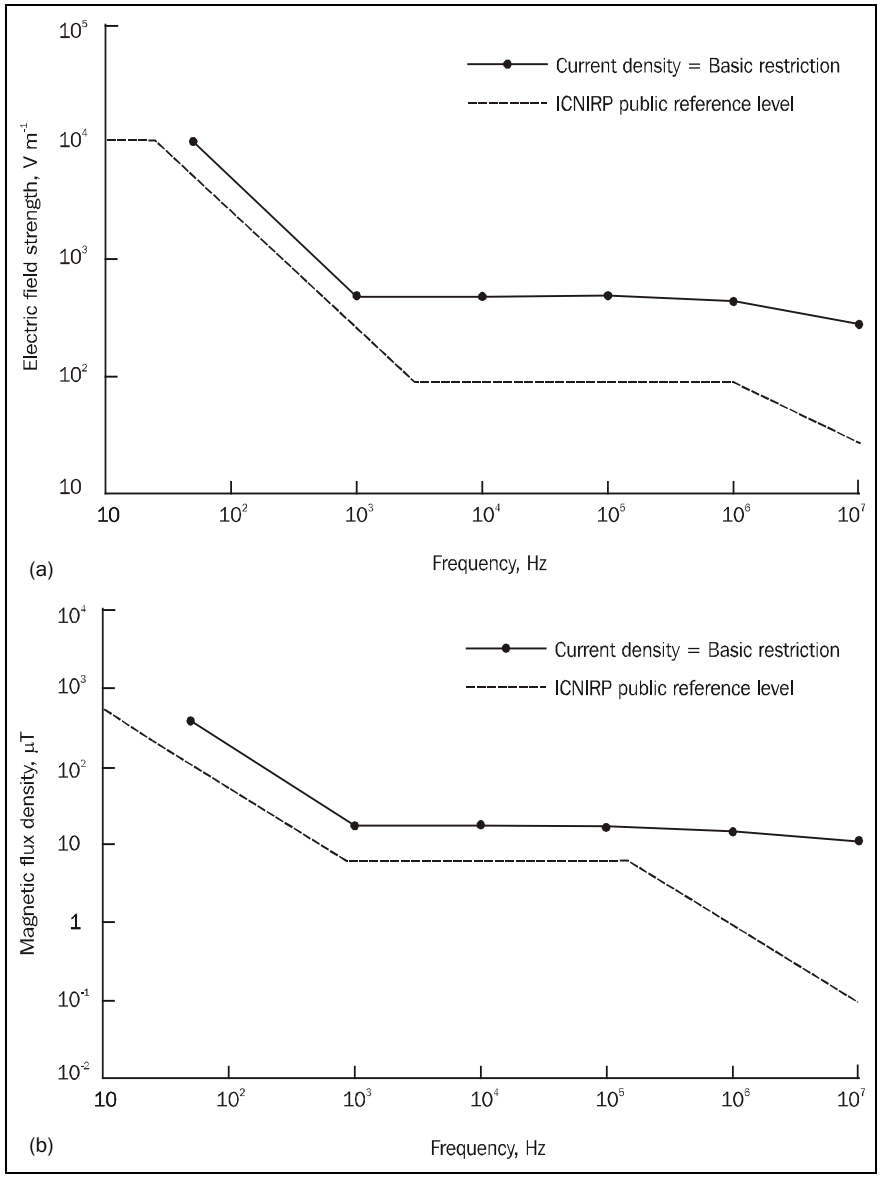
Whole-body

120 It is considered that limiting whole-body heat load included by exposure to RF fields to less than 0.4 W kg^{-1} will prevent heat-related disorders. For most adults it is unnecessary to additionally account for high rates of physical work and/or hot, humid environments.

