European Health Risk Assessment Network on Electromagnetic Fields Exposure

Risk analysis of human exposure to electromagnetic fields

Deliverable Report D2 of EHFRAN project

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1 Introduction

Europe is facing the burden of environmental exposures to many new physical or chemical agents, some of which may be potentially detrimental to public health or wellbeing. Among these agents, electromagnetic fields (EMF) are one of the most diffuse and ubiquitous, especially as many new technologies and novel applications based on EMF are being developed and commercialized.

Research on the possible health and biological effects of EMF is being carried out by many research laboratories and centres both within Europe and North America, as well as in Japan and other countries. These activities are supported to various extents by national and international public funding agencies and organizations and by private funding bodies. The extent and diversity of these activities, encompassing many areas of medical and biological research, as well as the latest developments in physics and engineering, makes it particularly difficult to provide relevant, authoritative and timely input for the development of public health policies. Furthermore, it is possible that specific assessments for one application can be misinterpreted or inappropriately applied to other sources or exposure conditions.

In order to help to provide answers to these needs, the European Commission (EC) has funded the European Health Risk Assessment Network on Electromagnetic Fields Exposure (EFHRAN). This project has the specific aim of establishing a wide-ranging network of recognised experts in relevant disciplines that interact and co-operate to perform a health risk assessment of exposure to EMF at all frequencies. The network consists of an co-ordinator and associated participants from universities and research centres in seven European countries, and 16 collaborating partners from a further eight countries, which include the World Health Organization (WHO) and three stakeholder associations.

1.1 Objectives and structure of report

EFHRAN is the first project to produce a risk assessment network on EMF and health issues. By so doing, EFHRAN will provide the EC and EU with a means to allow these bodies to react to the present health concerns of exposure to EMF in full understanding of the scientific issues. EFHRAN is also expected to provide input for future risk management steps, and the structure of the project is designed with sufficient flexibility to allow updated assessments in the future.

EFHRAN builds upon the expertise and experience gained by a previous European Co-ordination Action, the Effects of the Exposure to Electromagnetic Fields: from Science to Public Health and Safer Workplace (EMF-NET). This was financed under the 6th Framework Programme by the European Commission. Briefly, the main aims of EMF-NET were to collate the results of ongoing research into the effects of EMF that were funded by the European Commission or under other national and international actions, and to provide advice for the development of policy options by the European Union and other stakeholders. In addition, it provided observations on existing research projects in terms of priorities, gaps in knowledge, results, and on emerging technology to provide judicious and policy relevant information concerning the health implications of exposure to EMF. Such information was intended to facilitate the development of policy options covering public health and consumer protection, health and safety at work, European competitiveness, and environmental issues. (Complete details of EMF-NET and its many reports and deliverables are available online at http://web.jrc.ec.europa.eu/emf-net/).

EFHRAN has been specifically designed to achieve the following strategic objectives:

- *Monitor and search for evidence of health risks related to EMF exposure*
- *Characterize and, where appropriate, quantify potential health risk posed by EMF exposure*
- *Enhance the EC's ability to respond rapidly to health issues and concerns related to EMF using scientifically sound advice and analyses*
- *Improve the compilation of knowledge and its dissemination on issues related to EMF and health.*

In order to achieve these objectives, the activities of EFHRAN have been divided into five specific objectives: risk analysis and hazard identification; exposure assessment; dose assessment; risk characterisation; and risk management. These objectives have been further divided into nine work packages (WP). This report represents the main output and deliverable of WP 4.

This report considers and reviews the latest published research exploring possible effects on humans from EMF in order to identify any potential health concerns. Both epidemiological and experimental studies are considered, for cancer and non-cancer endpoints with separate analyses made for low, intermediate and high frequencies. For the purposes of this document, low frequencies are defined as time-varying EMF with frequencies of up to 300 Hz; intermediate frequencies as EMF of 300 Hz to 100 kHz; and high frequencies as EMF with frequencies between 100 kHz and 300 GHz.

Many studies have been published over the last 30 years or more on the biological and health effects of exposure on low, intermediate, and high frequency fields. It was not feasible to try and evaluate all the studies on an individual basis. Therefore a number of recent reviews were consulted to establish a current consensus opinion regarding the evidence of health effects. These were the 39 reports from EMF-NET (published between 2004 and 2009) and the two reports from the Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR, 2007, 2009a). These provided a starting point for the health risk analysis. Also consulted were the monograph on extremely low frequency fields (ELF) by a WHO Task Group (WHO, 2007) and the epidemiological review on health effects of radiofrequency exposure from the International Commission for Non-Ionizing Radiation Protection (ICNIRP) Standing Committee on Epidemiology (Ahlbom et al, 2004; ICNIRP, 2009). More recent studies not available to either SCENIHR or EMF-NET and published after August 2008 were evaluated separately, and their results incorporated into the consensus opinion. In this way, it was possible to construct an updated health risk assessment.

In order to evaluate the strength of evidence for adverse effects arising as a consequence of exposure to EMF, EMF-NET had used a very simple, yet powerful, four point classification system that itself was based on the system used by the International Agency for Research on Cancer (IARC) to estimate the carcinogenic risk to humans from a wide range of chemicals and physical agents, including static and extremely low frequency electric and magnetic fields (IARC, 2002). EFHRAN decided to adopt the same classification system to evaluate the strength of evidence for any particular effect. The four classifications and criteria for inclusion into any particular category are shown in Table 1.

Clearly, a classification of *sufficient evidence* requires there to have been much high quality research that produces a consistent outcome; independent replication is also considered a key element. Similarly, *evidence suggesting a lack of effects* indicates that several studies have reported the absence of field-related effects using a range of appropriate models and relevant exposure conditions.

2 Low frequencies (up to 300 Hz)

For more than a century, exposure to extremely low frequency (ELF) electric and magnetic fields has been ubiquitous, related to the production, transmission, distribution and use of electric currents. Intensified research into possible adverse health effects of exposure started already in the late 1970s, with epidemiological and experimental

Classification	*Necessary inclusion criteria*
Sufficient evidence	• when a positive relationship is observed between the exposure and the effect investigated • when the effect is replicated in several studies by independent investigators or under different protocols, and when there is a consistent exposure-response relationship • when confounding factors could be ruled out with reasonable confidence
Limited evidence	• when the evidence of the effect is restricted to a few studies, or when there are unsolved questions regarding the adequacy of the design, conduct or interpretation of the study • when confounding factors could not be ruled out in the studies with reasonable confidence
Inadequate evidence	• when the studies are of insufficient quality, consistency or statistical power to permit a conclusion
Evidence suggesting a lack of effects	• when no effects are reported in several studies by independent investigators under different protocols involving at least two species or two cell types and a sufficient range of field intensities

Table 1. The four point system used in this report to classify the strength of evidence for any particular effect; a similar system was used by EMF-NET.

studies mainly on outcomes such as cancer, neurodegenerative diseases, cardiovascular diseases, reproductive effects, and non-specific symptoms affecting well-being. On the exposure side, research has focussed on residential exposures, for instance people living close to power lines, on occupational exposures such as for electricians, and on the use of electric household appliances. While some studies estimated exposure in a crude way, like using simply the distance between the residence and the nearest power line, using broad job titles to categorize occupational exposure or asking study participants about past use of electric appliances, assessment methods have been refined over the years and comprehensive stationary or personal measurements as well as detailed job-exposure-matrices based on work activities have been developed. In addition to studies on health effects (WHO, 2007), many measurement surveys have been conducted to better understand the distribution of exposure in time and space and the relative contribution of the various exposure sources to an individual's total ELF exposure. For all European countries where measurement data are available (described in EFHRAN Deliverable D4: Report on the level of exposure in the European Union), it appears that average exposure over 24 hours is usually well below 0.1 microtesla (µT), and the proportion of the general population exposed to average ELF magnetic fields above 0.2 µT is small, i.e., between 1-5%; average exposures to magnetic fields exceeding 1 µT are exceptional but may occur in residences just beneath high-voltage power lines or with transformers in the basement or in certain occupations, e.g., among electric welders, electricians, electric power engineers, or locomotive engineers.

