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Research

Recent Research on electromagnetic fields and Health Risk, nineteenth report from SSM's Scientific Council on Electromagnetic Fields, 2024

2025:04

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SSM 2025:04

SSM perspektiv

Bakgrund

Strålsäkerhetsmyndighetens (SSM) vetenskapliga råd om elektromagnetiska fält följer aktuell forskning om potentiella hälsorisker vid exponering för elektromagnetiska fält och ger myndigheten råd i bedömningen av möjliga hälsorisker. Rådet ger vägledning när myndigheten behöver yttra sig i policyfrågor eller när vetenskaplig pr vning är nödvändig. Rådet ska årligen lämna en skriftlig rapport om det aktuella forsknings- och kunskapsläget.

Detta är en konsensusrapport, vilket innebär att alla medlemmar i vetenskapliga rådet står bakom hela rapporten. Detta bedöms stärka de slutsatser som dras i rapporten.

Rapportens främsta syfte är att täcka in föregående års forskning inom området elektromagnetiska fält (EMF) och hälsa, men också att sätta denna forskning i ett sammanhang med den befintliga kunskapen. Rapporten ger myndigheten en överblick och utgör ett viktigt underlag för riskbedömning.

Resultat

Denna rapport granskar studier om elektromagnetiska fält (EMF) och hälsorisker som publicerats från januari 2023 till och med december 2023. Rapporten är den nittonde i en serie årliga vetenskapliga översikter som fortlöpande diskuterar och bedömer relevanta nya studier och sätter dem i kontext av tillgänglig kunskap. Rapporten omfattar olika områden av EMF (statisk, lågfrekvent, intermediär och radiofrekvent strålning) samt olika typer av studier såsom biologiska, mänskliga och epidemiologiska studier. Resultatet är en successivt framväxande hälsoriskbedömning av exponering för EMF.

Inga nya fastställda orsakssamband mellan EMF-exponering och hälsorisk har identifierats.

De studier som presenteras i rapporten löser inte frågan om det konsekvent observerade sambandet mellan exponering för lågfrekventa magnetfält (ELF-MF) och barndomsleukemi i epidemiologiska studier är kausalt eller ej.

Ny forskning om hjärntumörer och mobiltelefonanvändning ligger i linje med tidigare studier som i huvudsak antyder frånvaro av risk. Sköldkörteln är potentiellt kraftigt exponerad vid mobilsamtal, men få studier har hittills genomförts kring sköldkörtelcancer.

När det gäller djurstudier är det svårt att dra generella slutsatser, annat än att effekter av RF-EMF-exponering under vissa omständigheter observeras i experimentella djurstudier. Observationer av ökad oxidativ stress, som tidigare rapporter från SSM har redovisat, fortsätter att rapporteras – ibland även vid nivåer under nuvarande referensvärden. Oxidativ stress är en naturlig biologisk process som ibland kan vara inblandad i sjukdomsutveckling, men under vilka omständigheter oxidativ stress orsakad av svag radiovågsexponering kan påverka människors hälsa återstår att undersöka.

Det är anmärkningsvärt att nya studier återigen visar att människors perceptionströsklar är lägre vid hybridexponering än vid enbart DC- eller AC-fältexponering.

Relevans

Resultaten från forskningsöversikten ger inget skäl att ändra några referensnivåer eller rekommendationer inom området. Däremot visar de biologiska effekter som observerats i vissa djurstudier vid svag exponering för radiovågor tydligt vikten av att upprätthålla miljöbalkens försiktighetsprincip.

SSM:s rekommendation om att använda handsfree vid mobiltelefonsamtal kvarstår, även om trender för förekomsten av gliom inte ger stöd för en ökad risk orsakad av exponering för mobiltelefonens radiovågor. De observerade biologiska effekterna och osäkerheter kring eventuella långtidseffekter motiverar fortsatt försiktighet.

Inga nya resultat som tydligt förändrar misstanken om ett orsakssamband mellan svaga lågfrekventa magnetfält och barndomsleukemi har framkommit i rapporten. Myndigheternas rekommendation om att generellt begränsa exponeringen för lågfrekventa magnetfält med anledning av den observerade ökade förekomsten av barndomsleukemi nära kraftledningar kvarstår oförändrad.

Behov av vidare forskning

Trots att inga hälsorisker kopplade till svaga elektromagnetiska fält har kunnat påvisas hittills, anser myndigheten att fortsatt forskning är viktig, särskilt vad gäller långtidseffekter eftersom i princip hela befolkningen är exponerad. En central fråga är att vidare undersöka sambandet mellan exponering för radiovågor och oxidativ stress som observerats i djurstudier, samt att fastställa om ett sådant samband även förekommer hos människor och i så fall i vilken utsträckning det kan påverka människors hälsa. En annan viktig fråga är att klargöra kopplingen mellan svaga lågfrekventa magnetfält och barndomsleukemi som observerats i epidemiologiska studier.

Trådlös informationsteknik utvecklas ständigt och nya frekvensområden kommer att tas i bruk. Även om det i dagsläget inte finns någon etablerad verkningsmekanism för hälsopåverkan från svag radiovågsexponering, behövs mer forskning om de nya frekvensområden som används för 5G. Myndigheten uppmuntrar forskare att inleda epidemiologiska studier på detta område. Exempelvis finns idag mycket få studier inom 26 GHz-bandet.

Nya tekniker för induktiv trådlös energitransfer, baserade på magnetfält i intermediärfrekvensområdet, kommer sannolikt att införas för många olika tillämpningar inom en snar framtid. Till skillnad från trådlös kommunikationsteknik resulterar trådlös energitransfer i princip alltid i relativt starka lokala fält. Det gör det mycket viktigt att få ett robust underlag för riskbedömning av sådana fält. Idag saknas studier inom detta frekvensområde, vilket medför ett särskilt behov av forskning på området.

Trots den ökande användningen av tillämpningar inom det intermediära frekvensområdet i det elektromagnetiska spektrumet (300 Hz–10 MHz) är den vetenskapliga utvärderingen av potentiella hälsorisker i detta område fortfarande mycket begränsad. De få studier som rådet identifierat inom detta område har dock inte visat på några hälsoeffekter under gällande referensnivåer. Årsrapporten innehåller även ett avsnitt där studier som bedömts ha otillräcklig kvalitet listas. Liksom föregående år har många studier uteslutits på grund av bristande kvalitet (se bilaga). Ur ett vetenskapligt perspektiv är studier med låg kvalitet irrelevanta. De innebär även ett slöseri med pengar, mänskliga resurser och, i många fall, försöksdjur.

Projektinformation

Kontaktperson SSM: Karl Herlin
Referens: SSM2025-3211 / 4530606

SSM perspective

Background

The Swedish Radiation Safety Authority's (SSM) Scientific Council on Electromagnetic Fields monitors current research on potential health risks in relation to exposure to electromagnetic fields and provides the authority with advice on assessing possible health risks. The Council gives guidance when the authority must give an opinion on policy matters when scientific testing is necessary. The council is required to submit a written report each year on the current research and knowledge situation.

This is a consensus report, which means that all members of the Scientific Council agree with the complete report. This increases the strength of the given conclusions. The report has the primary objective of covering the previous year's research in the area of electromagnetic fields (EMF) and health but also to place this in the context of present knowledge. The report gives the authority an overview and provides an important basis for risk assessment.

Results

This report reviews studies on electromagnetic fields (EMF) and health risks, published from January 2023 up to and including December 2023. The report is the nineteenth in a series of annual scientific reviews, which consecutively discusses and assesses relevant new studies and put these in the context of available information. The report covers different areas of EMF (static, low frequency, intermediate and radio frequency fields) and different types of studies such as biological, human and epidemiological studies. The result will be a gradually developing health risk assessment of exposure to EMF.

No new established causal relationships between EMF exposure and health risk have been identified.

The studies presented in this report do not resolve whether the consistently observed association between ELF magnetic field (ELF-MF) exposure and childhood leukaemia in epidemiology is causal or not.

New research on brain tumours and mobile phone use is in line with previous research suggesting mostly an absence of risk. The thyroid gland is potentially highly exposed during mobile phone calls but little research on thyroid cancer has been conducted so far.

Concerning studies on animals, it is difficult to draw general conclusions other than that under certain circumstances some effects from RF-EMF exposure are observed in experimental animals. The observations of increased oxidative stress reported in previous SSM reports continue to be found, some even below current reference levels. Oxidative stress is a natural biological process that can sometimes be involved in pathogenesis, but under what circumstances oxidative stress due to weak radio wave exposure may affect human health remains to be investigated.

It is notable that new studies again revealed that human perception thresholds are lower in hybrid exposure conditions than in DC or AC field exposure alone.

Relevance

The results of the research review give no reason to change any reference levels or recommendations in the field. However, the observations of biological effects in animals due to weak radio wave exposure reported in some studies clearly show the importance of maintaining the Swedish Environmental Code precautionary thinking.

SSM´s hands-free recommendation for mobile phone calls remains even though trends of glioma incidences do not provide support for an increasing risk caused by mobile phone radio wave exposure. However, observed biological effects and uncertainties regarding possible long term effects justify caution.

No new findings that clearly change the suspicion of a causal link between weak low-frequency magnetic fields and childhood leukaemia have emerged in the report. The Swedish authorities' recommendation to generally limit exposure to low frequency magnetic fields due to the observed increased incidence of childhood leukaemia close to power lines remains unchanged.

Need for further research
Despite the fact that no health risks associated with weak electromagnetic fields have been demonstrated up to date, the authority considers that further research is important, in particular regarding long-term effects as more or less the entire population is exposed. One key issue here is to further investigate the relationship between radio wave exposure and oxidative stress observed in animal studies and to establish whether a relationship in humans exists and, if so, to what extent it may affect human health. Another important issue is to clarify the association between weak low frequency magnetic fields and childhood leukaemia as observed in epidemiological studies.

Wireless information technology is constantly evolving and new frequency ranges will be used. Even though there is no established mechanism for affecting health from weak radio wave exposure, there is need for more research covering the novel frequency domains used for 5G. The authority encourages researchers to start undertaking epidemiological studies in this area. For example, there are currently very few studies in the 26 GHz band.

New technologies for inductive wireless energy transfer based on intermediate frequency magnetic fields will probably be implemented for many different applications in the near future. In contrast to wireless information communication technology, wireless energy transfer in principle always results in relatively strong local fields. This makes it very important to obtain a robust basis for risk assessment of such fields. Today, there is a lack of studies in this frequency domain, and therefore, there is a special need for research in this area.

Despite the increasing use of applications in the intermediate frequency (IF) range of the electromagnetic spectrum (300 Hz-10 MHz), scientific evaluation of potential health risks in that range is scarce. However, the few studies identified by the council in this area have not indicated any health effects below current reference levels. The annual report also includes a section where studies that lack satisfactory quality have been listed. This year, as well as last year, many studies have been excluded due to poor quality (see appendix). From a scientific perspective, studies of poor quality are irrelevant. They are also a waste of money, human resources and, in many cases, experimental animals.