FIGURE 2

(a) *Comparison of the ICNIRP general public reference level and NRPB quasistatic calculations of the electric field strength required to produce a current density equal to the ICNIRP basic restriction on induced current density with averaging over 1 cm² in the brain, spinal cord and retina*

(b) *Comparison of the ICNIRP general public reference level and NRPB quasistatic calculations of the magnetic flux density required to produce a current density equal to the ICNIRP basic restriction on induced current density with averaging over 1 cm² in the brain, spinal cord and retina*



Partial-body

121 With regard to partial-body (localised) heating, limiting the rise in the temperature of the head and spinal cord to 38°C, of the other tissues of the neck and trunk (with the exception of the testes) to 39°C, and of the limbs to 40°C, should avoid any heat-induced damage in the tissues of these regions of the body. For the testes, the increase in temperature should be limited to 1°C, because of their greater sensitivity to heat. It is concluded that occupational basic restrictions on exposure should be aimed at limiting localised temperature rises to these values.

122 Calculations on possible temperature rises in the head and eye indicate the need to restrict localised SAR to about 8 W kg^{-1} averaged over a 10 g cube. These calculations also indicate that the highest average SAR over any contiguous 10 g mass is typically at least 50% greater than this. Adequate protection is therefore afforded by restricting localised SAR in the head and trunk to 10 W kg^{-1} averaged over any contiguous 10 g mass. However, given the range of published dosimetric data relating temperature rise with localised SAR, further dosimetric studies addressing this topic should be carried out.

Reference levels

123 Calculations have been carried out by NRPB, to judge the appropriateness of the ICNIRP external power density and limb current reference levels for occupational exposure to plane wave EMFs of frequencies greater than 100 kHz (see Figure 3). These indicate that the reference levels for occupational exposure are appropriate for use at the initial stage of assessing compliance with basic restrictions on SAR.

General public exposure

Whole-body

124 General community protection, including for people potentially susceptible to heat-related disorders, will be assured if the whole-body RF heat load is below an SAR of about 0.1 W kg^{-1}. This will provide protection to older people, infants, children, pregnant women, other adults taking certain medications, and to people undertaking cognitively demanding tasks.

125 For frequencies between 100 kHz and 10 GHz this agrees reasonably well with the ICNIRP exposure guidelines basic restriction of 0.08 W kg^{-1} for the general public.

Partial-body

126 With regard to partial-body (localised) heating, limiting the rise in temperature of the head and spinal cord, and of the embryo and fetus, to 38°C, of the other tissues of the neck and trunk (with the exception of the testes) to 39°C, and of the limbs to 40°C, should avoid heat-induced damage in the tissues of these regions of the body. For the testes, the increase in temperature should be limited to 1°C, because of their greater sensitivity to heat. It is concluded that general public basic restrictions on exposure should be aimed at limiting localised temperature rises to these values.

127 Computational studies have been published on temperature rises that might arise from exposure of the head associated with the use of mobile phones. These studies provide insight on possible temperatures that could result from a localised SAR of 2 W kg^{-1} averaged over 10 g mass of tissue. This value is one that has been adopted by ICNIRP as a basic restriction on localised SAR in the head and trunk for general public exposure and recommended by IEGMP, the Department of Health and the Board of NRPB as being appropriate for restricting exposure associated with mobile telephony. Computational results indicate localised temperature increases up to around 0.2–0.25°C could result in the brain from a localised SAR of 2 W kg^{-1}. Little work has been carried out on thermal dosimetry of the fetus or with computational models incorporating