2.1 Current consensus opinion

Although numerous studies have been completed in this field, the evidence remains ambiguous. The major reasons are that study results are inconsistent and many studies suffered from methodological shortcomings. It is therefore important to continuously review the body of evidence. This has recently been done by the World Health Organization (WHO, 2007), the EMF-NET project of the European Union (EMF-NET, 2009), and the Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR) of the European Commission (SCENIHR, 2009a). In all, these risk analyses by international organisations are well in line with assessments of those of national authorities responsible for radiation protection issues. Comparing the risk assessments by WHO, EMF-NET and SCENIHR shows little disparities, hence, the 2009 report of SCENIHR is used to illustrate the current consensus opinion (SCENIHR, 2009a). The SCENIHR report included scientific publications up to the end of 2008.

SCENIHR reported limited evidence for an association between exposure to ELF magnetic fields and the risk of childhood leukaemia (SCENIHR, 2009a). This was based on a classification performed by the International Agency for Research on Cancer in 2001, ranking ELF magnetic fields as possibly carcinogenic to humans (IARC, 2002). The classifications then as well as today were based on the facts that epidemiological studies showed a rather consistent association between magnetic fields above approximately 0.3/0.4 µT and a doubling in risk for childhood leukaemia, although chance, bias and confounding could not be ruled out as an explanation with reasonable confidence, and a lack of support from experimental studies or mechanistic modelling.

Since the assessment in 2001, further epidemiological studies were conducted, however, they did not provide further insight but were all consistent with the previous assessment (Schüz and Ahlbom, 2008), and the new experimental studies did not strengthen the biological plausibility of the observed association either (SCENIHR, 2009a). SCENIHR has noted that overall little targeted research has been done to reconcile the data and suggests ELF magnetic fields and childhood leukaemia as a high priority research area (SCENIHR, 2009b). For other cancers than childhood leukaemia there was either inadequate evidence or some evidence against an association (SCENIHR, 2009a).

SCENIHR further reported that some recent studies support previous notions that the risk of Alzheimer's Disease may be linked to exposure to ELF magnetic fields (SCENIHR, 2009a). While the majority of studies has been done in relation to occupational exposures, the first study on residential exposures has been conducted in Switzerland suggesting an increased risk of Alzheimer's Disease among people living close to high-voltage power lines (Huss et al, 2009). Based on these findings, SCENIHR has classified ELF magnetic fields and Alzheimer's Disease as a high priority for further research (SCENIHR, 2009b). For other neurodegenerative diseases the evidence appears to be weaker. The possible association between occupational exposure to ELF magnetic fields and the risk of amyotrophic lateral sclerosis is discussed in detail in the WHO risk assessment (WHO, 2007). However, the evidence was classified as inadequate mainly due to possible confounding by electric shocks or chemical exposures at the respective work places, and since then no new influential studies have been published. For Parkinson's Disease and multiple sclerosis there are fewer studies, but they show no consistent indications of an increased risk. For cardiovascular diseases more recent studies suggest an absence of any association (SCENIHR, 2009a).

Lastly, SCENIHR (2009a) concluded that there is no consistent relationship between exposure to ELF fields and a variety of self-reported symptoms, such as skin irritations, headache, sleep problems, concentration difficulties, or fatigue.

2.2 More recent studies

2.2.1 Epidemiology

With regard to the childhood leukaemia findings, new pilot activities have been started in an attempt to identify cohorts of children with increased ELF magnetic field exposure in order to reduce the impact of participation bias that has affected previous case-control studies; these activities aim at identifying residences with transformers leading to higher exposures in children (Ilonen et al, 2008) or suggest how to use existing birth cohort studies in this context (Greenland and Kheifets, 2009). A recent methodological study explains why further studies applying the simple distance-to-power-line metric are unlikely to provide new insights (Maslanyj et al, 2009). An ongoing activity is a follow up of the hypothesis that ELF magnetic field exposure is related to a poorer survival after childhood leukaemia, suggesting that ELF magnetic fields promote the growth of leukemic cells resulting in a recurrence of the disease. Indeed, a poorer survival has been observed in the hypothesis-generating study in the US (Foliart et al, 2006) which was broadly confirmed by a subsequent study from Germany (Svendsen et al, 2007), but since both studies included very small numbers of exposed children no firm conclusions can be drawn. An ongoing pooling project on this issue is expected to provide further insight as for this purpose cases enrolled in previous case-control studies from the US, the UK, Canada, Germany, Japan, New Zealand and the Nordic countries (Ahlbom et al, 2000) are followed up for vital status.

Mezei et al (2008) conducted a meta-analysis of 13 studies on residential exposure to ELF magnetic fields and the risk of brain tumours in children and observed a statistically non-significant 70% increased effect estimate at exposures above 0.3/0.4 µT; a pooling project of the original studies is ongoing. A recent US case-control study of occupational exposures and risk of brain tumours in adults did not show an association (Coble et al, 2009). This was consistent with findings of a recent meta-analysis pooling more than 20 studies (Kheifets et al, 2008). It was concluded that while a small increase of 10% was observed in the summary risk estimate, the more recent and methodologically improved studies showed weaker associations than the earlier studies, providing little evidence for an association. Yenugadhati et al (2009) explored associations between various occupations and the risk of lung cancer in a Canadian case-control study and discuss a possible role of exposure to EMF for some of their findings; however, due to this rather indirect approach the evidence remains unchanged.

All of the recent studies on neurodegenerative diseases had already been included in the SCENIHR report (SCENIHR, 2009a) and no new studies have appeared in the meantime. Another US study on cardiovascular disease confirmed the previous notion of an absence of an association (Cooper et al, 2009).

2.2.2 Experimental studies

There have been very few recent studies that have investigated the effects of low frequency fields on volunteers. Overall, these studies only provide very limited additional information, and they do not substantially alter the previous health risk assessment.

Bellieni et al (2008) investigated the effects of fields generated by electric motors in incubators may have on autonomic function in newborn babies. Transient changes in the total power and spectral components of heart rate variability (HRV) were noted when the motors were running. Confirmatory studies are required to determine the significance of this observation. Lednev et al (2008) reported that heart rate variability in adults was affected by exposure to very weak fields (above 2 µT); the direction of change was dependent on the frequency used.