Project information
Contact person SSM: Karl Herlin
Reference: SSM2025-3211 / 4530606

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Preface

The Swedish Radiation Safety Authority's Scientific Council for Electromagnetic Fields (EMF) and Health was established in 2002. The Council's main task is to follow and evaluate scientific developments and provide advice to the authority. In a series of annual reviews, the Council consecutively discusses and assesses relevant new data and places these in the context of available information. The result will be a gradually developing health risk assessment of exposure to EMF. The Council presented its first report in 2003. A brief overview of whether or how the evidence for health effects has changed over the first decade of reports was included in the eleventh report. The present report is number nineteen in the series and covers studies published from January 2023 up to and including December 2023.

The composition of the Council that prepared this report has been:

- Anke Huss, PhD, epidemiology, University of Utrecht, the Netherlands (chair)
- Karl Herlin, MSc, Physics, The Swedish Radiation Safety Authority, Sweden (scientific secretary)
- Aslak Harbo Poulsen, PhD, epidemiology, Danish Cancer Society, Copenhagen, Denmark
- Florence Poulletier de Gannes, PhD, cell biology, Research engineer, French National Centre for Scientific Research, Talence, France
- Maria Rosaria Scarfi, PhD, cell biology, National Research Council, Naples, Italy
- Janine-Alison Schmidt, PhD, Pathology, Bundesamt für Strahlenschutz, BfS, Germany
- Frank de Vocht, PhD, Epidemiology, University of Bristol, The United Kingdom
- Cornelia Sauter, PhD, Somnology, Charité – Universitätsmedizin, Germany
- Rosanna Pinto, PhD, Dosimetry, Bioelectromagnetic Laboratory of the Technical Unit of Radiation Biology and Human Health of ENEA, Italien

Declarations of conflicts of interest are available at the Swedish Radiation Safety Authority.

Stockholm/Utrecht in January 2024

Anke Huss

Chair

Executive Summary

Static Fields

Epidemiological Studies

The conclusion of the report of last year was that occupational exposure from magnetic resonance imaging (MRI) caused acute and transient symptoms, but long-term consequences for health remained unclear. Increasing number of occupationally exposed persons warranted more systematic and comprehensive research on this topic. This conclusion remains unchanged with this year's two studies: One very small study on congenital diaphragmatic hernia (left-CDH), and the other an ecological study on geomagnetic fields and cardiovascular disease. Both studies did not provide clear evidence for or against associations with the exposure.

Human Studies

The only study from 2023 confirms the previous results that perception thresholds were lower in the hybrid EF exposure condition than in the AC and DC exposure alone. Although perception under real-world conditions may not be comparable to experimental conditions, the results contribute important findings on the impact of the DC component on human hybrid EF perception. The results may have implications on the planning and construction process of high voltage power lines and provide guidance for the development of cut-off values especially for highly sensitive people.

Animal Studies

A total of 14 articles have been selected to describe the scientific activities related to the study of the health effects of *in vivo* exposure to static magnetic fields (SMF) and static electric fields (SEF). Except for two papers that utilized *in vivo* exposure to the SEF, the remaining articles investigated the effects of exposure to SMF. Nine articles studied the effects of exposure on rodents (8 with mice and 1 with rats), while the other 6 papers utilized different animal species, with a particular focus on the marine environment.

Exposure to uniform SMFs of diabetic mice appeared to have no noticeable effects on blood glucose levels. However, exposure to spatial gradient SMFs seemed to exacerbate physiological and pathological abnormalities, as well as induce an increase in blood glucose and oxidative stress in diabetic mice.

Behavioral studies appeared to indicate improvement in the performance of exposed animals compared to sham-exposed ones. This seemed to hold true for SMF values ranging from 0.32 T to 14.1 T. Exposure also appeared to increase the expression levels of certain proteins involved in defining oxidative stress. Similar effects have been described for exposure to a SEF of 53.6 kV/m.

Exposure to an SMF of 9.4 T appeared to inhibit the growth of an injected gastrointestinal stromal tumor in exposed mice. Combined exposure to SMF and 20 mg/kg of imatinib mesylate seemed to have tumor-reducing effects like those of the group treated with the highest dose of the drug (80 mg/kg), without showing any side effects.

Regarding other species, only potential behavioral effects related to exposure to SMFs ranging between 230 μT and 14.5 T were evaluated. Despite the diversity of the species analyzed and the levels of SMF, there appeared to be no significant effects on the considered endpoints except for some sporadic exceptions.

Cell Studies

No paper was included in this report.

Extremely low frequency fields

Epidemiological Studies

An Australian family-based case-control study on occupational ELF-MF exposure and follicular lymphoma did not provide clear evidence of presence or absence of risk.

An Italian case-control study on exposure from overhead power lines and distance to transformer stations and childhood leukaemia reported risk estimates that were not conflicting with previous reports, but that also did not elucidate possible underlying explanations for the results.

A register-based Californian study on proximity to power lines and childhood leukaemia reported that pesticide exposure could be an independent risk factor for the disease, but was unlikely to have confounded previous reports on the association with magnetic field exposures.

Somewhat perplexing, several systematic reviews published during the reporting period mixed different exposures (ELF-MF and RF-EMF) and also different exposure assessment methods and types of outcomes together. Quantitative results from such efforts are not interpretable.

Human studies

In conclusion, the re-publication of a study on audio frequency magnetic fields did not contribute any new findings. The authors reported again a small but negative effect of audio frequency magnetic fields on some parts of the reaction process when conducting a working memory task. It should be mentioned that the design of the study is not suitable to investigate very small effects that can be expected for this type of stimulation. One of the two systematic reviews did not provide new insights regarding ELF human studies, the other systematic review was excluded due to methodological shortcomings.

Animal Studies

In 2023, 9 papers were published concerning the study of health effects related to in vivo exposure to MF or EF at ELF. Except for a single paper addressing exposure to 4.2 Hz magnetic fields, the others involved medium- or long-term exposure to MF or EF at 50 Hz. Six studies focused on experiments conducted on rodents, observing various endpoints: behavior and oxidative stress (3 papers), reproduction, cancer, and immune system (one article each). Regarding the effects on behavior and oxidative stress, exposure to EF at 10 kV/m appears to reduce anxiety behavior alongside an increase in serotonin levels and a decrease in cortisol levels. Conversely, exposure to MF appears to increase anxious behavior in exposed animals.

Only one paper concerned the study of MF exposure at 100 µT on the reproductive system of rats: in the examined conditions the ELF-MF exposure seemed to reduce spermatocyte count and motility and to induce structural changes in testicular tissue.

Only one study investigated the effect of 4.2 Hz MF exposure on mice injected with 5 × 106 MDA-MB231 cells to develop a breast cancer cell metastasis mouse model. Mice survival was prolonged by 31.5% and 46% in mice exposed to 0.1 T and 0.4 T, respectively (dose-response effect), Moreover both exposure levels could reduce lung metastasis in a dose-dependent manner.

The effect on humoral immune system of ELF-MF exposure (from 1 µT up to 2000 µT) was analyzed: The exposure to a B-field of 1 µT seemed to significantly decrease the expression of AID gene at in contrast the MF exposure at 500 µT could increase serum IL-6 and activate the differentiation of B cells to plasma cells enhancing humoral responses.

Regarding other animal species, the conducted studies have shown that 50 Hz MF exposure appears to influence the normal behavior of zebrafish, bats, and honeybees, with sporadic increases in ROS levels and ↑ Hsp70 expression levels.

Summarizing, the very different animal models describing dissimilar effects following ELF-MF exposure in the 7 mT range and below demonstrates again the absence of knowledge on biological-relevant effects of ELF-MF, except on oxidative stress and behavior.

Cell Studies

The report incorporates findings from four in vitro studies examining the impact of ELF-EMF exposure. Specifically, it reveals that ELF-EMF exposure disrupts epigenetic processes in the porcine myometrium, alters the expression of DNA methylation-related enzymes, correlates with changes in gene expression, and triggers proteomic alterations along with an increase in cell viability. Furthermore, it indicates no significant effects on differentiation stages or gene expression in B cells. These findings enhance our understanding of potential impacts from ELF-MF exposure across various cellular contexts.

Intermediary fields

Epidemiological Studies

This year, one study from Japan investigated whether exposure of pregnant women to induction cooking could affect birth outcomes, in particular gestational age and low birth weight. While the authors concluded that the increased odds ratios observed in their study did not indicate increased risks of premature birth, the observations reported here remain of interest. This is because of the relatively high exposures experienced by the foetus, and the scarcity of epidemiological studies on the matter.

Human Studies

No study on intermediate fields was published in 2023.

Animal Studies

This year, two animal studies were published concerning physiology & pathophysiology.

Cell Studies

As for the previous reporting period, no in vitro studies on intermediate frequency range were found.

Radiofrequency fields

Epidemiological Studies

Last year, two studies reported a few associations between different aspects of mobile phone use and some semen quality parameters. This was likely chance findings due to the number of analyses. This year one cross sectional study also found an association between mobile phone use and total sperm count and concentration, this could however also be due to chance findings or residual confounding e.g. from lifestyle.

Yet another incidence trend study found no overall increase in brain tumours, indicating that mobile phones are not a major driver of brain tumour risk.

This year we saw the first of the long awaited WHO reviews published which highlighted difficulty to disentangle biophysical effects from the exposure and behavioural aspects that are related to exposure. A number of other new systematic reviews and meta-analyses that were published this year did not provide additional insights, either because too few primary studies of decent quality were available or because vastly different exposure and/or outcomes were combined in single meta-analyses. Such pooling is not informative, especially if rationale or justification for the pooling is not provided.

Human Studies

Like already elaborated in the last SSM report, results concerning RF-EMF effects on the human EEG continue to be inconsistent. Whereas none of the frequency bands of the wake EEG was affected in the eyes open and closed condition in a study on RF-EMF of 5G mobile communication far field, two GSM studies reported modulations in dependence of the eye condition, one in the theta frequency band, and the other in a frequency range that represents part of the theta and the alpha band in the eyes open condition only. Differences in methods might still be the main reason for the different results.

Animal Studies

As in previous years, effects on brain and behavior are the endpoints most often investigated. Other endpoints are rare and include effects on cancer, thermophysiology, reproductive system and other tissues and organs. This year, all included studies showed effects of exposure. However, within a study, effects were seen mostly on some but not all of the analyzed endpoints or only at specific time points. The exposure parameters, such as frequency, duration and exposure level, again vary considerably between studies.

A major limitation is the use of a very small number of animals per group in 11 of 13 experimental studies (excluding systematic reviews). In 5 studies, the sample size was only 3 animals in some of the experiments performed. In some publications, it is unclear how animals of each group were selected for the different experiments. A small sample size can lead to false-positive as well as to false-negative results (see section on effects in animal studies).

Two comprehensive systematic reviews were published on cancer and reproduction that showed either low to inadequate or uncertain evidence for health effects that did not allow to inform decisions at a regulatory level.

It is of concern that, similar to previous reports, a high number of studies had to be excluded because of insufficient or missing exposure description and/or dosimetry, but also due to other shortcomings (see appendix).

Overall, it is therefore difficult to draw a conclusion other than that under certain circumstances some effects from RF-EMF exposure are observed in experimental animals. It is striking, however, that most of the included experimental studies in this and the last year's report only examined male animals.