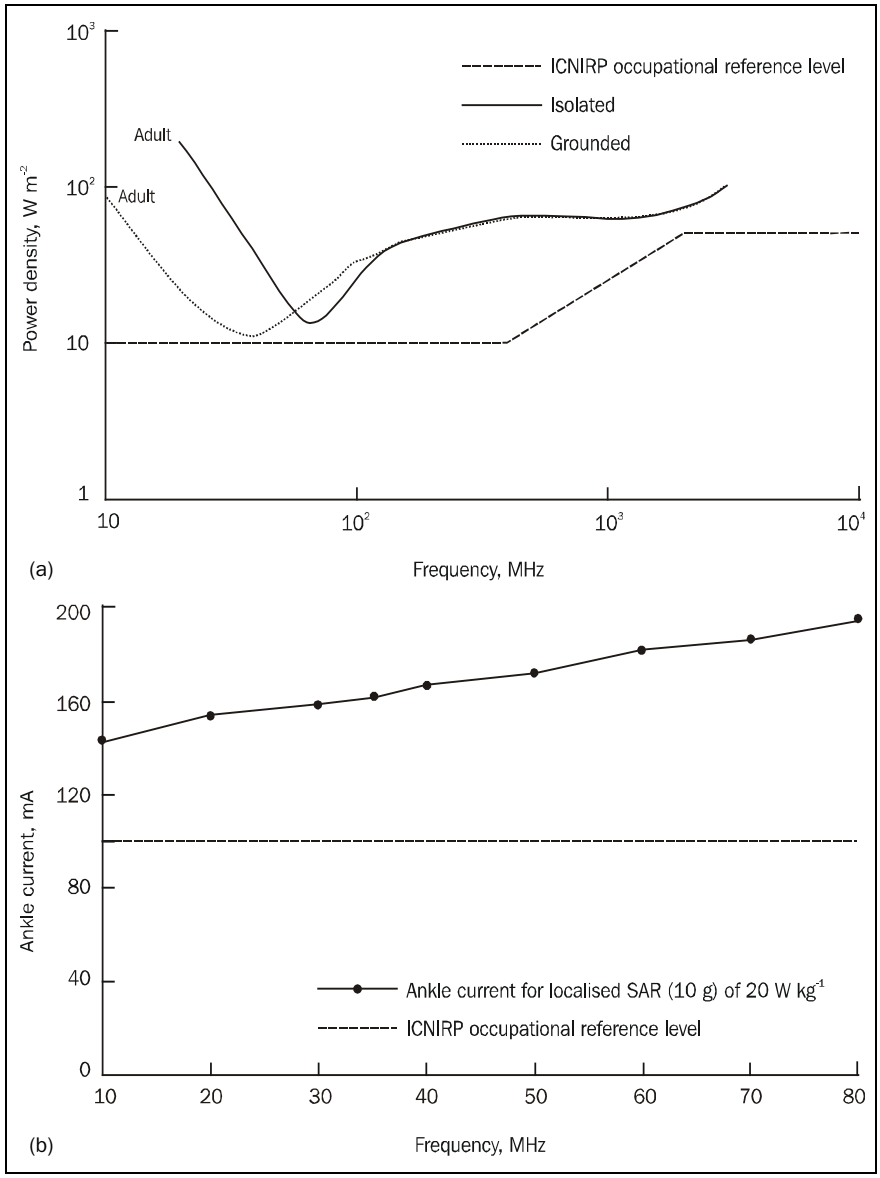
reduced organ perfusion rates as might be relevant to people with cardiovascular or other diseases.

128 Taking into account uncertainties related to partial-body exposure, the above conclusions on limiting temperature increases associated with general public exposure to fields of frequencies between 100 kHz and 10 GHz agree reasonably well with the current ICNIRP basic restriction on localised SAR (2 W kg^{-1}) and with the recommendations for restricting exposure associated with mobile telephony from IEGMP and the Board of NRPB.

FIGURE 3

(a) *Comparison of the ICNIRP occupational reference level and NRPB plane wave calculations of the power density required to produce a whole-body SAR equal to the ICNIRP basic restriction*

(b) *Comparison of the ICNIRP occupational reference level and NRPB calculations of the induced ankle current required to produce a maximum localised SAR averaged over 10 g anywhere in the leg equal to the corresponding ICNIRP basic restriction*



Reference levels

129 Calculations have been carried out by NRPB, to judge the appropriateness of the external power density and limb current reference levels for general public exposure to plane wave EMFs of frequencies greater than 100 kHz (see Figure 4). They suggest that the ICNIRP reference levels for general public exposure are generally conservative for assessing compliance with basic restrictions on SAR. However, the exception is for the exposure of small children under worst-case exposure conditions at frequencies between about 50 and 100 MHz and above about 1 GHz.