Cook et al (2009) reported changes in alpha activity measured over the occipital-parietal regions of the brain after acute exposure of volunteers to two weak pulsed magnetic field sequences (+/- 200 µT peak). The direction of change depended on the specific sequence used.

Albert et al (2009) found no evidence that exposure of male and female volunteers to a 60 Hz magnetic field at 200 µT for 4 h exposure could cause DNA damage in peripheral blood leukocytes as assayed using the alkaline comet assay, or the increased the incidence of micronuclei. Two independent studies have examined the effects of occupational exposure to magnetic fields by examining peripheral blood of exposed workers. At best, these provide only weak evidence for a field-related effect on natural killer cell activity (Gobba et al, 2009) and antioxidant activity (Sharifian et al, 2009).

Lastly, Skomro et al (2009) found that repeated, acute exposures to low frequency magnetic fields at 3 or 4 µT had no consistent effect on the content of calcium, magnesium and fluoride ions in saliva.

2.3 Summary and Conclusions

The strength of evidence for each health outcome is summarised in Table 2. These have been derived from the previous evaluations of EMF-NET (2009) and SCENIHR (2009a) coupled, where relevant, with the more recent data described in the present evaluation.

For none of the diseases is there sufficient evidence for a causal association between exposure to low frequency fields and the risk of the respective disease.

There is limited evidence for an association between magnetic fields and the risk of leukaemia in children. This evaluation reflects the current state of knowledge that epidemiological studies have shown an association between residential exposures to power frequency magnetic fields at above approximately 0.3/0.4 µT and a two-fold risk of childhood leukaemia with some degree of consistency, but the observed association alone is not sufficient to conclude a causal relationship. This is because of three reasons:

i) there is no known mechanistic explanation for the observed association and none of the hypotheses put forward to explain it has received any convincing support from data;
ii) overall, experimental studies do not provide evidence that low frequency magnetic fields are carcinogenic;

iii) a combination of chance, bias and confounding may well have produced a spurious association in the epidemiological studies.

It is unlikely that further epidemiological studies of the same design as used earlier will provide any new insight. New concepts to identify cohorts of children with higher exposures may turn out to be promising. If the hypothesis of a poorer survival of children with leukaemia will be confirmed by other studies, this will increase the biological plausibility of a causal association. Conversely, further methodological work investigating the impact of possible biases in the childhood leukaemia studies may shift the evidence in the opposite direction.

Outcome	Strength of evidence
Cancer outcomes	
Leukaemia in children	Limited
Brain tumours in children	Inadequate
Brain tumours in adults	Inadequate
Breast cancer in adults	Lack of effect
Other cancer (children or adults)	Inadequate
Neurodegenerative diseases	
Alzheimer's disease	Inadequate
Amyotrophic lateral sclerosis (ALS)	Inadequate
Other neurodegenerative diseases	Inadequate
Reproductive outcomes	
All outcomes	Inadequate
Cardiovascular diseases	
All diseases	Lack of effect
Well-being	
Electrical hypersensitivity (EHS)	Lack of effect
Symptoms	Inadequate

Table 2. The strength of evidence for any health outcome being associated with exposure to low frequency magnetic fields as suggested by EMF-NET (2009) and SCENIHR (2009a) and modified by the results of more recent research.

There is inadequate evidence with respect to several diseases, however, the reasons for these evaluations are varying. For Alzheimer's Disease the evidence is suggestive; however compared to the childhood leukaemia case, the studies are fewer and less consistent. As recent, methodologically superior studies suggest an association, there is ample justification to demand further studies into this topic. The situation is similar for childhood brain tumours, where awaited results of an ongoing pooled analysis may make a re-evaluation necessary. Amyotrophic lateral sclerosis is a third outcome for which there is some indication of an elevated risk, but data are not consistent enough to conclude limited evidence.

For brain tumours in adults, it appears that more recent studies rather suggest a lack of an effect, but due to positive findings in some studies the classification of inadequate evidence remains.

For all other cancers, other neurodegenerative diseases and for subjective symptoms, the classification of inadequate evidence displays rather lack of data. However, due to the weak biological plausibility there appears to be no emerging demand to conduct further studies.

There is lack of evidence for breast cancer and cardiovascular disease. For breast cancer, there were no new studies, but as there were already a large number of studies available at the time of the previous evaluations, this assessment is quite robust. For cardiovascular disease there was one new study confirming the absence of an association.

There is continuing debate about whether non-specific symptoms may be caused by exposure to ELF fields, and whether some individuals show increased sensitivity to exposure, commonly termed electrical hypersensitivity (EHS). As this is a long-lasting discussion with a series of failures to demonstrate EHS, the overall evaluation suggests a lack of effect. Given the uncertainty regarding the role played by EMF in the aetiology of this condition, the World Health Organization (WHO) has proposed that EHS should be better termed Idiopathic Environmental Intolerance with attribution to EMF.

3 Intermediate frequencies (300 Hz – 100 kHz)

Exposure to intermediate frequency (IF) fields has in the past largely been restricted to long-range radio, welding devices, cathode-ray based monitors and magnetic resonance imaging (MRI). However, sources and exposures to these fields are now increasing due to the development of new and emerging technologies, such as anti-theft devices, badge readers and induction hobs and hotplates; compact fluorescent lights also produce fields in the IF range. However, explicit data on the possible health effects of IF fields remain limited.

3.1 Current consensus opinion

For the purposes of risk assessment, IF fields have only been considered as a separate entity relatively recently. Largely depending on the definition of their frequency range, IF fields have been considered in various reviews and monographs with either low or high frequency fields. IF fields can induce electric fields and currents as seen with low frequency fields but they can also induce heating as known from high frequency fields. Assessments of possible hazards at intermediate frequencies are based primarily on extrapolation from knowledge about these higher and lower frequencies (SCENIHR, 2007, 2009a).

Very little useful epidemiological data are available. The existing evidence largely comes from older studies that tended to used job title as surrogate for exposure. Groups studied include uses of visual display units (VDUs) associated with personal computers and radio and telegraph operators. Outcomes studied included cancer as well as effects on the eye, the cardiovascular system and reproductive effects. Although no particular risks were indentified, the quality of the studies is limited, and any hazards remain unclear.

There have been some animal studies exploring the effects of IF fields from VDUs, particularly on reproduction and development. This older literature has been well reviewed. Effects studies with humans are less common, although some studies have investigated effects on skin and symptoms. With the demise of cathode-ray based monitors, more recent work exploring health risks associated with computer use in humans has concentrated on ergonomic issues (and is not considered here). Despite some limited evidence from animal studies that have reported field-dependent effects on reproduction and development, there is no consistent or conclusive evidence of field-dependent adverse effects.

Overall, SCENIHR (2009a) concluded that there was insufficient data for a health risk assessment, so the overall evaluation for all health endpoints has to be considered to be inadequate.

3.2 More recent studies

3.2.1 Epidemiology

No recent epidemiological studies investigating risks of IF fields have been published.