Cell Studies

As in previous years, there is a large variety of endpoints, cell types and exposure parameters investigated with varying results. Therefore, although it is difficult to draw general conclusions, it should be noted that when RF is given alone, in most cases no effects are measured. The opposite is for combined exposures. The additional eleven studies recognized were not considered due to the scanty experimental quality (mainly lack of dosimetry and/or sham-controls). Thus, as for the previous years, quality remains one of the most important aspects to be improved in bioelectromagnetic research.

Sammanfattning

Statiska fält

Epidemiologiska Studier

Slutsatsen i förra årets rapport var att yrkesmässig exponering för magnetresonanstomografi (MRI) orsakade akuta och övergående symtom, men att långsiktiga hälsoeffekter fortfarande var oklara. Ett ökande antal yrkesmässigt exponerade personer motiverade mer systematisk och omfattande forskning inom detta område. Denna slutsats förblir oförändrad med årets två studier: en mycket liten studie om medfödd diafragmabråck (vänstersidig CDH) och en ekologisk studie om geomagnetiska fält och hjärt-kärlsjukdomar. Ingen av studierna gav tydliga bevis vare sig för eller emot samband med exponeringen.

Studier på Människor

Den enda studien från 2023 bekräftar tidigare resultat att perceptionströsklar var lägre vid hybrid exponering för elektriska fält (EF) jämfört med exponering för enbart växelström (AC) eller likström (DC). Även om perception i verkliga förhållanden kanske inte är direkt jämförbar med experimentella förhållanden, bidrar resultaten med viktiga insikter om likströmskomponentens påverkan på hybrid EF-perception hos människor. Resultaten kan ha implikationer för planering och konstruktion av kraftledningar och ge vägledning vid utveckling av gränsvärden, särskilt för personer med hög känslighet.

Djurstudier

Totalt har 14 artiklar valts ut för att beskriva den vetenskapliga aktiviteten kring studier av hälsoeffekter av in vivo-exponering för statiska magnetfält (SMF) och statiska elektriska fält (SEF). Förutom två artiklar som använde in vivo-exponering för SEF, undersökte övriga artiklar effekterna av exponering för SMF.

Nio artiklar studerade effekterna av exponering på gnagare (åtta på möss och en på råttor), medan de övriga sex artiklarna använde andra djurarter, med särskilt fokus på den marina miljön.

Exponering för homogena SMF hos möss med diabetes verkade inte ha någon märkbar effekt på blodsockernivåerna. Däremot tycktes exponering för spatialt gradient-SMF förvärra fysiologiska och patologiska avvikelser samt öka blodsocker och oxidativ stress hos diabetiska möss.

Beteendestudier visade en förbättring i prestation hos exponerade djur jämfört med skenexponerade. Detta gällde SMF-värden mellan 0,32 T och 14,1 T. Exponering tycktes också öka uttrycket av vissa proteiner som är involverade i reglering av oxidativ stress. Liknande effekter har beskrivits vid exponering för ett SEF på 53,6 kV/m.

Exponering för ett SMF på 9,4 T verkade hämma tillväxten av en injicerad gastrointestinal stromatumör hos exponerade möss. Kombinerad exponering för SMF och 20 mg/kg av imatinib mesylat tycktes ha tumörhämmande effekter liknande de i gruppen som behandlades med den högsta läkemedelsdosen (80 mg/kg), utan att visa några biverkningar.

Vad gäller andra djurarter undersöktes endast potentiella beteendeeffekter av exponering för SMF mellan 230 µT och 14,5 T. Trots mångfalden av analyserade arter och SMF-nivåer observerades inga signifikanta effekter på de utvärderade parametrarna, förutom vissa enstaka undantag.

Cellstudier

Ingen studie inkluderades i denna rapport.

Extremt lågfrekventa fält (ELF)

Epidemiologiska Studier

En australiensisk familjebaserad fall-kontrollstudie om yrkesmässig exponering för ELF-MF och follikulärt lymfom gav inga tydliga bevis vare sig för eller emot en risk.
En italiensk fall-kontrollstudie om exponering från luftledningar och avstånd till transformatorstationer och barnleukemi rapporterade riskestimat som var i linje med tidigare studier, men som inte klargjorde eventuella bakomliggande mekanismer.
En registerbaserad studie från Kalifornien om närhet till kraftledningar och barnleukemi visade att exponering för bekämpningsmedel kan vara en oberoende riskfaktor för sjukdomen, men att det sannolikt inte har påverkat tidigare rapporterade samband med magnetfältsexponering.
Något förbryllande var att flera systematiska översikter publicerade under rapporteringsperioden blandade olika typer av exponeringar (ELF-MF och RF-EMF) samt olika exponeringsbedömningsmetoder och utfallstyper. Kvantitativa resultat från sådana översikter är därför svåra att tolka.

Studier på Människor

Sammanfattningsvis bidrog ompubliceringen av en studie om ljudfrekventa magnetfält inte med några nya fynd. Författarna rapporterade återigen en liten men negativ effekt av ljudfrekventa magnetfält på vissa delar av reaktionsprocessen vid genomförande av en arbetsminnesuppgift. Det bör noteras att studiedesignen inte lämpar sig för att undersöka mycket små effekter, vilket kan förväntas vid denna typ av stimulering.
Av två systematiska översikter tillförde den ena inga nya insikter om ELF-MF och studier på människor, medan den andra exkluderades på grund av metodologiska brister.

Djurstudier

Under 2023 publicerades nio studier om hälsoeffekter av in vivo-exponering för magnetfält (MF) eller elektriska fält (EF) vid ELF-frekvenser. Förutom en studie om exponering för 4,2 Hz magnetfält, undersökte övriga studier exponering för MF eller EF vid 50 Hz under medellånga till långa tidsperioder.
Sex av studierna fokuserade på experiment på gnagare, där olika parametrar analyserades: beteende och oxidativ stress (tre studier), reproduktion, cancer och immunsystemet (en studie vardera).

När det gäller beteende och oxidativ stress verkade exponering för ett elektriskt fält på 10 kV/m minska ångestbeteende, samtidigt som serotoninnivåerna ökade och kortisolnivåerna minskade. Däremot verkade exponering för magnetfält öka ångestbeteende hos exponerade djur.

Endast en studie undersökte effekterna av MF-exponering vid 100 µT på råttors reproduktionssystem. Under de undersökta förhållandena verkade ELF-MF-exponering minska antalet och rörligheten hos spermatocyter samt orsaka strukturella förändringar i testikelvävnaden.

En annan studie undersökte effekten av 4,2 Hz MF-exponering på möss som injicerats med 5×10^6 MDA-MB231-celler för att utveckla en modell för bröstcancermetastas. Överlevnaden för mössen förlängdes med 31,5 % och 46 % vid exponering för 0,1 T respektive 0,4 T (dos-respons-effekt). Dessutom kunde båda exponeringsnivåerna minska lungmetastaser i en dosberoende relation.

Effekten av ELF-MF-exponering (från 1 µT upp till 2000 µT) på det humorala immunsystemet analyserades i en studie. Exponering för ett magnetfält på 1 µT verkade signifikant minska uttrycket av AID-genen, medan exponering vid 500 µT ökade serum-IL-6 och aktiverade differentieringen av B-celler till plasmaceller, vilket förstärkte humorala immunsvar.

När det gäller andra djurarter visade några studier att exponering för 50 Hz MF påverkade normalt beteende hos zebrafiskar, fladdermöss och bin, med sporadiska ökningar av ROS-nivåer i en studie och höjda Hsp70-uttrycksnivåer i en studie.

Sammanfattningsvis visar de olika djurmodellerna och de varierande resultaten efter ELF-MF-exponering i intervallet 7 mT och lägre återigen bristen på kunskap om biologiskt relevanta effekter av ELF-MF, med undantag för dess effekter på oxidativ stress och beteende.

Cellstudier

Rapporten inkluderar resultat från fyra in vitro-studier som undersökt effekterna av ELF-EMF-exponering. Studierna visar att ELF-EMF-exponering påverkar epigenetiska processer i svinens myometrium, förändrar uttrycket av DNA-metyleringsrelaterade enzymer, korrelerar med förändringar i genuttryck och inducerar proteomiska förändringar samt en ökning i cellviabilitet. Vidare påvisades inga signifikanta effekter på differentieringsstadier eller genuttryck i B-celler. Dessa resultat bidrar till en ökad förståelse av potentiella effekter av ELF-MF-exponering i olika cellulära sammanhang.

Intermediära Fält

Epidemiologiska Studier

I år undersökte en japansk studie huruvida exponering av gravida kvinnor för intermediära fält från induktionshällar kunde påverka födelseutfall, särskilt graviditetslängd och låg födelsevikt. Författarna drog slutsatsen att de observerade ökade odds-kvoterna i deras studie inte indikerade en ökad risk för en för tidig födsel. Trots detta förblir resultaten av intresse på grund av den relativt höga exponeringen som fostret utsätts för och den begränsade mängden epidemiologiska studier inom området.

Studier på Människor

Under 2023 publicerades ingen studie om intermediära fält.

Djurstudier

Två djurstudier publicerades under året som berörde fysiologi och patofysiologi.

Cellstudier

Likt föregående rapporteringsperiod identifierades inga in vitro-studier om intermediära fält.

Radiofrekventa Fält

Epidemiologiska Studier

Förra året rapporterade två studier vissa samband mellan olika aspekter av mobiltelefonanvändning och vissa parametrar för sädeskvalitet. Dessa samband var troligtvis slumpmässiga fynd på grund av det stora antalet analyser. I år fann en tvärsnittsstudie också ett samband mellan mobiltelefonanvändning och totalt spermieantal samt koncentration, men detta kan också vara en slumpmässig association eller bero på kvarstående störfaktorer, exempelvis livsstilsfaktorer.

Ytterligare en incidensstudie fann ingen generell ökning av hjärntumörer, vilket tyder på att mobiltelefoner inte är en betydande faktor för risken att utveckla hjärntumörer.

I år publicerades den första av de länge efterlängtade WHO-översikterna. Den lyfte fram svårigheten att särskilja biofysiska effekter från exponeringen och beteenderelaterade aspekter kopplade till exponeringen. Flera nya systematiska översikter och metaanalyser publicerades också under året, men dessa gav inga ytterligare insikter. Orsakerna var antingen att för få primärstudier av tillräcklig kvalitet fanns tillgängliga eller att många olika exponeringsförhållanden och/eller utfall kombinerades i enskilda metaanalyser. Sådan sammanslagning är inte informativ, särskilt om ingen motivering eller förklaring till metoden ges.

Studier på Människor

Som tidigare utvecklats i den senaste SSM-rapporten fortsätter resultaten om RF-EMF-effekter på mänsklig EEG att vara inkonsekventa.

I en studie om RF-EMF från 5G-mobilkommunikationens fjärrfält påverkades ingen av vaken-EEG:s frekvensband i vare sig öppna eller slutna ögon-förhållanden. Däremot rapporterade två GSM-studier förändringar beroende på ögonförhållandet: en i thetafrekvensbandet och en annan i en frekvens som täcker delar av theta- och alfafrekvensbanden, men endast i det öppna ögonförhållandet. Metodologiska skillnader kan fortfarande vara den främsta orsaken till de varierande resultaten.