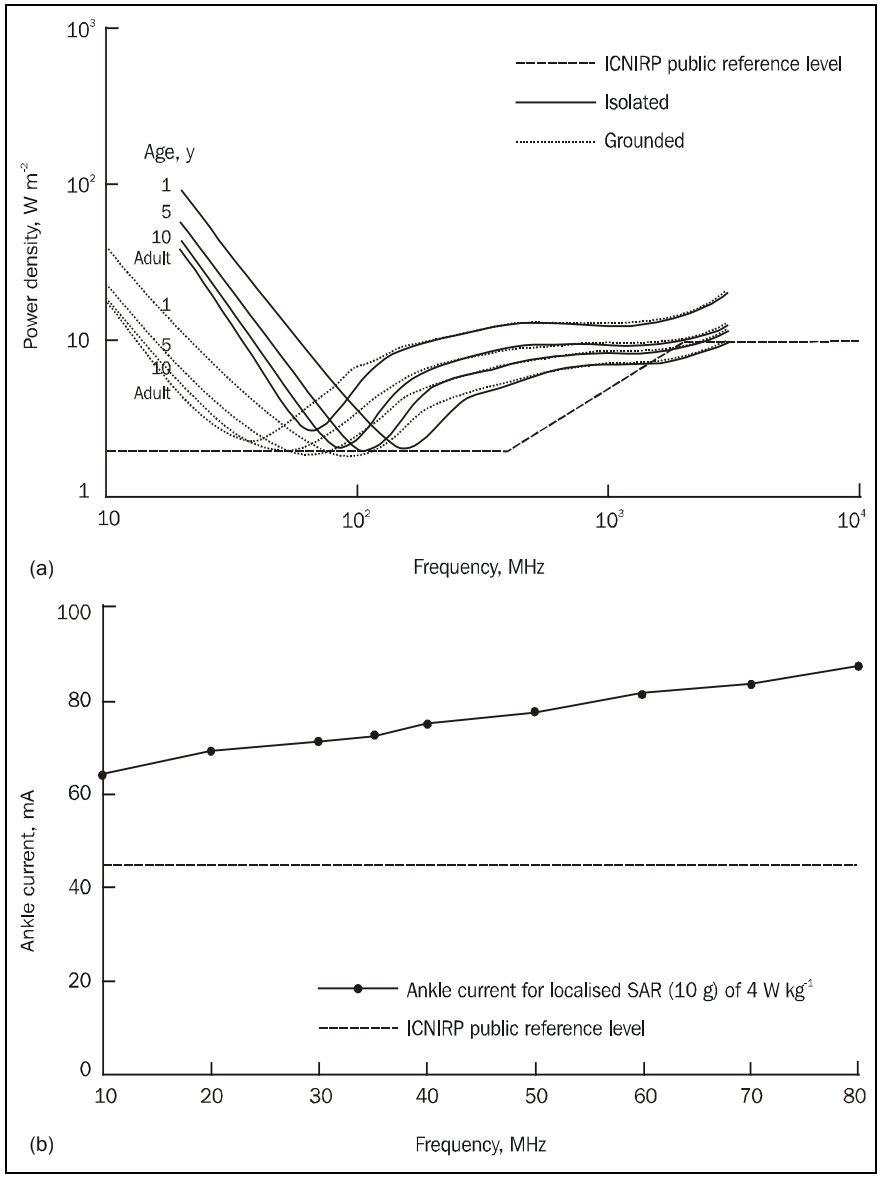


FIGURE 4

(a) *Comparison of the ICNIRP general public reference level and NRPB plane wave calculations of the power density required to produce a whole-body SAR equal to the ICNIRP basic restriction*

(b) *Comparison of the ICNIRP general public reference level and NRPB calculations of the induced ankle current required to produce a maximum localised SAR averaged over 10 g anywhere in the leg equal to the corresponding ICNIRP basic restriction*

130 It is considered that the appropriateness of the field reference levels for exposure of the general public needs to be reviewed for frequencies between about 50 and 100 MHz and above 1 GHz. Nevertheless, given the conservative assumptions used to derive the basic restrictions for the general public and the assumption of optimal coupling to the field in deriving the reference levels, it is considered appropriate to use the ICNIRP reference levels at present.