3.2.2 Experimental studies

No recent volunteer studies investigating IF fields have appeared.

3.3 Summary and Conclusions

Interest in the potential of IF fields to cause adverse effects has been sporadic at best and no recent research appears to have used the exposures and signals associated with new or emerging technologies. The available evidence is insufficient to conclude that an association exists between exposure and the risk of any disease.

Given the lack of recent data, it is not possible to revise the existing classification, and therefore the strength of evidence for all outcomes remains as *inadequate* (Table 3). Given that occupational exposures to these frequencies are increasing, it would be useful if well targeted studies could be performed as a priority to address this lack of research.

Outcome	Strength of evidence
All outcomes	Inadequate

Table 3. The strength of evidence for any health outcome being associated with exposure to intermediate frequency fields as suggested by EMF-NET (2009) and SCENIHR (2009a); there is lack of more recent research.

4 High frequencies (100 kHz – 300 GHz)

Research into the possible effects of exposure to low level radiofrequency (RF) fields has increased over the last decade or so following the widespread increase in mobile phone usage and the roll out of base station networks. More recently, concerns have been raised about DECT cordless phones, and interest in the potential health effects of wireless LANs and Wi-Fi has followed the introduction of these applications into schools, homes and workplaces. However, the effects of RF fields associated with commonly occurring sources in the environment, such as broadcasting, radar, and microwave communication links have been considered for many years before that, and a quite extensive effects literature had been generated. ICNIRP have reviewed much of these data (Ahlbom et al, 2004, 2009; ICNIRP 2009; van Rongen et al, 2009).

4.1 Current consensus opinion

Early epidemiological investigations centred on a variety of occupational groups with the potential for high exposures to RF fields, such as radar technicians, and radio and telegraph operators, with interest focussed on brain tumour and leukaemia risks. In general, no raised risks for any cancer were found, although the size and quality of many of these studies was limited, and they suffered from a potential for bias and misclassification of exposure. Other studies investigated risks to people living near radio or TV transmitters. These studies did not demonstrate the existence of a hazard, but they relied on very crude measures of exposure (distance from broadcasting masts).

Very few volunteer studies have been undertaken, but a range of *in vivo* and *in vitro* studies indicated that consistent effects were seen only with exposures that increased whole body or localised tissue temperatures by about a degree or more. Such thermal responses remain a cornerstone of existing guidelines limiting human exposures to RF fields (e.g. ICNIRP, 1998). Effects of RF fields in the absence of overt heating have been reported, but they remain controversial, and the interaction mechanism whereby such effects may be caused remains elusive.

More recent studies investigating the health risks of RF fields have been summarised and reviewed by EMF-NET as well as by SCENIHR (2007, 2009a). These studies have concentrated on cancer risks from the use of mobile phones, but other endpoints and sources have been considered; attention is also starting to be given to new and emerging technology, such as ultra wide band signals.

SCENIHR (2009a) reviewed the evidence from the various national studies and pooled analyses from parts of the Interphone study: severe concerns were raised about reporting bias that may exist in these data. Nonetheless, it was concluded that this evidence, combined with the results of animal and cellular studies indicated that exposure to RF fields was unlikely to lead to an increase in brain cancer or parotid gland tumours in humans. However, it was noted that since the widespread duration of exposure of humans to the fields from mobile phones was shorter than the induction time of some cancers, further studies were required to identify whether exposure periods in excess of ten years may pose some cancer risk. Regarding shorter periods of exposure, it was concluded that mobile phone use for less than ten years was not associated with increased cancer incidence. In addition, SCENIHR (2009a) concluded that two well-conducted case-control studies investigating the association between the fields from broadcast transmitters and childhood leukaemia provided no evidence for such an association.

On non-cancer outcomes, it was concluded that the available scientific evidence failed to provide support for an effect of RF fields on self-reported symptoms. Although an association between RF exposure and single symptoms was indicated in a few cross-sectional studies, there was a lack of consistency in these findings, and several provocation studies indicated a lack of effect on well-being using handset or base stations signals (SCENIHR, 2009a). Further, there was no evidence from a number of studies that those reporting sensitivity to RF exposure or healthy controls could reliably detect the presence of either GSM or UMTS signals significantly better than chance. The possibility that nocebo effects may play a role in symptom formation was highlighted.

Regarding effects of RF fields on the brain and nervous system, several studies using volunteers have not reported any consistent effects on various behaviours or cognitive functions, although sporadic changes were noted in some studies. A large number of studies have reported that exposure is without detectable effect on either the auditory or visual systems. Some, but not all studies have reported effects on sleep and sleep encephalogram (EEG) patterns, and others have reported on specific EEG components during exposure. However, SCENIHR questioned the relevance of these subtle changes to health, and noted that no interaction mechanism could be identified.

Epidemiological studies investigating the effects of RF fields on adverse pregnancy outcomes are limited mainly to occupational exposures among physiotherapists (SCENIHR, 2007). Despite some positive findings, no consistent adverse outcome has been reported, but the available results do not allow any definite conclusions to be drawn due to the limited statistical power and potential recall bias in the data. Including more recent data did not change this conclusion (SCENIHR, 2009a).

A large Danish cohort study reported that the overall scores for behavioural problems at age seven were increased in children of mothers who had used mobile phones during or after pregnancy. Exposures from the phones would have been very low, making it doubtful that fields could have anything to do with the observed association.

Studies investigating effects of RF fields on fertility or sperm quality in men also have failed to provide consistent evidence of adverse effects. These have investigated occupational exposures in the Norwegian Navy and in those attending infertility clinics. However these studies suffer from a number of weaknesses, including self reporting of endpoints, and a lack of measurement of RF fields in the occupational studies, and confounding due to lifestyle differences in the clinic studies, making them inadequate for the purposes of risk assessment.

4.2 More recent studies

4.2.1 Epidemiology

Results of the Interphone international analyses of glioma and meningioma have recently been published (the Interphone Study Group, 2010). Analyses included 2708 glioma and 2409 meningioma cases and their matched controls. A reduced OR related to ever having been a regular mobile phone user was seen for glioma (OR 0.81, 95% CI: 0.70, 0.94) and meningioma (OR 0.79; 95% CI 0.68, 0.91), possibly reflecting participation bias or other methodological limitations. No elevated OR was observed 10 or more years after first phone use (glioma: OR 0.98, 95% CI 0.76, 1.26; meningioma: OR 0.83, 95% CI 0.61, 1.14). Odds ratios were below 1.0 for all deciles of lifetime number of phone calls and nine deciles of cumulative call time. In the tenth decile of recalled cumulative call time, 1640 hours or longer, the odds ratio was 1.40 (95% CI 1.03, 1.89) for glioma, and 1.15 (95% CI 0.81, 1.62) for meningioma; but there are implausible values of reported use in this group. Odds ratios for glioma tended to be greater in the temporal lobe than in other lobes of the brain, but the confidence intervals around the lobe-specific estimates were wide. Odds ratios for glioma tended to be greater in subjects who reported usual phone use on the same side of the head as their tumour than on the opposite side. Overall, no increase in risk of either glioma or meningioma was observed in association with use of mobile phones. There were suggestions of an increased risk of glioma at the highest exposure levels, but biases and errors prevent a causal interpretation. The possible effects of long-term heavy use of mobile phones require further investigation.