Djurstudier

Precis som tidigare år undersöks oftast effekter på hjärna och beteende, medan andra parametrar – såsom effekter på cancer, termofysiologi, reproduktionssystem och andra vävnader och organ – är mer sällsynta.

I år visade samtliga inkluderade djurstudier någon form av effekt av exponering. Dock observerades dessa effekter oftast endast på vissa, men inte alla, analyserade parametrar inom en och samma studie eller endast vid vissa tidpunkter. Exponeringsparametrarna, såsom frekvens, varaktighet och exponeringsnivå, varierar återigen avsevärt mellan studierna.

En stor begränsning är att elva av tretton experimentella studier (exklusive systematiska översikter) använde sig av mycket små djurgrupper. I fem studier var urvalsstorleken så låg som tre djur i vissa experiment. I vissa publikationer är det oklart hur djuren i varje grupp valdes ut för olika experiment. Små urvalsstorlekar kan leda till både falskt positiva och falskt negativa resultat (se avsnittet om effekter i djurstudier).

Två omfattande systematiska översikter publicerades om cancer och reproduktion. De visade antingen låg till otillräcklig eller osäker evidens för hälsoeffekter, vilket innebär att de inte kan användas som beslutsunderlag på regulatorisk nivå.

Det är fortsatt bekymmersamt att, liksom i tidigare rapporter, ett stort antal studier exkluderades på grund av bristande eller otillräcklig beskrivning av exponeringen och/eller dosimetri, samt andra metodologiska brister (se exkluderade studier).

Sammanfattningsvis är det därför svårt att dra någon annan slutsats än att RF-EMF-exponering i vissa fall kan ge upphov till effekter hos försöksdjur. Det är dock anmärkningsvärt att de flesta inkluderade experimentella studier i både årets och förra årets rapport endast undersökte hanliga djur.

Cellstudier

Liksom tidigare år finns en stor variation i undersökta parametrar, celltyper och exponeringsförhållanden, vilket leder till varierande resultat. Därför är det svårt att dra generella slutsatser.

Det bör dock noteras att när RF-exponering ges ensam, påvisas i de flesta fall inga effekter. Däremot observeras effekter oftare vid kombinerad exponering.

Elva ytterligare studier identifierades men inkluderades inte på grund av bristande experimentell kvalitet, främst avseende dosimetri och/eller användning av skenkontroller. Precis som tidigare år kvarstår bristande kvalitet som en av de största utmaningarna inom bioelektromagnetisk forskning.

Preamble

In this preamble we explain the principles and methods that the Council uses to achieve its goals. Relevant research for electromagnetic fields (EMF) health risk assessment can be divided into broad sectors such as epidemiologic studies, experimental studies in humans, animals and in vitro studies. Where relevant, studies on biophysical mechanisms, dosimetry, and exposure assessment can also be considered. A health risk assessment evaluates the evidence within each of these sectors with the aim to eventually weigh together the evidence across the sectors to provide an overall assessment. Such an overall assessment should address the question of whether or not a hazard exists, i.e. if a causal relation exists between exposure and some adverse health effect. The answer to this question is not necessarily a definitive yes or no, but may express the likelihood for the existence of a hazard. If such a hazard is judged to be present, subsequently exposure information should be taken into account to perform a risk assessment to address the magnitude of the health impact to determine if the hazard can be a risk, and the shape of the exposure-response function, i.e. the magnitude of the risk for various exposure levels and exposure patterns.

As a general rule, only articles that are published in English language peer-reviewed scientific journals[1] since the previous report are considered by the Council. A main task is to evaluate and assess these articles and the scientific weight that is to be given to each of them. However, some of the studies have been evaluated but have been excluded in the Council report either because the scope is not relevant (e.g. therapeutical studies), or because their scientific quality is insufficient. For example, poorly described exposures (e.g. missing crucial information to understand or reproduce what was done) and missing unexposed (sham) controls are reasons for exclusion. Such studies are normally not commented upon in the annual Council reports (and not included in the reference list of the report)[2]. Reasons why individual studies were excluded are listed in the appendix to the report. Systematic reviews and meta-analyses are mentioned and evaluated, whereas narrative and opinion reviews are generally not considered.

The Council considers it to be of importance to evaluate both studies indicating that exposure to electromagnetic fields has an effect as well as studies indicating a lack of an effect. In the case of studies indicating effects, the evaluation focuses on alternative factors that may explain the result. For instance, in epidemiological studies it is assessed with what degree of certainty it can be ruled out that an observed effect is the result of bias, e.g. confounding or selection bias, or chance. In the case of studies that do not indicate effects, it is assessed whether this might be the result of (masking) bias, e.g. because of too small exposure contrasts or too crude exposure assessment. It also has to be evaluated whether the lack of an observed effect could be the result of chance, a possibility that is a particular problem in small studies with low statistical power. Obviously, the presence or absence of statistical significance as generally determined by statistical p-values and/or confidence intervals, is only one of many factors in this evaluation. Indeed, the evaluation considers a number of characteristics of the study. Some of these characteristics are rather general, such as study size, assessment of participation rate, level of exposure, and quality of exposure assessment. Particularly important aspects are the observed effect size, and the internal and external consistency of the results including aspects such as exposure-response relation. Other characteristics are specific to the study in question and may involve aspects such as dosimetry, method for assessment of biological or health endpoint(s) and the relevance of any experimental biological model used.[3]

It should be noted that the result of this process is not an assessment that a specific study is unequivocally providing evidence for or against an association. Rather, the assessment relies on the body of evidence. The evaluation of the individual studies within a sector of research is followed by the assessment of the overall strength of evidence from that sector with respect to a given outcome.

In an overall evaluation phase, the available evidence may be integrated over the various sectors of research. This involves integrating the existing relevant evidence on a particular endpoint from studies in humans, from animal models, from in *vitro studies*, and from other relevant areas. In such a final integrative stage of evaluation the plausibility of the observed or hypothetical mechanism(s) of action and the evidence for that mechanism(s) are considered. The overall result of the integrative phase of evaluation, combining the degree of evidence from across epidemiology, human and animal experimental studies, *in vitro* studies and other data depends on how much weight is given to each line of evidence from different categories. For assessing effects on humans, human epidemiology is, by definition, an essential and primordial source of evidence since it deals with real-life exposures under realistic conditions in the species of interest. The epidemiological data are, therefore, given higher weight in the overall evaluation stage. However, epidemiological data should ideally be supported by experimental studies and mechanistic evidence to establish a causal link between exposure and health. Where this is relevant and possible, also effects on other species are taken into account.

An example demonstrating some of the difficulties in making an overall assessment is the evaluation of ELF magnetic fields and their possible causal association with childhood leukaemia. While a range of epidemiological studies indicated an association between exposure to ELF magnetic fields and an increased occurrence of childhood leukaemia, there is lack of support for a causal relation from observations in experimental models and a plausible biophysical mechanism of action is missing. This had led the International Agency for Research on Cancer (IARC) to the overall evaluation of ELF magnetic fields as “possibly carcinogenic to humans” (Group 2B) in 2001.

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[1] Articles are primarily identified through searches in relevant scientific literature databases; however, the searches will never give a complete list of published articles. Neither will the list of articles that do not fulfil quality criteria be complete.

[2] Articles not taken into account due to insufficient scientific quality are listed in an appendix and reasons for not being taken into account are indicated.

[3] For a further discussion of aspects of study quality, see for example the Preamble of the IARC (International Agency for Research on Cancer) Monograph Series (IARC, 2002).

Effects in animal studies

A striking finding in this and previous SSM reports is the high number of animal studies showing statistically significant effects after exposure. The following text deals with possible factors other than exposure that could underlie this observation. Moreover, the associated challenges for interpreting such findings are discussed.

One important issue is that many studies are not hypothesis-driven. Without a solid hypothesis and clear research objectives, there is a high risk that the results will not be informative. These types of exploratory studies often assess a range of exposure-outcome associations. However, in situations where a dataset is subjected to statistical testing multiple times - either at multiple time-points or within multiple subgroups or for multiple end-points – the probability of a false-positive finding is amplified [1]. Although there are various approaches to correct for multiple testing, many studies, in which this would be necessary, do not report such a correction.

Another issue is how the available data is analyzed and reported: some combinations or comparisons of the dataset may lead to statistically significant effects, while others may not. If not all results are described transparently in the publication, but only those that led to statistically significant effects, misinterpretations can easily occur. This is also known as p-value hacking [2].

P-value hacking may be a result of the "publish or perish" mindset and the fact that studies showing effects are much more likely to get published than studies showing no effects (publication bias). However, while the p-value can be a useful statistical measure, it is commonly misused and misinterpreted as concisely summarized by the American Statistical Association (ASA) [3].

ASA states that "good statistical practice is an essential component of good laboratory practice"[3] and study quality is essential when it comes to the interpretation of observed (statistically significant) effects. If studies do not implement randomization and blinding, bias can be introduced that influences the results because of uncontrolled differences in animals or experimental conditions in different groups and because researchers could make judgments and interpretations (consciously or subconsciously) that support their preferred hypothesis [4]. Systematic reviews have shown that animal experiments that do not report randomization or other bias-reducing measures such as blinding, are more likely to report exaggerated effects that meet conventional measures of statistical significance [4]. However, a small number of studies - including some of the studies in this year's SSM report - even lack very basic information, such as the age of the animals, or the modulation of the electromagnetic field. Such information would be essential for a replication of the study. Replications are important to assess if observed effects in (exploratory) studies were caused by the exposure or were possibly due to chance or bias.

Another issue is the recurrent use of small animal numbers (in extreme cases less than 5 animals per group), as also observed in publications summarized in this SSM report. Studies including too few animals ("underpowered studies") have a high risk of producing false-negative as well as false-positive results, or to overestimate the magnitude of the association [5]. This could be mitigated by a priori sample size calculations (power analysis). Unfortunately, power analyses are not often performed or reported - a previous review found that less than 10% of publications reported such a calculation [6]. However, determining the appropriate sample size a priori to prevent the use of too small or too large sample sizes, would be in line with the 3R principle (replace, reduce, refine) [7]. The implication is that a study that uses too few animals to answer a specific research question will be uninformative by design, and such unnecessary use of laboratory animals should be prevented.

Last but not least, an observed biological effect (no matter if statistically significant or not) in response to an intervention does not necessarily imply a negative impact on health. This is best illustrated when the endpoint under investigation is a large biological system consisting of dozens or more interacting components, such as the immune system. If one component in this system is affected, we cannot infer anything about the function of the other components or the final state of the endpoint of interest. For example, the affected component could be compensated by the other components without any negative impact on the function of the whole system. However, many authors are content with reporting an observed effect within a complex system of interrelated components, without discussing its clinical relevance, or possible implications for health.

All of these factors above mean that even if all summarized animal studies report effects, this does not automatically translate to evidence of health effects in animals or humans.