Recommendations

131 The ICNIRP basic restrictions on whole-body and localised SAR should be used for restricting occupational and general public exposure to EMFs of frequencies greater than 100 kHz (see the appendix). Similarly, the ICNIRP reference levels for contact currents should be used for analysing the possibility of indirect effects of exposure (shock and/or burn).

132 Electrical effects on body tissues are also possible at frequencies above 100 kHz and up to about 10 MHz; hence basic restrictions to prevent these effects should apply up to 10 MHz.

133 The ICNIRP reference levels should be used at the initial stage of assessing compliance with basic restrictions on exposure.

134 Further investigations of compliance, that are indicated by exceeding these reference levels, should use the most up to date dosimetry data.

Further precautionary measures

135 The background and indicators for considering the possible need for further precautionary measures are discussed in detail in Chapter 6 of the associated science review document (NRPB, 2004).

Power frequency fields

136 There remain concerns about possible effects of exposure of children to power frequency magnetic fields. The view of NRPB is that it is important to consider the possible need for further precautionary measures in respect of exposure of children to power frequency magnetic fields.

Radiofrequency fields

137 With respect to RF exposures and health, NRPB has noted the conclusions of the AGNIR report on RF fields and human health (AGNIR, 2003).

138 It is concluded that the scientific evidence for RF fields causing adverse health effects at levels to which the generally public are normally exposed is much weaker than that for power frequency magnetic fields. It is also noted that there is a great deal of ongoing scientific research on RF fields, in particular on mobile telephony, and health. There is a need to constantly monitor the results of this research and keep the guidelines under review.

Recommendation

139 The government should consider the need for further precautionary measures in respect of exposure of people to EMFs. In doing so, it should note that the overall evidence for adverse effects of EMFs on health at levels of exposure normally experienced by the general public is weak. The least weak evidence is for the exposure of children to power frequency magnetic fields and childhood leukaemia.

Future development of exposure guidelines

140 Recommendations for studies of the possible effects of EMF exposure, including epidemiological studies, especially in relation to cancer, reproductive and behavioural effects, have been given in a number of recent reviews (see NRPB, 2004). The following recommendations are specifically aimed at developing guidance through research in key areas where continuing uncertainty limits the rigour with which appropriate restrictions on exposure can be formulated.

Static magnetic fields

141 Epidemiological studies should be carried out of the long-term risks to health of prolonged occupational exposure to static magnetic fields. Additional studies of occupational health – for example, using questionnaires – to derive indices of health status should also be considered. These studies in human populations should be complemented by long-term animal studies in static fields in excess of 2 T.

142 Further study should be carried out of the potential long-term effects of static magnetic fields greater than 1 T on potentially susceptible metabolic reactions, such as those in which radical pairs are transiently generated. These should be complemented by volunteer and *in vitro* studies of magnetic field induced changes in metabolism using modern, molecular approaches, such as genomics, proteomics and metabolomics.

143 The degree to which vertigo, nausea and other acute effects are a feature of occupational exposure to fields in excess of 2 T should be investigated.

Power frequency surface charge effects

144 Further exploration of the thresholds for surface electric charge effects induced by exposure to power frequency electric fields should be carried out in both occupational situations and those encountered by the general public.

Weak induced electric field effects

145 The susceptibility of the brain and other electrically excitable tissue to weak electric field interactions remains largely unexplored. Further study of the mechanism of phosphene induction and its frequency response through neurophysiological investigation of induced electric field effects on retinal neuronal circuitry, and similar studies of the threshold and frequency response of neural networks in other brain tissue, are required to clarify the degree to which phosphene data can be extrapolated to the rest of the brain.

146 These studies would be usefully supplemented by further macrodosimetric and microdosimetric investigation of the induced fields and currents in the retina in volunteer studies of phosphenes.

147 Volunteer studies are required to identify behavioural and cognitive functions affected by exposure. Animal models should be used to supplement these data.

148 The degree to which sensitivity may be increased in people with conditions such as epilepsy should be investigated through neurophysiological and behavioural investigation using *in vitro* and animal models of these conditions.