Deltour et al (2009) found no clear change in the overall trends in incidence rates of brain tumours between 1998 and 2003 in the Nordic countries (Denmark, Finland, Norway, Sweden). The findings do not indicate an observable effect of mobile phone use, as the rates were either stable, decreasing, or continuing a gradual increase that started before the introduction of mobile phones. The lack of a trend change in incidence rates up to 2003 suggests either that the induction period for brain tumours due to mobile phone use exceeds the exposure duration of this study, the risk in this population is too small to be observed, the risk is restricted to subgroups of brain tumors or users, or there is no risk.

Recent epidemiological studies based on RF field strength predictions for each participant provide little evidence for an association between RF fields and childhood leukaemia risk, and weaken findings from earlier reports on leukaemia clusters around radio and television broadcast transmitters (Schüz and Ahlbom, 2008). Ha et al (2007) conducted a case-control study in South Korea, with a correction of the main results table in a reply to a letter by Schüz et al (2008). The study involved 1,928 childhood leukaemia cases and RF exposure was calculated using a field prediction program. Although there was an excess of leukaemias in the 2 km circles of the transmitters (a relative risk estimate of 2.15, 95% CI 1.00-4.67), no association was seen between childhood leukaemia risk and the predicted field strengths (0.83, 95% CI 0.63-1.08 for the highest quartile of exposure); in the intermediate categories, relative risks were often statistically significantly decreased.

Schüz et al (2009) conducted a large nationwide cohort study in Denmark of 420,095 persons whose first mobile phone subscription was between 1982 and 1995, who were followed through 2003 for hospital contacts for a diagnosis of a CNS disorder. Effect estimates were increased by 10–20% for migraine and vertigo. No associations were seen for amyotrophic lateral sclerosis, multiple sclerosis or epilepsy in women. Effect estimates decreased by 30–40% were observed for dementia (Alzheimer disease, vascular and other dementia), Parkinson’s disease and epilepsy among men. The excesses of migraine and vertigo deserve further attention. An interplay of a healthy cohort effect and reversed causation bias due to prodromal symptoms impedes detection of a possible association with dementia and Parkinson's disease.

A large, case control study by Elliott et al (2010) examined whether proximity to a mobile phone base station during pregnancy raised the risk of developing cancer in children aged 0-4 years. The study identified 1397 children in the UK national cancer registry 1999-2001 with leukaemia, non-Hodgkin's lymphoma or a tumour in the brain or CNS, and it compared each of these with four matched controls. Consistent with earlier studies investigating the childhood leukaemia risk and predicted field strengths from broadcast transmitters, this study found no evidence of an association between the risk of early childhood cancers and proximity to base stations during pregnancy. Although distance from a base station is not necessarily a good exposure metric, no associations were seen also using modelled estimates of exposure.

Development
Vrijheid et al (2010) investigated early behavioural development of children from mothers who had used a mobile phone during pregnancy. Mothers (n = 587) completed questions about mobile phone use in week 32 of pregnancy, and children were tested at 14 months of age using the Bayley Scales of Infant Development. Only small differences were found between the offspring of mobile phone users and non-users, which the authors attributed to possible confounding. No trend was found with amount of mobile phone use within users.

Symptoms and increased sensitivity
The MobilEe study is a population-based cross-sectional study consisting of 1,498 children (aged 8-12 years) and 1,524 adolescents (aged 13-17 years) from four towns and cities in southern Germany (Thomas et al, 2008). Personal exposures to GSM signals (both uplink and downlink), DECT cordless phones and WLANs (but not TV bands or FM radio) were individually measured for 24 h using a compact dosimeter[1] placed on the upper arm, and acute symptoms were recorded three times during that day. Chronic symptoms during the last sixth months were assessed by computer-assisted personal interview, as were mental health and behavioural problems. Differences in exposure over the day and between children and adolescents were noted, but exposures overall were less than 1% of the reference level for public exposure recommended by ICNIRP (1988).

Kühnlein et al (2009) analysed the MobilEe data on chronic symptoms (including headache, sleeping problems and fatigue) from 1,433 children using logistic regression models adjusted for potential confounders. The exposure data were categorized into low and high groups using standard and nonparametric function methods. No significant differences were seen between the categorized exposures and any of the symptoms considered. Thus well-being in children did not appear to be affected by exposure to RF fields at environmental levels.

Using a German version of the Strengths and Difficulties Questionnaire, a possible effect of exposure on behaviour was reported by Thomas et al (2010) as part of the MobilEe study. Compared to subjects in the lowest exposure quartile, those in the highest exposure quartile exhibited an increased prevalence of conduct problems (usually characterised as aggressive and destructive activities) for both adolescents and children; the other three categories of behaviours assessed were not significantly altered for either group. Overall, an association between exposure and total behavioural problems was seen for the adolescents (OR 2.2; 95% CI 1.1-4.5) but not for the children (1.3; 0.7-2.6). However, the authors urged that these results must be treated with caution, particularly since the behavioural measures were only assessed once, and they recommended further study.

[1]The merits and shortcomings of the two dosimeters (exposimeters) that have been used in personal measurement studies are discussed by Röösli et al (2010).

QUEBEB is a large, cross-sectional study investigating symptoms due mobile phone base stations among adults in Germany. In the first phase of the study (Blettner et al, 2010), a sample of 30,047 participants (aged 14-69 years), selected from a panel of 73,000 households used for nationwide health surveys, completed a postal questionnaire that included questions about 38 symptoms and health complaints. Participants also answered whether they were worried about health effects of base stations and if their health was adversely affected by them. It was found that nearly 19% of participants were concerned about health effects from base stations, and about 10% attributed adverse consequences from field exposure. The summary health score of people calculated to be living within 500 m of a base station was slightly higher than that of those living further away, perhaps suggesting a weak effect, but in absolute terms, this difference was less than many of those obtained for other variables in this analysis, especially gender.

In the second phase of the QUEBEB study (Berg-Beckhoff et al, 2010), five standardised health questionnaires were completed by 1326 participants in urban areas and RF fields were measured using an Antennessa dosimeter. The fields were measured during the day for five minutes in each of four locations on the participant's bed. Combined exposures were calculated for three base station downlink frequencies, and for all RF fields excluding the corresponding uplink frequencies: a person was considered to have been exposed when the field exceeded 0.1 V m^{-1} and not exposed below that value. All field measurements were far below guideline values, and neither measure of exposure was associated with a significant change of the scores in any of the questionnaires. However, sleep disturbances and health complaints were related to the belief that health is seriously affected by mobile phone base stations.

The Swiss Qualifex project is an ongoing, prospective cohort study that is investigating whether RF field exposure under real-life conditions can cause symptoms or impair health-related quality of life (Röösli et al, 2008). Participants are drawn from the urban and suburban areas of Basel. A exposure prediction model has been developed that can calculate long-term average, personal RF field exposure with reasonable accuracy to measured field values, both indoors and outdoors (Frei et al, 2009, 2010; Bürgi et al, 2010). About 1500 persons are taking part in a written questionnaire study about exposure to RF fields and health status; effects on sleep quality are being further examined in a subset of these participants. Results of these studies have yet to be published.