Effekter i djurstudier

En anmärkningsvärd observation i denna och tidigare SSM-rapporter är det höga antalet djurstudier som visar statistiskt signifikanta effekter efter exponering. Nedanstående text behandlar möjliga faktorer, utöver själva exponeringen, som kan ligga bakom denna observation. Dessutom diskuteras de utmaningar som är förknippade med att tolka sådana resultat.

En viktig aspekt är att många studier inte är hypotesdrivna. Utan en tydlig hypotes och klara forskningsmål finns en hög risk att resultaten blir svårtolkade och icke-informativa. Dessa typer av explorativa studier testar ofta ett stort antal samband mellan exponering och utfall. När en datamängd testas statistiskt flera gånger – antingen vid flera tidpunkter, inom flera subgrupper eller för flera utfall – ökar sannolikheten för falskt positiva fynd [1]. Även om det finns olika metoder för att korrigera för multipla tester, rapporterar många studier där detta skulle vara nödvändigt inte någon sådan korrigering.

En annan aspekt gäller hur tillgängliga data analyseras och rapporteras: vissa kombinationer eller jämförelser av datamängden kan resultera i statistiskt signifikanta effekter, medan andra inte gör det. Om inte alla resultat redovisas transparent i publikationen, utan endast de som visade statistisk signifikans, kan misstolkningar lätt uppstå. Detta fenomen kallas även “p-hacking” [2].

P-hacking kan vara en konsekvens av den akademiska kulturen "publish or perish" och det faktum att studier som visar effekter har en högre sannolikhet att bli publicerade än studier som inte visar några effekter (publiceringsbias). Även om p-värdet kan vara ett användbart statistiskt mått, missbrukas och misstolkas det ofta, vilket American Statistical Association (ASA) tydligt har sammanfattat [3].

ASA betonar att "god statistisk praxis är en väsentlig del av god laboratoriepraxis" [3] och att studiekvalitet är avgörande vid tolkning av observerade (statistiskt signifikanta) effekter. Om studier inte implementerar randomisering och blinding kan bias introduceras, vilket påverkar resultaten genom okontrollerade skillnader mellan djur eller experimentella förhållanden i olika grupper. Forskare kan även (medvetet eller omedvetet) göra tolkningar som stödjer deras föredragna hypotes [4]. Systematiska översikter har visat att djurexperiment som inte rapporterar randomisering eller andra åtgärder för att minska bias, oftare rapporterar överdrivna effekter som uppfyller konventionella kriterier för statistisk signifikans [4]. Dock saknas i vissa studier – inklusive några i årets SSM-rapport – till och med grundläggande information, såsom djurens ålder eller modulationsparametrarna för det elektromagnetiska fältet. Sådan information är nödvändig för att kunna replikera studien. Replikeringar är viktiga för att avgöra om observerade effekter i explorativa studier beror på exponeringen eller om de snarare är resultat av slump eller bias.

Ytterligare en återkommande problematik är användningen av små djurgrupper (i extrema fall färre än fem djur per grupp), vilket även observerats i studier som sammanfattas i denna SSM-rapport. Studier med för få djur (underpowered studies) har en hög risk att generera både falskt negativa och falskt positiva resultat samt att överskatta styrkan i ett samband [5]. Detta kan motverkas genom att beräkna lämplig urvalsstorlek i förväg (power-analys). Tyvärr utförs eller rapporteras power-analyser sällan – en tidigare genomgång visade att mindre än 10 % av publikationerna innehöll en sådan beräkning [6]. Att bestämma lämplig urvalsstorlek i förväg, för att undvika att använda för små eller för stora grupper, skulle också vara i linje med 3R-principen (Replace, Reduce, Refine) [7]. Det innebär att en studie som använder för få djur för att besvara en specifik forskningsfråga blir icke-informativ redan i designstadiet, och sådan onödig användning av laboratoriedjur bör undvikas.

Slutligen betyder en observerad biologisk effekt (oavsett om den är statistiskt signifikant eller ej) som svar på en exponering inte nödvändigtvis att det föreligger en negativ hälsoeffekt. Detta blir särskilt tydligt när den undersökta parametern är ett komplext biologiskt system med många interagerande komponenter, såsom immunsystemet. Om en komponent i systemet påverkas kan man inte dra några slutsatser om funktionen hos de övriga komponenterna eller det slutliga tillståndet hos systemet som helhet. Exempelvis kan den påverkade komponenten kompenseras av andra delar av systemet utan någon negativ inverkan på dess funktion. Trots detta nöjer sig många forskare med att rapportera en observerad effekt inom ett komplext system av samverkande faktorer, utan att diskutera dess kliniska relevans eller potentiella hälsoimplikationer.

Alla dessa faktorer innebär att även om samtliga djurstudier i denna rapport visar effekter, betyder det inte automatiskt att det finns belägg för hälsoeffekter hos djur eller människor.

1 Static Fields

1.1 Epidemiological Studies

Last years' summary on static field (or MRI) exposure and health effects remained essentially unchanged from the years before: Occupational exposure from magnetic resonance imaging (MRI) caused acute and transient symptoms, but long-term consequences for health remained unclear. Given that exposure to static fields from MRI is relatively high, and the number of occupationally exposed persons is increasing, more systematic and comprehensive research on this topic is warranted.

Danzer et al. [8] evaluated neurodevelopmental outcomes of foetuses scanned at 1.5-T versus 3 T (n=75 and 25, respectively). Scans were performed between 2012 and 2019 in The Children's Hospital of Philadelphia, US, and patient files were analysed retrospectively. Children were included if they had undergone scanning due to left congenital diaphragmatic hernia (left-CDH), as standard care of this population included postnatal neurodevelopmental progress. All scanned children with left-CDH that were scanned and had follow-up information were included in the study, and none had undergone foetal intervention. Children scanned in the 3 T scanner were born a bit earlier than 1.5 T scanned children. Bayley Scales of Infant Development were assessed around 18-21 months of age, and no statistically significant differences were observed for cognitive, motor or language development, including subscale scores (receptive, expressive language scores), or risk of neuromuscular hypotonicity. The authors concluded that their findings indicated that 3 T vs 1.5 T scanning did not confer greater risks to the developing foetus.
The added value of this study is the amount and detail of follow-up information, including the standardised assessment. However, the power of the study was very limited with such a small study size and only strong effects could have been observed.

In an ecological study using open-source data, Chai et al. [9] explored correlations between the geo-magnetic field and national incidence of cardiovascular disease over a period of 24 years (1996-2019), which corresponds to two solar cycles, for 204 countries including six territories without recognized sovereignty. Intensity, direction and fluctuation of the geo-magnetic field were considered. They analysed total geo-magnetic field (tGMF) and its horizontal (hGMF)component (measured in nT) as well as geomagnetic disturbance (GMD, aka geomagnetic storms). Cardiovascular disease included mortality, incidence and prevalence from all cardiovascular disease, ischaemic heart disease and stroke, and were available for the complete 24 year period and annually. Country covariates were indicators of weather (max and min temperature and specific weather events) and economy (GNI, divided in higher-, upper middle-, low middle-, and low-income groups), which were also aggregated to annual values. Cardiovascular mortality was positively associated with tGMF and negatively correlated with hGMF. In high income countries GMD frequency was positively correlated with total CVDs. The authors conclude: "Stable and long-term horizontal component of GMF may be beneficial to cardiac health. Unstable and short-term GMF called GMD could be a hazard to cardiac health."
The study suffers from considerable missing data (~20% of temperature and 25% of weather events, and GNI levels for 6 territories. Analysis consists of a large amount of models with no prior hypotheses for testing, and without adjustment for multiple comparisons. Models were only adjusted for national confounders related to weather and economy. Models were only adjusted for national confounders related to weather and economy and no factors known to be associated with cardiovascular disease incidence (for example differences between countries in smoking rates,

nutrition, exercise and other lifestyle factors), likely indicating that the consistent positive correlations with total geo-magnetic field and negative correlations with the horizontal geo-magnetic field component, indicate some artefact.

1.1.1 Conclusions on epidemiological studies

The conclusion of the report of last year was that occupational exposure from magnetic resonance imaging (MRI) caused acute and transient symptoms, but long-term consequences for health remained unclear. Increasing number of occupationally exposed persons warranted more systematic and comprehensive research on this topic. This conclusion remains unchanged with this year's two studies: One very small study on congenital diaphragmatic hernia (left-CDH), and the other an ecological study on geomagnetic fields and cardiovascular disease. Both studies did not provide clear evidence for or against associations with the exposure (Table 1.1).

Table 1.1: Epidemiological studies investigating static fields.

Endpoints	Reference	Exposure assessment	Study design, Population	Results
Infant development (Bayley scales)	Danzer et al, 2023	1.5 or 3T scan procedures during pregnancy	Case series of 100 children scanned for congenital diaphragmatic hernia	No greater increased risks was observed, but study was limited in power to observe smaller risks.
Cardiovascular diseases	Chai et al, 2023	Geomagnetic field over two solar cycles (24 years)	Ecological studies in 204 countries	Authors report positive correlations with total geomagnetic field, and negative associations with horizontal geomagnetic field component, indicating a possible artefact in the data.

1.2 Human Studies

In the last year it was concluded that people are able to reliably perceive even very low combinations of AC and DC field strengths (1kv/m each).

The only study related to DC (direct current) and low frequency (AC, alternating current) electric fields published in 2023 refers to Kursawe et al. [10]. The article is the third in a row on human electric fields (EF) perception thresholds in the context of high voltage power lines. In the first article Jankowiak et al. (2021) presented the results of a pilot study on the identification of environmental and experimental parameters influencing human EF perception thresholds for AC, DC and hybrid EF exposure (see also SSM report from 2022). Since the results revealed that perception thresholds were lower in the hybrid EF exposure condition than in the AC and DC exposure alone, Kursawe et al. (2021) investigated the role of the single components and the hybrid exposure condition systematically in a larger study population under double-blind conditions (see also SSM report from 2022). The results again indicated that perception thresholds were lower in the hybrid EF exposure condition than in the AC and DC exposure alone. In the present publication, Kursawe et al. (2023) evaluated the influence of the DC component on hybrid EF perception in a subset of 49 highly sensitive participants. The 30 females and 19 males (age range between 24 and 79 years; mean age: 51 years) were all successfully able to detect a hybrid EF with 4 kV/m AC and 2 kV/m DC in the previous study of the prior study (Kursawe et al. [11]). The same exclusion criteria applied as before and guaranteed no medical conditions interfering with the protocol as confirmed by a detailed medical examination. The experiment took place in a specialized exposure laboratory, and authors refer to the technical details to Jankowiak et al. (2021) (see also SSM report 2022). Participants underwent four test conditions with four different DC EF strengths (1, 2, 3, 4 kV/m) and five different AC EF strengths (1, 2, 4, 8, 14 kV/m) per condition. Each total EF strength was applied eight times, resulting in 40 exposure and 40 sham trials per condition. Each trial started with an onset period of 3s, followed by 5s period for "perception", and ended with a 4s response period. After each trial participants had to choose one of four possible answers ("yes - certain", "yes - uncertain", "no - uncertain", "no - certain") to the question whether they perceived an electric field. Between the conditions, a 15 min break was set up. To quantify the answers the sensitivity index d′ = z (hit) - z (false alarms) was determined after applying a log-linear transformation of hits and false alarm rates. A 4 x 5 repeated measure ANOVA with four levels of DC EF strength and five levels of AC EF strength revealed significant interaction effects and indicated that DC EF had a significant influence on detection performance that was most evident when the two highest AC EF strengths (8, 14 kV/m) were present. Pearson r correlations of individual detection thresholds (referring to d′= 1) between the current and the former study of Jankowiak et al. (2021) revealed a good accordance in detection performance. The authors related differences in perception ability to individual differences in body hair, since body hair plays a major role in the perception of AC EF, and point out the necessity to focus on individual factors in future studies.