149 For time-varying fields of frequencies less than 100 kHz, there is a growing consensus that the appropriate dosimetric quantity with which to express basic restrictions on EMF exposure should be induced electric field strength (NRPB,

2004). This represents a change from the practice used by many bodies concerned with the development of EMF exposure guidelines (eg ICNIRP, 1998; NRPB, 1999), where, for this frequency range, basic restrictions are expressed in terms of induced current density.

150 In the further development of EMF exposure guidelines, consideration should be given to the basic restrictions for time-varying electric and magnetic fields of frequencies up to 100 kHz being based on limiting electric field strength internal to the body.

Whole-body SAR

151 The distribution of heat sensitivity in the general population is not well understood; in particular, there is some uncertainty regarding the heat loads that people with varying susceptibilities to heat can tolerate. Raised maternal body temperature can adversely affect prenatal and possibly early postnatal development, particularly that of the CNS, but thresholds have not been rigorously identified. More quantitative studies should be carried out, especially on development of the cerebral cortex, during prenatal and postnatal exposure using both morphological and functional endpoints.

Localised SAR

152 With regard to localised heating, acute animal studies have shown that tissue necrosis can be induced when local temperatures exceed 41°C for an hour or more. Further studies should be carried out of the effects of prolonged and/or chronic exposure at lower temperatures, especially those that might result from functional changes induced, for example, by heating of the brain or endocrine glands.

153 For exposure to mobile phones, there are conflicting reports as to whether there is a significant increase in the SAR absorbed in the head, and particularly in the brain, for children compared to adults. This is an area where clarification is needed.

154 Further work should be carried out to provide more knowledge of the quantitative relationship between localised temperature increases and SAR in the head and eye, trunk, embryo and fetus including using models incorporating reduced organ blood perfusion rate. Particular attention should be given to the acquisition of reliable measurements of the thermal parameters of human tissues, including perfusion rates.

155 The metric used in the ICNIRP guidelines – the SAR averaged over any 10 g of contiguous tissue – does not distinguish between compact and diffuse patterns of heating which are likely to have different thermal effects. The consequences of a cubic averaging region for exposure guidelines should be investigated.

Dosimetry and reference levels

156 An important requirement in future dosimetry is the development of an adult female voxel model and also child models that are not simply scaled adults, along with the appropriate age-dependent tissue dielectric parameters.

157 The appropriateness of the field reference levels for exposure of the general public needs to be reviewed for frequencies between about 50 and 100 MHz and above 1 GHz (see paragraphs 129 and 130).

158 Induced electric fields need to be calculated averaged over a 1 mm cube in the brain, spinal cord and retina for low frequency electric and magnetic field exposures.

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Appendix

SUMMARY OF ICNIRP EXPOSURE GUIDELINES

TABLE A1 *Basic restrictions for time-varying electric and magnetic fields for frequencies up to 10 GHz*

Exposure characteristics	Frequency range	Current density for head and trunk (mA m^{-2}) (rms)	Whole-body average SAR (W kg^{-1})	Localised SAR (head and trunk) (W kg^{-1})	Localised SAR (limbs) (W kg^{-1})
Occupational	Up to 1 Hz	40	–	–	–
	1 Hz – 4 Hz	$40/f$	–	–	–
	4 Hz – 1 kHz	10	–	–	–
	1 kHz – 100 kHz	$f/100$	–	–	–
	100 kHz – 10 MHz	$f/100$	0.4	10	20
	10 MHz – 10 GHz	–	0.4	10	20
General public	Up to 1 Hz	8	–	–	–
	1 Hz – 4 Hz	$8/f$	–	–	–
	4 Hz – 1 kHz	2	–	–	–
	1 kHz – 100 kHz	$f/500$	–	–	–
	100 kHz – 10 MHz	$f/500$	0.08	2	4
	10 MHz – 10 GHz	–	0.08	2	4

Notes

(a) f is the frequency in hertz.

(b) Because of electrical inhomogeneity of the body, current densities should be averaged over a cross-section of 1 cm^2 perpendicular to the current direction.