Landgrebe et al (2009) assessed the occurrence and severity of tinnitus in people who self-report hypersensitivity to EMFs and matched controls who did not report such sensitivity. It was found that tinnitus was reported significantly more often in hypersensitive subjects (n = 69) compared to controls (n = 80) but there were no differences between the groups in tinnitus duration or severity. In addition, the risk of tinnitus was not associated with mobile phone use, which is consisted with the results of an earlier study by Davidson and Lutman (2007).

Lastly, two cross-sectional studies indicate differences between those who perceive themselves as sensitive to signals from mobile phones alone and those with sensitivity to electrical equipment in general. Differences were observed in symptom severity and prevalence, in general health status, and in self-reported personality traits such as anxiety, depression, exhaustion and stress (Rubin et al, 2008; Johansson et al, 2010). Such differences could be of importance in the management of these groups of patients to ensure delivery of appropriate medical treatment.

4.2.2 Experimental studies

Laboratory studies have continued to investigate the effects of exposure of volunteers to the signals associated with mobile phones. Recent well-performed studies have found that these signals appear to be without significant effect on cognitive function, although some studies report subtle effects on the electrical activity of the brain. Very few experimental studies have been conducted using children, and it is still not clear whether children are more sensitive to RF fields than adults. Overall, all the results of the recent studies are consistent with the evaluations previously reached by EMF-NET (2009) and SCENIHR (2009a) and generally add confidence to these health risk assessments.

Sensory-related functions

Consistent with most earlier results, recent experimental studies have showed that short-term exposure to mobile phone signals does not appear to have any measurable effect on auditory function or the early processing of auditory information.

As part of the European project investigating effects of EMF on hearing (EMFnEAR), Parazzini et al (2009) reported that 20 min exposure to UMTS signals from a modified handset producing an SAR of 0.07 W kg^{-1} in the region of the cochlear did not have any consistent effect on auditory function as measured using a battery of tests, including hearing threshold levels, distortion product otoacoustic emissions, and event-related potentials (ERPs) recorded while performing an auditory oddball task. A similar lack of effects was observed when a patch antenna system was used to deliver UMTS signals at 1.75 W kg^{-1} for 20 min (Parazzini et al, 2010).

Kwon et al (2010a) found that short-term exposure to a GSM signal (902 MHz pulsed at 217 Hz, SAR of 0.8 W kg^{-1}) did not engender any changes in the amplitudes, latencies or interwave intervals of the main components (waves I, III and IV) of the auditory brainstem response (ABR) in 17 healthy volunteers. In addition, Kwon et al (2009) investigated the effects of short-term exposure to GSM signals (peak SAR of 1.2 W kg^{-1}) on a component of the EEG associated with early auditory discrimination processing, called mismatch negativity (MMN). MMN produced in response to a specific change in tone during a series of standard auditory stimuli was measured in 17 healthy volunteers. Compared to sham exposure, no changes in MMN were observed during exposure. Further, Kwon et al (2010b) used the same paradigm and study design to investigate the effects of GSM signals on 17 school-age children. As with adults, short-term exposure to a GSM signal (peak SAR of 1.2 W kg^{-1}) had no significant effect on MMN nor on other components of the EEG associated with sensory encoding and attention shifting.

Electroencephalography studies

Previously SCENIHR (2009a) concluded that there was some evidence that exposure to RF fields may influence brain activity as measured in EEG studies. Several studies have investigated this possibility further.

Using an antenna-based exposure system, Henrikis et al (2008a, 2008b) investigated the effects on the power of the EEG from short-term, intermittent exposure (1 min on, 1 min off) to 450 MHz fields pulse-modulated at different frequencies: the SAR averaged over 1 g of tissue was estimated at about 0.3 W kg^{-1}. In the first study, 13 subjects were exposed at modulations of 7, 14 or 21 Hz (Henrikis et al, 2008a). Overall, significant increases in EEG power in the alpha and beta (but not theta) frequency bands were seen using 14 and 21 Hz; no significant effects were seen using 7 Hz. Only the changes in the alpha band persisted beyond the first 30 s of exposure. Differences between individuals in responsiveness to exposure were striking, with three subjects in particular showing very large effects. These differences in sensitivity were explored further in a second study (Henrikis et al, 2008b). This found that between 13 and 31% of subjects tested showed a significant increase in beta power of the EEG in response to exposure to microwaves modulated at between 7 and 217 Hz.

Hountala et al (2008) explored the effects of exposure to (unmodulated) 900 or 1800 MHz on volunteers while performing an auditory memory task. In this task, a tone indicated that a list of digits was to be presented which had to be recalled. A significant effect on the EEG 500 ms prior to the tone was reported, as well as sex-related differences that depended on the frequency of the field. Spectral power coherence was used to analyse the EEG, which was considered useful to reveal very small effects.

De Tommaso et al (2009) explored the effects on the EEG of acute exposure on left hand side of the head to pulsed 900 MHz fields of 10 volunteers using the paradigm of contingent negative variation (CNV). Subjects were presented with a warning tone followed 3 s later by a second tone when they had to press a response button. Compared to the results with a phone turned off, both exposure (maximum local SAR of 0.5 W kg^{-1}) and sham exposure (where the RF signal was sent to an internal load) resulted in decreases in initial CNV amplitude, and greater habituation to the warning tone. It was suggested that both the RF fields and the low frequency magnetic fields produced by the phone battery had exerted the same effect and reduced arousal and expectation of the warning tone, although the low number of volunteers investigated, and possible laterality effects, were acknowledged.

In an extension of an earlier study showing field-related effects on the eyes-closed, resting EEG in young subjects, Vecchio et al (2010) investigated the effect of age. Compared to young subjects, elderly subjects showed significant increases in inter-hemispheric synchronization of frontal and temporal alpha rhythms following exposure to a GSM signal (45 min at 0.5 W kg^{-1}).

Stefanics et al (2008) reported that exposure of 29 subjects to UMTS signals for 20 min had no significant effect on the latency or amplitude of the major ERP components measured while performing an auditory oddball task. In addition, no effects were seen on attentional mechanisms, as measured by analysis of early evoked gamma activity. The average SAR in the head was estimated to be less than 2 W kg^{-1}. Using a non-linear method of EEG analysis, Carrubba et al (2010) detected ERPs in the EEGs of 18 out of 20 volunteers exposed to electric field pulses (0.7 ms, 0.3 Hz, at 100 V m^{-1}). Time averaging analysis, however, did not detect these potentials.

Sleep

Previous studies that have examined the effects of RF fields on sleep parameters and sleep EEG in volunteers have provided some evidence to suggest field-related responses may occur (for example, see studies by Regel et al, 2007; Hung et al, 2007). However, no recent studies appear to have examined these possibilities.