1.2.1 Conclusions on static human studies

The only study from 2023 confirms the previous results that perception thresholds were lower in the hybrid EF exposure condition than in the AC and DC exposure alone. Although perception under real-world conditions may not be comparable to experimental conditions, the results contribute important findings on the impact of the DC component on human hybrid EF perception. The results may have implications on the planning and construction process of high voltage power lines and provide guidance for the development of cut-off values especially for highly sensitive people (Table 1.2).

Table 1.2: Human studies investigating static fields.

Endpoints	Reference	Exposure condition	Sample	Results
Perception threshold of AC and DC EF	Kursawe et al. (2023)	DC EF: 1, 2, 3, 4 kV/m condition AC EF: 1, 2, 4, 8, 14 kV/m	49 healthy participants with above-average EF detection ability (30 female, 19 male) age range: 24 to 79 years, mean: 51 years	DC-EF had a significant influence on detection performance that was most evident when the two highest AC EF strengths (8, 14 kV/m) were present

1.3 Animal Studies

Last year's summary on *in vivo* experiments aimed to study biological effects of static field exposure reported some but inconsistent effects on behaviour, cognition, reproductive and developmental toxicity and oxidative stress. The conclusions of the report were essentially unchanged from the ones of the years before.

1.3.1 Rodents

Physiology & Pathophysiology

Lv et al. [12] studied the effects of SMF exposure on hepatic function and metabolism in obese and diabetic mice. A total of 48 male C57BL/6 J mice were divided in six groups ($n = 8$): sham exposure and normal diet, SMF exposure and normal diet, sham exposure and fat diet (obese mice), SMF exposure and fat diet (obese mice), sham exposure and fat diet + streptozocin (diabetic mice), SMF exposure and fat diet + streptozocin (diabetic mice). The SMF exposure was at 0.55 ± 0.15 T, 4 h/d for 8 weeks. Results showed that SMF exposure could significantly ameliorate the development of hepatic injury in obese and diabetic mice by inhibiting inflammatory level, by improving glycolipid metabolism through the regulation of proteins glucose transporter GLUT1 and GLUT4 and of genes Glucose-6-phosphatase (G6pc), Pyruvate Dehydrogenase Kinase 4 (Pdk4), glycogen synthase 2 (Gys2) and pyruvate kinase (Pkl) (all of them participating in glucose metabolism), by regulating iron metabolism (lower Ferritin Heavy Chain (FTH1) expression), by balancing redox level (regulation on mitochondrial function and MAPKs/Nrf2/HO-1 pathway) and by activating autophagy (upregulation of patatin like phospholipase domain containing 2 (PNPLA2) expression).

In the study by Yu et al. [13] the effects of quasi-uniform and gradient high SMF on both type 1 (T1D) and type 2 (T2D) diabetes mice were investigated. A total of 194 C57BL/6J diabetic mice were divided into five groups: a healthy group, a gradient SMF group (diabetic mice under gradient SMF conditions 1.0 T– 8.5 T), a sham 1 group (diabetic mice with sham exposure comparable to the gradient SMF group), a quasi-uniform SMF group (diabetic mice under quasi-uniform SMF conditions 9.2 T – 9.4 T) and finally, a sham 2 group (diabetic mice with sham exposure comparable to quasi-uniform SMF group). All the exposures lasted 14 h. At the end of exposure, the open field (OF) test was used to evaluate the locomotion and exploration activities of mice. Moreover, a complete blood count, blood biochemical analysis, the enzyme activity assay (tissue levels of superoxide dismutase (SOD) and malondialdehyde (MDA)) and a histomorphological analysis were carried out. The study results showed that exposure to quasi-uniform SMF did not produce noticeable damage in the diabetic mice. Moreover, no effects of both exposures on the OF test were evidenced, even if gradient SMFs increased blood glucose in T1D/T2D mice and mortality in severe T1D mice. The blood analysis and the tissues examinations revealed that the gradient SMF seemed to exacerbate physiological and pathological abnormalities in diabetic mice, such as inducing increased uric acid (UA) levels and histomorphological changes in the liver, kidney, and spleen. Additionally, both interleukin 6 (IL-6) and tumour necrosis factor alpha (TNFα) were significantly increased in the liver, kidney, and spleen of severe T1D mice after gradient SMF exposure. Finally, gradient SMFs exposure increased oxidative stress in diabetic mice through a decrease of SOD levels and an increase of MDA levels in the kidney tissue of T1D mice.

Behaviour and Oxidative Stress

In the study of Cardoso Brito et al. [14] the possible effect of SMF exposure on the alprazolam-induced rat behaviour was investigated. The alprazolam is a psychotropic drug able to change rat behavior in the elevated plus-maze test (EPM); for this reason 66 male Wistar rats were assigned to one of the following groups ($n = 11$): Sham Magnetic + Saline (SMS), North Pole + Saline (NPS), South Pole + Saline (SPS), Sham magnetic + alprazolam (SMA), NP + alprazolam (NPA), and SP + alprazolam (SPA). Animals were stimulated with a SMF of 3.2 T provided by magnets placed on their heads. After five days of stimulation, they received alprazolam or saline (1 mg/kg), and their behavior was evaluated. The SMA and NPA groups showed an increased number of entries and time in the open arms as well as an increased head dipping and end-arm activity compared to the SMS group. SPA showed a decrease in these measures when compared to SMA. These results showed that the south magnetic pole of a SMF seemed to block the alprazolam effect in the space–time variables of the open arms and ethological anxiolytic-like behaviour in the EPM.

In the study by Cote et al. [15] various experiments were conducted on wild type (WT) and otolith mutant (head-tilt $NOX3^{het}$ and tilted Otop1) mice, to assess behavioural and neural responses, specifically to investigate the role of otoconia, to high strength SMF exposure (14.1 T for 30 min). Otoconia are bio-crystals which couple mechanical forces to the sensory hair cells in the utricle and saccule, a process essential for us to sense linear acceleration and gravity for the purpose of maintaining bodily balance. The *het* and *tlt* mutant mice serve as models of otolith organ dysfunction resulting from mutations of genes critical for the otoconia formation: NOX3 in *het* mice and OTOP1 in the *tlt* mice. Results from this comprehensive study indicated that WT mice exhibited locomotor circling behaviour, a significant reduction in rearing, acquired a conditioned taste aversion (CTA) after pairing SMF exposure with saccharin, and presented a significant c-Fos expression in brainstem vestibular and visceral nuclei. Mutant *het* mice, lacking otoconia, displayed no disturbance in locomotor behaviour and showed decreased induction of c-Fos in the brain. Mutant *tlt* mice failed to acquire SMF induced CTA, although they exhibited SMF responses in rearing and circling like WT mice. This study individuated the otolith organ as one of the possible sites of SMF effects, manifesting as vestibular perturbation.

Fan et al. [16] investigated the effects of moderate SMF exposure on the lifespan and healthspan of mice. A total of 24 C57BL/6 adult mice (52 weeks old) were divided into three groups ($n = 8$): sham exposed, upward SMF exposure, and downward SMF exposure (ranging from 70 to 220 mT, head to toe, 16 hours/day for the first five weeks and 24 hours/day until their death). The health status of the mice was evaluated using three different tests: i) the Open Field (OF) test, conducted after 4 weeks and 55 weeks of exposure, to assess the mental state of the mice; ii) the EPM test, conducted after 4 and 9 weeks of exposure, to measure the anxiety levels of the mice; iii) the Morris Water Maze (MWM) test, conducted after 32 weeks of exposure, to evaluate spatial learning and memory abilities. Blood samples were collected from the mice after 43 weeks of SMF exposure for comprehensive analysis. Additionally, oxidative stress in the brain of the mice was assessed. The study results revealed that SMF exposure (both upward and downward) extended both the median and maximum lifespan of the mice. The EPM test indicated that upward SMF exposure increased the time spent in the open arm by 237.39% ($p < 0.05$) and 141.25% ($p = 0.05$) at 4 and 9 weeks of exposure, respectively, compared to the sham group. Furthermore, there were no significant differences in total travelled distance and total average velocity between the SMF treatment group and the sham group. The OF test showed that SMF-exposed mice spent more time in the centre area compared to the sham group. Additionally, in the OF test, the total travelled distance and total average velocity were significantly higher in the SMF groups compared to the sham group. The

MWM test showed that SMFs could enhance spatial learning ability and spatial memory, as indicated by a significant decrease in escape latency (one of the outcomes of the MWM test) in the upward and downward SMF groups compared to the sham group. Moreover, the swimming speed was faster in the SMF group than in the sham group during the 4-day training, suggesting an improved physical state of the SMF-treated mice. Examinations of brain tissue revealed that SMFs could have a reduction in oxidative stress in the brains of aged mice.

In the study conducted by Le Ster et al. [17], the effects of exposure to ultrahigh SMF on the inner ear of mice were investigated. Three groups of mice (n = 8) were sham exposed or exposed to either 11.7 T or 17.2 T, for 10 sessions of 2 hours over a period of 5 weeks. Before, during and 2 weeks after the exposure period mice underwent behavioural tests (balance beam, rotarod and swimming test) to evaluate their short-term and long-term motor coordination and balance thus assessing the mice's vestibular system. After two weeks of exposure an auditory brainstem response (ABR) test was performed to assess the functional integrity of cochlea. Although mice displayed transient rotating behaviour immediately after exposure, no effects were observed in all other investigated endpoints.

Xu et al. [18] investigated the potential role of the nuclear factor erythroid 2–related factor 2 (Nrf2) in the hippocampus on the effect of 24 h exposure to SEF, at 53.6 kV/m for 7 days and 14 days on oxidative stress and learning memory. Two separate experiments were conducted. In the first experiment, two groups (n = 10) of ICR mice were either sham exposed or continuously exposed to SEF for 7 days. Following exposure, hippocampal samples were collected to assess the protein expression levels of Nrf2 and the gene expression levels of Nrf2, SOD2, and glutathione peroxidase 1 (GSH-PX1). In the second experiment, four groups (n = 20) of ICR mice were established: the sham group, the SEF exposed group, the sham + INH group and the SEF exposed + INH group. INH, which is isoniazid, a type of Nrf2 signalling pathway inhibitor, was administered to the mice via oral gavage once a day (5 mL/kg body weight). The MWM test was performed at the end of the experiment, followed by hippocampal sampling for further biochemical assays (protein and genes expression levels, oxidative stress indices). This study revealed that the protein levels of Nrf2 in both the cytoplasm and nucleus as well as the mRNA levels of GSHPX1 and SOD2 (downstream antioxidant genes), significantly increased after exposure to 56.3 kV/m SEF for 7 days and 14 days. Additionally, SEF exposure activated the Nrf2 signalling pathway. Furthermore, the results of the second experiment indicated that the inhibition of Nrf2 signalling by isoniazid could impede SEF-induced gene transcription and protein expression, leading to a reduction in antioxidant capacity, an elevation in the level of lipid peroxide product, and irreversible damage to learning and memory.