(c) For frequencies up to 100 kHz, peak current density values can be obtained by multiplying the rms value by $\sqrt{2}$ (~ 1.414). For pulses of duration t_p the equivalent frequency to apply in the basic restrictions should be calculated as $f = 1/(2t_p)$.

(d) For frequencies up to 100 kHz and for pulsed magnetic fields, the maximum current density associated with the pulses can be calculated from the rise/fall times and the maximum rate of change of magnetic flux density. The induced current density can then be compared with the appropriate basic restriction.

(e) All SAR values are to be averaged over any 6-minute period.

(f) Localised SAR averaging mass is any 10 g of contiguous tissue; the maximum SAR so obtained should be the value used for the estimation of exposure.

(g) For pulses of duration t_p the equivalent frequency to apply in the basic restrictions should be calculated as $f = 1/(2t_p)$. In addition, for pulsed exposures in the frequency range from 0.3 GHz to 10 GHz and for localised exposure of the head, in order to limit or avoid auditory effects caused by thermoelastic expansion, an additional basic restriction is recommended. This is that the specific absorption should not exceed 10 mJ kg^{-1} for workers and 2 mJ kg^{-1} for the general public, averaged over 10 g of tissue.

Exposure characteristics	Power density ($W\ m^{-2}$)
Occupational exposure	50
General public	10

TABLE A2 *Basic restrictions for power density for frequencies between 10 and 300 GHz*

Notes

(a) Power densities are to be averaged over any 20 cm^2 of exposed area and any $68/f^{1.05}$-minute period (where f is the frequency in gigahertz) to compensate for progressively shorter penetration depth as the frequency increases.

(b) Spatial maximum power densities, averaged over 1 cm^2, should not exceed 20 times the values above.

Frequency range	Electric field strength, E ($V\ m^{-1}$)	Magnetic field strength, H ($A\ m^{-1}$)	Magnetic flux density, B (μT)	Equivalent plane wave power density, S_{eq} ($W\ m^{-2}$)
Up to 1 Hz	–	163 000	200 000	–
1 Hz – 8 Hz	20 000	$163\,000/f^2$	$200\,000/f^2$	–
8 Hz – 25 Hz	20 000	$20\,000/f$	$25\,000/f$	–
0.025 kHz – 0.82 kHz	$500/f$	$20/f$	$25/f$	–
0.82 kHz – 65 kHz	610	24.4	30.7	–
0.065 MHz – 1 MHz	610	$1.6/f$	$2.0/f$	–
1 MHz – 10 MHz	$610/f$	$1.6/f$	$2.0/f$	–
10 MHz – 400 MHz	61	0.16	0.2	10
400 MHz – 2000 MHz	$3f^{1/2}$	$0.008f^{1/2}$	$0.01f^{1/2}$	$f/40$
2 GHz – 300 GHz	137	0.36	0.45	50

TABLE A3 *Reference levels for occupational exposure to time-varying electric and magnetic fields (unperturbed rms values)*

Notes

(a) f is the frequency as indicated in the frequency range column.

(b) Provided that basic restrictions are met and adverse indirect effects can be excluded, field strength values can be exceeded.

(c) For frequencies between 100 kHz and 10 GHz, S_{eq}, E^2, H^2 and B^2, are to be averaged over any 6-minute period.

(d) For peak values at frequencies up to 100 kHz, see Table A1, note (c).

(e) Between 100 kHz and 10 MHz, peak values for the field strengths are obtained by interpolation from the 1.5-fold peak at 100 kHz to the 32-fold peak at 10 MHz. For frequencies exceeding 10 MHz it is suggested that the peak equivalent plane wave power density, as averaged over the pulse width, does not exceed 1000 times the S_{eq} restrictions, or that the field strength does not exceed 32 times the field strength exposure levels given in the table.

(f) For frequencies exceeding 10 GHz, S_{eq}, E^2, H^2 and B^2 are to be averaged over any $68/f^{1.05}$-minute period (where f is the frequency in gigahertz).