Cognitive effects

Results of recent studies investigating possible effects of mobile phone signals on behaviour and cognition are largely consistent with earlier well performed studies, and there is little evidence that short-term exposures can have strong effects on attention, memory or executive functions. Little is known about the consequences of long-term mobile phone use on human cognitive function.

In a double-blind study using around 160 volunteers, Cinel et al (2008) found that exposure to either modulated or unmodulated 888 MHz (average SAR of 1.4 W kg^{-1}) for about 40 min was without detectable effect on tests of short-term memory, vigilance and attention (a significant result in one test was attributed to chance). Some previous studies had suggested that changes in performance during exposure depended on the cognitive load, but varying the task difficulty here did not have any effect. There were also no effects attributable to laterality of exposure.

Luria et al (2009) reported that the performance of a spatial working memory task could be transiently affected in 48 right-handed, male volunteers exposed to pulsed 915 MHz fields for 1 h. The task required the subjects to make a response with either the left or right hand, while being exposed on one side of the head using a pair modified handsets. Compared to other conditions, the average reaction times of right-hand responses under left–side exposure conditions were significantly longer during the first two blocks of trials (each lasting about 5 min) but these changes became insignificant after allowing for multiple comparisons. There were no field-related effects on accuracy of responding.

Furubayashi et al (2009) exposed 54 female volunteers (11 of whom reported symptoms to mobile phone signals) to 2.14 GHz from a W-CDMA base station at 10 V m^{-1} for 30 min. Whole body average SAR was calculated to be 1.5 mW kg^{-1}. Compared to sham-exposure and exposure to audible noise, continuous or intermittent (field turned on/off every 5 min) exposure had no significant effect on the performance of a precued choice reaction time task, and there were no effects on skin temperature, cutaneous blood flow or heart rate.

Symptoms and increased sensitivity
Investigations into the provocation of subjective symptoms by RF fields and the possibility that some individuals may show increased responsiveness (EHS) have continued (see Rubin et al (2010) for a review).

Consistent with earlier provocation studies with GSM signals, Nam et al (2009) reported that CDMA signals could not be detected by either non-sensitive individuals or those reporting EHS, nor did these signals have any significant effect on subjective symptoms, such as headache or dizziness. In this study, volunteers were exposed for 30 min using a modified handset to pulsed 835 MHz at a local peak in the brain of about 1.2 W kg^{-1}. A significant difference between EHS and non-sensitive groups was noted, but this was attributed to a bias between the groups in reporting the presence or absence of the field. Kwon et al (2008) investigated whether a pulsed 902 MHz field from a modified handset (SAR of 1.2 W kg^{-1}) could be perceived in 82 volunteers, six of which reported some sensitivity to mobile phone signals. In a series of double-blind trials, all subjects were unable to discriminate between real and sham exposure at levels significantly better than chance or to determine whether the field changed during a trial (from off to on, or from on to off). Two additional volunteers who achieved a very high rate of correct performance in detecting the field could not replicate this result in further trials one month later, suggesting a chance phenomenon.

As part of the study using mentioned above, Furubayashi et al (2009) found that both females who self-report symptoms to mobile phone signals and those who do not were unable to reliably detect the presence of a W-CDMA signal. However, significant differences in mood states were seen between these two groups: for example, those reporting symptoms had higher levels of anxiety, fatigue and confusion, and they experienced more discomfort during testing irrespective of the exposure conditions.

Examining the potential role of heavy metal ions in EHS, Ghezel-Ahmadi et al (2010) found that overall levels of lead, mercury and cadmium in the blood were not different between 132 patients reporting EHS and 101 non-sensitive subjects; higher levels of cadmium were found in controls but these were attributed in part to the increased numbers of smokers in the controls compared to the patients.

4.3 Summary and Conclusions

The strength of evidence for each health outcome is summarised in Table 4. These have been derived from the previous evaluations of EMF-NET (2009) and SCENIHR (2009a) coupled with the more recent data described in the present evaluation. For none of these outcomes is there sufficient evidence of a causal association between exposure and disease.

Results from the international analyses of glioma and meningioma in the Interphone study have not demonstrated an increased risk of these diseases in relation to mobile telephone use. There were, however, suggestions of an increased risk of glioma, and much less so of meningioma, observed among the heaviest users, particularly among subjects who reported usual phone use on the same side of the head as their tumour and, for glioma, for tumours in the temporal lobe, but biases and errors prevent a causal interpretation. The strength of evidence regarding adult brain tumours is therefore considered inadequate.

Consistent with an earlier paper, a South Korean study using predictors of RF field intensity provides little evidence for an association between exposure from broadcast transmitters and the risk of childhood leukaemia. A study from the UK found no association between proximity to a mobile phone base station during pregnancy and early childhood leukaemia risk. Therefore the evidence regarding effects from low level, whole body exposures associated with base stations and broadcast transmitters is weak, rather suggesting a lack of effect based on few but large studies. Whether the higher but more localised exposures from mobile phones themselves could contribute to an increased risk of leukaemia in children and adolescents remains to be determined; therefore the overall evidence is considered inadequate (Table 4).

Provocation and cross-sectional studies have not indicated the existence of field-related symptoms or of hypersensitivity to EMF, and some point to nocebo effects in the development of symptoms. However, a nationwide cohort study of mobile phone users in Demark reported an increase in migraine and vertigo, and basic differences in physiology and psychology have been suggested between those who report EHS and those who do not. Overall, this suggests that there is evidence suggesting a lack of effect regarding hypersensitivity, but the classification regarding symptoms should be considered inadequate, and further studies are necessary to perform an improved health risk assessment.

SCENHIR (2007, 2009a) considered that the available epidemiological evidence regarding adverse pregnancy outcomes and cardiovascular disease did not allow any definite conclusions. In the absence of new data,
the classification for both outcomes therefore remains as inadequate.

At present, there is also inadequate evidence regarding the possibility of an association between long-term RF field exposure and increased risks of dementia and Parkinson's disease. A growing number of laboratory studies indicate that the fields associated with mobile phones do not have any detectable effect on sensory function and the early processing of information, or a significant influence on any tested cognitive function. This suggests that acute exposures up to guideline values are without significant risk. However, there is also evidence that exposure to specific modulated fields, including those from mobile phones, may have subtle effects on the spontaneous EEG and increase the power of the alpha frequency band, but only in some individuals. The mechanisms behind this increased responsiveness are not clear at present, and the consequences for health of these subtle changes remain to be determined. No new studies appear to have investigated the possibility of field-dependent effects on sleep and sleep EEG.

Outcome	Strength of evidence
Cancer outcomes	
Leukaemia in children	Inadequate
Brain tumours in children	Inadequate
Brain tumours in adults	Inadequate
Breast cancer in adults	Inadequate
Other cancer (children or adults)	Inadequate
Neurodegenerative diseases	
Alzheimer’s disease	Inadequate
Amyotrophic lateral sclerosis (ALS)	Inadequate
Other neurodegenerative diseases	Inadequate
Reproductive outcomes	
All outcomes	Inadequate
Cardiovascular diseases	
All diseases	Inadequate
Well-being	
Electrical hypersensitivity (EHS)	Lack of effect
Symptoms	Inadequate

Table 4. The strength of evidence for any health outcome being associated with exposure to RF fields as suggested by EMF-NET (2009) and SCENIHR (2009a) and modified by the results of more recent research.