Cancer

The study by Tian et al. [19] investigated the effect of high level SMF exposure (9.4 T) on the development of implanted gastrointestinal stromal tumours in mice. A total of 36 mice were injected with five million of human gastrointestinal stromal tumour (GIST-T1) cells and divided into six groups (n = 6) including a sham group, a 5 mg/kg drug group, a 9.4 T SMF group, a 20 mg/kg drug group, a 20 mg/kg + 9.4 T SMF group and an 80 mg/kg drug group. The mice in the sham group were treated with saline, while those in the pharmacotherapy groups received daily intraperitoneally injections of imatinib mesylate at 5, 20 or 80 mg/kg, respectively. Mice in the SMF and imatinib combined group were injected with 20 mg/kg imatinib mesylate followed by 9.4 T SMF exposure every day. The exposure lasted 10 h/d for 20 days. The results of the study showed that the tumour growth was inhibited by up to 62.88% in the group exposed to 9.4 T SMF alone. Furthermore, the group treated with 9.4 T SMF combined with 20 mg/kg imatinib mesylate showed a 92.75% tumour suppression rate, which was close to the anti-tumor effect observed with a high dose (80 mg/kg) of imatinib. However, the 80 mg/kg imatinib group exhibited severe side effects (significantly reduced body weight gain, abnormal liver function, and depressive behaviours), which were significantly reduced in the groups exposed to 9.4 T SMF combined with 20 mg/kg imatinib mesylate.

Immune system

In the study by Dong et al. [20], the effects of the exposure to a SEF (56.3 ± 1.4 kV/m for 7 or 14 days) on the in vivo proliferation level of B lymphocytes were examined. Four groups of mice (n = 10) were either sham exposed or exposed to SEF for 7 days or 14 days. At the end of the exposure period, B lymphocytes were collected from the spleen of mice. No effect was observed in the group exposed for 7 days compared to the sham group. However, SEF exposure significantly increased the proliferation level of B lymphocytes after 14 days of exposure.

1.3.2 Other animal species

Behaviour and Oxidative Stress

Chapman et al. [21] investigated the effects of SMF exposure, like that from renewable energy subsea power cables, on several species of marine invertebrates: the common starfish (*Asterias rubens*), European edible sea urchin (*Echinus esculentus*), velvet swimming crab (*Necora puber*), and common periwinkle (*Littorina littorea*). Thirty animals from each invertebrate species were divided into sham and exposed groups (SMF of 500 µT for 24 hours). The righting reflex time was used to evaluate the behavioural effects of the exposure. After the behavioural tests, hemolymph or coelomic fluid was extracted. The study found no significant differences in the righting durations for any of the species tested. Moreover, SMF exposure did not significantly affect total hemocyte/coelomocyte counts.

Durif et al. [22] examined the behavior of juvenile lumpfish (*Cyclopterus lumpus*) during the exposure to a SMF of 230 µT for 30 min. The intensity of the SMF corresponded to the field at 1 m from a high-power submarine cable. Two groups (either sham or SMF exposed) of lumpfish (*n* = 24) were filmed during the exposure. The results of this study evidenced that juvenile lumpfish activity, defined as the time that the fish spent swimming relative to stationary pauses and the distance traveled, were unaffected by exposure. The swimming speed of juvenile lumpfish was reduced (by 16%, p = 0.042) when the coil was switched on, indicating that the fish could either sense the MF or the induced electric field created by the movement of the fish through the magnetic field.

The study conducted by Tang et al. [23] studied the effects of SMF exposure on the development, behavior and immune response in zebrafish embryos and larvae. Four groups of zebrafish embryos/larvae (*n* = 25) were sham exposed and SMF exposed to 0.4 T, 3.0 T, and 9.4 T for 2 hours at 24/96/120 hours past fertilization (hpf). Results showed that there was no significant difference in the number of spontaneous tail swings, heart rate, and body length of zebrafish larvae as well as in the expression of development-related genes *shha*, *pygo1*, *mylz3* and *runx2b* in all SMF exposed groups compared to sham exposed group. Behavior tests unveiled a notable reduction in both the average speed and duration of high-speed movements in zebrafish larvae for all three SMF groups. The migration of neutrophils in caudal fin injury, and the expression of pro-inflammatory cytokines was increased in the 0.4 T and 3.0 T groups. No dose-effect relationship was evidenced for this last endpoint.

The study conducted by He et al. [24] investigated the effects of short-time exposure to SMFs on the development of aphid *Macrosiphum rosae*, and additionally measured the enzymatic activity of superoxide dismutase (SOD), peroxidase (POD) and catalase (CAT). Nymph aphids were exposed (0.065T, 0.1T, 0.176T and 0.28T for 4 minutes, $n = 30$) and subsequently observed to record parameters such as survivorship, fecundity and oviposition period until the death of all individuals. The results indicated that the exposure to a 0.28 T SMF caused significant differences in total pre-oviposition period (prolongation of the four instar development and shortening of the first, second and third instar period). Moreover adult longevity and total longevity were significantly reduced compared to the control group. Furthermore, the activity of SOD, CAT and POD was influenced by SMF exposure albeit without a dose-effect relationship.

Liu et al. [25] evaluated the effects of 11.4 Tesla (T) SMF exposure on embryonic development using a zebrafish model. Multiple approaches, including morphological parameters, physiological behaviors, and analyses of the transcriptome at the molecular level, were employed. Three groups of zebrafish embryos ($n = 300$) were assigned: a control group, a 0.02 T group (it can be considered as sham exposure) and an 11.4 T group and were exposed from 6 hours post fertilization (hpf) to 24 hpf. No significant effects were observed in embryo mortality, hatching rate, body length, Left-Right patterning, locomotor behavior, etc. RNA-sequencing analysis revealed upregulation of tumor necrosis factor (TNF) inflammatory factors and activated TNF signaling pathways in the 11.4 T exposure group compared to the sham group.

1.3.3 Summary and conclusions on SF animal studies

A total of 14 articles have been selected to describe the scientific activities related to the study of the health effects of *in vivo* exposure to static magnetic fields (SMF) and static electric fields (SEF). Except for two papers that utilized *in vivo* exposure to the SEF, the remaining articles investigated the effects of exposure to SMF. Nine articles studied the effects of exposure on rodents (8 with mice and 1 with rats), while the other 6 papers utilized different animal species, with a particular focus on the marine environment.

Exposure to uniform SMFs of diabetic mice appeared to have no noticeable effects on blood glucose levels. However, exposure to spatial gradient SMFs seemed to exacerbate physiological and pathological abnormalities, as well as induce an increase in blood glucose and oxidative stress in diabetic mice.

Behavioral studies appeared to indicate improvement in the performance of exposed animals compared to sham-exposed ones. This seemed to hold true for SMF values ranging from 0.32 T to 14.1 T. Exposure also appeared to increase the expression levels of certain proteins involved in defining oxidative stress. Similar effects have been described for exposure to a SEF of 53.6 kV/m.

Exposure to an SMF of 9.4 T appeared to inhibit the growth of an injected gastrointestinal stromal tumor in exposed mice. Combined exposure to SMF and 20 mg/kg of imatinib mesylate seemed to have tumor-reducing effects like those of the group treated with the highest dose of the drug (80 mg/kg), without showing any side effects.

Regarding other species, only potential behavioral effects related to exposure to SMFs ranging between 230 μT and 14.5 T were evaluated. Despite the diversity of the species analyzed and the levels of SMF, there appeared to be no significant effects on the considered endpoints except for some sporadic exceptions (Table 1.3).

Table 1.3: Animal studies investigating static fields.

Endpoint	Reference	Exposure SMF or SEF	Exposure Duration & Species	Effect of SF exposure
Rodent Studies				
Physiology & Pathophysiology	Lv et al. [5]	0.55 ± 0.15 T	4 h/d for 8 weeks C57BL/6J mice	Attenuation of hepatic damage in obese and diabetic mice. No effects on improving glucose/insulin tolerance. ↓ lipid droplets accumulation. ↓ hepatic iron deposition.
	Yu et al. [6]	Quasi-uniform SMF (9.2 T-9.4 T) Gradient SMF 1.0 T– 8.5 T)	14 h type 1 (T1D) and type 2(T2D) diabetic C57BL/6J mice	Gradient SMFs ↑blood glucose, exacerbated physiological and pathological abnormalities, ↑oxidative stress in diabetic mice. ↑mortality in T1D mice
Behavior and Oxidative Stress	Cardoso Brito et al [7]	0.32 T	5 days Wistar rats	South magnetic pole of a SMF blocked the alprazolam effect in the space–time variables of the open arms and ethological anxiolytic-like behavior in the EPM test.
	Cote et al. [8]	14.1 T	30 min WT, head-tilt NOX3het and tilted Otop1 mice	In WT exposed mice: suppressed rearing, ↑latency to rear and locomotor circling. *Het* mice have no response to exposure. In *Tlt* exposed mice: significant locomotor circling, suppressed rearing.
	Fan et al. [9]	70–220 mT (head-to-toe)	16 h/d for 5 weeks, and then 24 h/d, 7 days a week until natural death. C57BL/6 mice	↑lifespan of the mice ↑ exploratory and locomotive activities of the aged mice. ↑ spatial learning ability and spatial memory. Ameliorative effect on oxidative stress in the brain of aged mice.
	Le Ster et al. [10]	11.7 T, 12.7 T	10 sessions of 2h over a period of 5 weeks mice	No effects
	Xu et al. [11]	53.6 kV/m	24 h/d for 7 days 24 h/d for 14 days mice	Both exposure durations significantly improved the expression levels of Nrf2 protein, of antioxidant genes, superoxide dismutase 2, and glutathione peroxidase 1. No significant difference in the expression level of the Nrf2 gene was found.