(g) No E-field value is provided for frequencies < 1 Hz, which are effectively static electric fields. Electric shock from low impedance sources is prevented by established electrical safety procedures for such equipment.

TABLE A4
Reference levels for general public exposure to time-varying electric and magnetic fields (unperturbed rms values)

Frequency range	Electric field strength, E ($V\,m^{-1}$)	Magnetic field strength, H ($A\,m^{-1}$)	Magnetic flux density, B (μT)	Equivalent plane wave power density, S_{eq} ($W\,m^{-2}$)
Up to 1 Hz	–	32 000	40 000	–
1 Hz – 8 Hz	10 000	$32\,000/f^2$	$40\,000/f^2$	–
8 Hz – 25 Hz	10 000	$4\,000/f$	$5\,000/f$	–
0.025 kHz – 0.8 kHz	$250/f$	$4/f$	$5/f$	–
0.8 kHz – 3 kHz	$250/f$	5	6.25	–
3 kHz – 150 kHz	87	5	6.25	–
0.15 MHz – 1 MHz	87	$0.73/f$	$0.92/f$	–
1 MHz – 10 MHz	$87/f^{1/2}$	$0.73/f$	$0.92/f$	–
10 MHz – 400 MHz	28	0.073	0.092	2
400 MHz – 2000 MHz	$1.375f^{1/2}$	$0.0037f^{1/2}$	$0.0046f^{1/2}$	$f/200$
2 GHz – 300 GHz	61	0.16	0.20	10

Notes

(a) f is the frequency as indicated in the frequency range column.

(b) Provided that basic restrictions are met and adverse indirect effects can be excluded, field strength values can be exceeded.

(c) For frequencies between 100 kHz and 10 GHz, S_{eq}, E^2, H^2 and B^2 are to be averaged over any 6-minute period.

(d) For peak values at frequencies up to 100 kHz, see Table A1, note (c).

(e) Between 100 kHz and 10 MHz, peak values for the field strengths are obtained by interpolation from the 1.5-fold peak at 100 kHz to the 32-fold peak at 10 MHz. For frequencies exceeding 10 MHz it is suggested that the peak equivalent plane wave power density, as averaged over the pulse width, does not exceed 1000 times the S_{eq} restrictions, or that the field strength does not exceed 32 times the field strength exposure levels given in the table.

(f) For frequencies exceeding 10 GHz, S_{eq}, E^2, H^2 and B^2 are to be averaged over any $68/f^{1.05}$-minute period (where f is the frequency in gigahertz).

(g) No E-field value is provided for frequencies < 1 Hz, which are effectively static electric fields. Perception of surface electric charges will not occur at field strengths less than 25 $kV\,m^{-1}$. Spark discharges causing stress or annoyance should be avoided.

TABLE A5
Reference levels for time-varying contact currents from conductive objects

Exposure characteristics	Frequency range	Maximum contact current (mA)
Occupational	Up to 2.5 kHz	1.0
	2.5 kHz – 100 kHz	$0.4f$
	100 kHz – 110 MHz	40
General public	Up to 2.5 kHz	0.5
	2.5 kHz – 100 kHz	$0.2f$
	100 kHz – 110 MHz	20

Notes

(a) f is the frequency in kilohertz.

(b) These values are set to avoid the possibility of indirect effects of exposure (shock and/or burn).

(c) NRPB notes that equation 11 in the ICNIRP guidelines (ICNIRP, 1998) that deals with the summation for limb current and contact current for multiple frequency sources was subsequently amended (ICNIRP, 1999).

Exposure characteristics	Current (mA)
Occupational	100
General public	45

TABLE A6
Reference levels for current induced in any limb at frequencies between 10 and 110 MHz

Notes

(a) The general public reference level is equal to the occupational reference level divided by √5.

(b) For compliance with the basic restriction on localised SAR, the square root of the time-averaged value of the square of the induced current over any 6-minute period forms the basis of the reference levels.

(c) NRPB notes that equation 11 in the ICNIRP guidelines (ICNIRP, 1998) that deals with the summation for limb current and contact current for multiple frequency sources was subsequently amended (ICNIRP, 1999).

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