5 Interaction mechanisms

While it well established that EMF at sufficiently high intensities will interact with living tissues to cause demonstrable biological effects, no mechanism have yet been established which could lead to adverse effects from exposures significantly below guideline values. However, given the continuing concerns over the possibility that EMF at environmental levels may be lead to increased risks of cancer or other adverse outcomes, there is a need to consider new proposals for interaction mechanisms and to explore these possibilities. Interaction mechanism at IF are considered to be a variable combination of those occurring at low and high frequencies.

5.1 Low frequencies

Interest is continuing into possible interaction mechanisms that could underpin biological effects at low frequencies: if the association between childhood leukaemia and exposure to magnetic fields is casual, then there has to be an interaction mechanism. There are two main possibly mechanisms that could elicit biological effects, either through direct effects caused by the magnetic field itself, or through the time-varying currents that are induced in living materials by the magnetic field. Arguably, the most promising mechanism that is being actively investigated is the one behind animal navigation. Birds and many other species, including some mammals, reptiles, amphibians, fish, crustaceans and insects, are known to orient and navigate in the geomagnetic field.

The biophysical mechanisms that underlie the avian magnetic compass are poorly understood. One mechanism that is gaining support is based on magnetically sensitive free-radical reactions. In particular, Maeda et al (2008) used spectroscopic observation of a carotenoid-porphyrin-fullerene model system to demonstrate that the lifetime of a photochemically formed radical pair is changed by application of 50 µT magnetic fields, and to measure the anisotropic chemical response that is essential for its operation as a chemical compass sensor. These experiments established the feasibility of chemical magnetoreception and provide insight into the features required for detection of the direction of the geomagnetic field.

5.2 High frequencies

The search for interaction mechanisms other than heating at radiofrequencies has continued without success. The main difficulty is that there are no well-established biological effects for which mechanisms can be elucidated.

A recent review by Sheppard et al (2008) considered the various main hypotheses that have been suggested: co-operativity, signal averaging, coherent detection, or by nonlinear dynamical systems, radical pair mechanism, role of magnetite. None of these possibilities has been validated experimentally. The only recent publications were related to the work of a group from the USA and the UK (Balzano et al, 2008; Kowalczuk et al, 2010) who used a doubly resonant cavity to search for the nonlinear RF energy conversion necessary for demodulation by living cells. The cavity operates in the TE(111) mode at 890 MHz and in the TE(113) mode at 1780 1MHz. Cells with a diode-like nonlinearity would generate second harmonic signals on exposure to a given RF signal. In none of the tested biological samples exposed at 890 MHz was a signal at double the frequency observed. The demodulation process thus does not seem to occur at this frequency range and is likely to be confined below around 10 MHz. The consensus opinion that heating remains the only established mechanism occurring in the GHz range is still valid.

6 Overall summary and conclusions

EFHRAN has the objective to monitor and search for evidence of the health risks associated with exposures to EMF at low, intermediate and high frequencies: low frequencies are defined as time-varying EMF with frequencies of up to 300 Hz; intermediate frequencies as EMF of 300 Hz to 100 kHz; and high frequencies as EMF with frequencies between 100 kHz and 300 GHz. As part of this objective, the present document reviews the latest research into possible health effects of EMF, and incorporates the results of these studies to the consensus opinions of both EMF-NET (2009) and SCENIHR (2009a) in order to construct an updated health risk assessment. Recent epidemiological and experimental studies have been included, as have both cancer and non-cancer endpoints.

In order to evaluate the strength of evidence for any given endpoint, a four point classification scheme has been used that was based on the system devised by IARC to estimate the carcinogenic risk to humans from a wide range of agents. The four points are: a) sufficient evidence; b) limited evidence; c) inadequate evidence; and d) evidence suggesting a lack of effects (see Table 1).

6.1 Low frequencies

Inclusion of the recent data has not necessitated any revisions to the existing consensus opinions of EMF-NET (2009) or SCENIHR (2009a). For none of the diseases is there sufficient evidence for a causal association between exposure and the risk of the disease (Table 5).

There is limited evidence for an association between magnetic fields and the risk of leukaemia in children. However, it is possible that a combination of chance, bias and confounding may have produced this result.

There is inadequate evidence for Alzheimer's Disease, childhood brain tumours, and Amyotrophic lateral sclerosis. However the data suggest some elevated risks may exist, particularly for Alzheimer's Disease, which suggest further studies on these outcomes would be useful. For all other cancers, other neurodegenerative diseases and for symptoms, there is also inadequate evidence, but there appears to be no justification to conduct further studies.

There is evidence suggesting a lack of effect for breast cancer, cardiovascular disease and for EHS.

6.2 Intermediate frequencies

There are no new data, so the opinions of EMF-NET (2009) and SCENIHR (2009a) remain unchanged.

There is inadequate evidence for all endpoints considered (Table 5). This suggests that further research is necessary to formulate a health risk assessment. High priority could be given to investigating the effects on pregnancy outcomes (SCEHIHR, 2009b). This is based on concerns that it is possible for pregnant shop assistants to work throughout the day in close proximity to anti-theft devices, and that these devices may not only produce high exposures, but some may exceed occupational guideline values.

6.3 High frequencies

Inclusion of the recent data has not necessitated any revisions to the existing consensus opinions of EMF-NET (2009) or SCENIHR (2009a). For none of the diseases is there sufficient evidence for a causal association between exposure and the risk of the disease, and the strength of evidence for many outcomes remains as inadequate (Table 5).

Results of the international analyses of glioma and meningioma risk in the Interphone study have been published. While an association between mobile phone use and risk of these diseases has not been demonstrated, the study does not either demonstrate an absence of risk. There is at this time inadequate evidence for all endpoints considered. Given that the majority of subjects in Interphone were light users compared to users today, particularly young people, and as the study did not include subjects who used phones for more than 12 years, further research is needed to evaluate the possible association between RF exposure and risk of tumours.

While increased responsiveness to RF fields has not been demonstrated in provocation studies, even in subjects that self-report hypersensitivity, the possibility remains that long-term mobile phone use may induce symptoms, such as migraine and vertigo, and further work is required to clarify this issue.

Adverse health outcome		Low frequency	IF	High frequency
Cancer	Leukaemia in children			
	Brain tumour in children			
	Brain tumour in adults			
	Breast cancer in adults			
	All other cancers			
Neurodegenerative diseases	Alzheimer's			
	ALS			
	Other diseases			
Reproductive outcomes	All			
Cardiovascular diseases	All			
Well-being	EHS			
	Symptoms			

Table 5. Summary of health risk assessments: the strength of evidence for any adverse outcome being associated with exposure to low, intermediate (IF) or high frequency electromagnetic fields. For no outcome at any frequency is there sufficient evidence of an effect, but there is limited evidence of an association between childhood leukaemia and low frequency magnetic fields (shown orange). There is evidence suggesting a lack of effects for four outcomes (shown green) and for all other outcomes the available evidence is inadequate to permit a conclusion (shown yellow).

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