Cancer	Tian et al. [12]	9.4 T	10 h/d for 20 days SPF BALB/c (Nu/Nu) mice	Inhibition of tumor growth up to 62.88% in SMF alone group. 92.75% tumor suppression in SMF combined with 20 mg/kg imatinib mesylate group close to the anti-tumor effect of high dose (80 mg/kg) drug.
Immune system	Dong et al. [13]	56.3 ± 1.4 kV/m	7 or 14 days mice	Proliferation level of B lymphocytes: ● no effect after the 7-days exposure. ● ↑ after 14-day exposure.
Other Species				
Behavior	Chapman et al. [14]	500 μT	24 h Marine invertebrates	No effects in the tested endpoints
	Durif et al. [15]	230 μT	30 min Lumpfish	No effects on juvenile lumpfish activity. -16 % swimming speed.
	Tang et al. [16]	0.4 T, 3.0 T, 9.4 T	2 h at 24/96/120 hour past fertilization Zebrafish embryos/larvae	No effects on physiological parameters. ↓ in both the average speed and duration of high-speed movements in zebrafish larvae for all three exposed groups. ↑ migration of neutrophils in caudal fin injury, and the expression of pro-inflammatory cytokines for the 0.4 and 3.0 T SMFs.
	He et al. [17]	0.065 T, 0.1 T, 0.176 T, 0.28 T	4 min Nymphs of Aphid Macrosiphum rosae	↓adult longevity @ 0.28T ↓total pre-oviposition period @ 0.28T
	Liu et al. [18]	11.4 T	18 hours Zebrafish embryos	No effects in embryo mortality, hatching rate, body length, Left-Right patterning, locomotor behavior, etc. Up-regulated tumor necrosis factor (TNF) inflammatory factors and activated TNF signaling pathways.

Abbreviations: ↓=decrease(d); ↑=increased; EPM: elevated plus-maze; Nrf2: nuclear factor erythroid 2–related factor 2;

1.4 Cell Studies

1.4.1 Conclusions on static field cell studies

No paper was included in this report.

2 Extremely Low Frequency Fields

2.1 Epidemiological Studies

In the last reporting period, there was one study addressing ELF-MF exposure and childhood leukaemia. Leukaemia risk was somewhat elevated in children living close to high-voltage power lines, in line with previous reports. Residential proximity to plant nurseries with presumably higher pesticide exposure, did not act as a strong confounder.
A large study on occupational exposure ELF-MF and electric shock in relation to risk of non-Hodgkin's lymphoma, chronic lymphocytic leukaemia and multiple myeloma did not observe increased risks, but exposure misclassification and healthy worker effects may have affected study results.

2.1.1 Adult Cancer

Khosravipour et al. [26] (2023a) conducted a second study based on the same study population below (see "other outcomes", Khosravipour 2023b) but with 1 additional participant (n=297)). It also uses the same study design, exposure assessment, and analytic design, but looked at thyroid hormones (T3, T4 and TSH). The study reported significant association of reduction in T3 and T4 with ELF-MF exposure, even after adjustment for shiftwork and occupational noise, and elevated levels of TSH which disappeared after adjustment for noise. Two- and 3-way interactions including ELF-MF exposure were significant for T4, but not for T3 or TSH. The study suffers from the same limitations as the other study by the same authors and as pointed out by the authors some residual confounding, e.g. due to sleep or diet which were not adjusted for may have influenced results.

Odutola et al. [27] conducted a family-based case–control study in Australia to examine the relationship between ELF-MF and follicular lymphoma. Follicular lymphoma cases were identified from population-based cancer registries in New South Wales (NSW) or Victoria. Cases were required to be 20 to 74 years of age, resident in New South Wales (NSW) or Victoria and diagnosed between 2011 and 2016 and to be able to give informed consent and have no history of haematopoietic malignancy. Of the 1778 eligible cases who the researchers were able to contact, 681 consented and completed the study lifetime job history questionnaire. Controls were related (siblings) and unrelated (spouses/ partners) relatives aged between 20 and 74 years with no history of haematopoietic malignancy. Participation rates for unrelated and related controls were 79.8% and 80.0%, respectively. Of those enrolled, 473 controls (91.5%) completed the lifetime job history questionnaire. An additional 711 unrelated controls from a preexisting case–control study with similar design, eligibility criteria and questionnaire were also included. Lifetime occupational history was self-reported using a lifetime calendar and linked to a modified INTEROCC ELF-MF job-exposure matrix, which was originally based on measurements and coded to ISCO-88 (International Classification of Occupations, 1988) codes. A 10-year latency between exposure and outcome was used in the analyses. Three exposure measures were calculated for each participant: average intensity (µT), total duration (years) and lifetime cumulative exposure (µT-years). These were each categorised in quartiles of exposure. Logistic regression models were adjusted for age, sex, ethnicity, state and smoking. Main analyses were complemented by various sensitivity analyses. No statistically significant association between follicular lymphoma and any of the exposure metrics was observed. Note that the p-value with average exposure was "borderline" (0.09) with increasing point estimates across categories.
This was a study of good quality, but with several reported limitations, mostly notably around the

JEM which relied on recalling jobs many years in the past and which was not developed for the Australian population and by its nature will be subject to (Berkson and classical) measurement error; the latter likely attenuating any results. Additionally, it is possible that too few participants may have had relevant exposure levels; e.g. for average intensity of exposure in the highest quartile was 0.16-1.87 μT.

2.1.2 Childhood cancer

Zagar et al. [28] presented an efficient numerical way to calculate exposure from all power lines in Slovenia and applied this to all 110-400 kV overhead power lines and 110 kV underground cables in the country. Magnetic field exposure was grouped into <0.1 μT (background), 0.1-0.2, 0.2-0.3, 0.3-<0.4 or ≥0.4 μT. In a next step all incident childhood cancer cases (age 0-14 years), all childhood leukaemia cases (age 0-19 years) and all brain tumour cases (age 0-29) that had been registered in the Slovenian cancer registry between 2005-2016 were assigned residential exposure. Only 0.5% of the population lived in areas with > 0.1 μT. Over the 12 years of cancer registration, only 1 exposed case of leukaemia (in the 0.1-0.2 μT group), and 1 exposed case of brain tumours (0.2-0.3 μT group) were observed. Due to the very low number of exposed persons, expected numbers of cancer cases were also very low. For example, for the exposure group of ≥0.4 μT, only 0.5 cases of any cancer were expected, and 0.2 cases for both leukaemia and brain tumours.
As such, the study is interesting in developing a numerically efficient way to model exposure to magnetic fields from overhead power lines for a whole country. Since Slovenia is a small country, only very few cases were expected and observed, and power of the study was much too small to assess the association between magnetic field exposure and incident cancers.

Malagoli et al. [29] investigated residential exposure to high voltage power lines, as a risk factor for childhood leukaemia (0-15 years of age) in a case-control study with 182 cases diagnosed 1989-2019 in the Italian childhood cancer register and 4 controls for each case matched on sex, birth year and province of residence, from national health service data. Distance to powerlines was determined from geocoded data on address at time of diagnosis and powerlines ≥132kV, active between 1998 and 2011. Field strength was based on measurements of power load in 2001 and data on phase configuration. Confounder data included air pollution (PM_{10}), indoor transformer stations, land use and sociodemographic indicators. Eight cases and 15 controls lived <100m from a powerline. Of these only one case had ≥ 0.4μT and 2 cases and one control had ≥0.1μT. In logistic regression models with >400 m as comparison group, living <100m from a powerline was associated with OR 2.0 (95%CI: 0.8-5.0) for any leukaemia and 2.2 (95%CI: 0.8-6.0) for acute lymphoblastic leukaemia. Exposure ≥0.1μT was associated with OR 7.5 (95%CI: 0.7-82.8) compared to <0-1μT. The authors conclude "In this Italian population, close proximity to high-voltage power lines was associated with an excess risk of childhood leukaemia."
Limitations of the study included the time frame of exposure assessment and the very low number of participants with any potentially relevant exposure. The results are in accord with previous studies but do not bring us closer to understanding why this is observed.

Nguyen et al. [30] (2023) re-analysed a previous study on ELF-MF exposure from power lines and childhood leukaemia in California, USA (Summarized in 2023 report: https://www.sciencedirect.com/science/article/pii/S0013935122007733?via%3Dihub). The space underneath power lines is sometimes occupied by commercial plant nurseries. Plant nurseries belong to the agricultural group of high users of pesticides, and pesticides have been associated with childhood leukaemia as well. Therefore, the authors evaluated whether pesticide exposure acted as a confounder for the association between ELF-MF and childhood leukaemia. The authors concluded that pesticide exposure could represent an independent risk factor for childhood leukaemia. However, childhood leukaemia risks for powerline proximity and magnetic fields exposure were not explained by pesticide exposure.

Malavolti et al. [31] (2023b) analysed the same dataset as described above (Malagoli et al 2023a) but focused on residential proximity to transformer stations converting electricity from 15 kV to 380 V. The study included all 13,434 such stations in two Italian provinces. Five cases of childhood leukaemia and 17 controls lived <25m from a powerline and 2 cases and 8 controls lived <15 m from transformer stations. With 15 m and 25 m cut point between exposed and unexposed, the respective ORs from leukaemia were 1.0 (95%CI: 0.2-4.9) and 1.2 (95%CI: 0.4-4.3). In sub analyses, point estimates were higher in children diagnosed after 5 years of age but based on even fewer cases and again with very wide confidence intervals. The authors conclude "While we found no overall association between residential proximity to transformer stations and childhood leukemia, there was some evidence for an elevated risk of childhood leukemia among children aged ≥5 years. Precision was limited by the low numbers of exposed children"
The limitations are shared with the previous study (Malagoli et al 2023a). For both studies the wide confidence limits means that the results could agree with a null association but would also be compatible with an elevated risk.

2.1.3 Reproduction/ birth outcomes

Irani et al. [32] attempted to systematically summarise and meta-analyse all studies on electromagnetic field exposure during pregnancy. Six cohort or case-control studies were included. The authors meta-analysed studies independently of whether extremely-low frequency magnetic field exposure were assessed, or radiofrequency electromagnetic fields. However, as these exposures have very different mechanisms on how they interact with living bodies, the result of this meta-analysis is not informative.

Zhou et al. [33] performed a systematic review and meta-analysis of studies addressing residential magnetic field exposure from power lines and different types of adverse birth outcomes. Overall, seven studies were included that assessed stillbirth, miscarriage, birth defects and preterm birth. Although exposure in the respective studies was assessed in different ways (e.g. distance to a power line, or residential address in a municipality where a power line crossed), meta-analyses across all different exposure assessment methods and outcomes were performed. The individual outcome groups were additionally meta-analysed separately. No statistically increased risks emerged from any of the presented analyses.
Because different exposure assessment methods and outcomes were combined, the quantitative results of this meta-analysis remain largely uninformative.

2.1.4 Neurodegenerative diseases

Duan et al. [34] performed a systematic review of genetic and non-genetic risk factors for amyotrophic lateral sclerosis (ALS). 163 studies on genetic risk factors and 67 studies on non-genetic risk factors were included. 16 non-genetic statistically significant factors were identified, including magnetic field exposure and electric shock.
This study can be seen as an effort to map all currently known risk factors for ALS. It is however not described how the different occupational and environmental studies were combined or what level of exposure was associated with the reported ORs, so regarding the specific questions around

occupational versus environmental exposures, or magnetic field exposures and/or shocks, the meta-analysis is not informative.

Vasta et al. [35] investigated if age of onset, or disease progression in ALS patients was modified by electromagnetic fields in an Italian cohort of 1098 ALS patients diagnosed between 2007 and 2014. Exposure to ELF from powerlines and repeater antenna (stated to be ELF) was established from residential address at time of diagnosis. Exposure from powerlines was quantified as length of line within different radii between 100 and 2000 m around residences. Exposure from antennas was quantified as 1/distance to antenna^2. For each metric, exposure was dichotomized as below or above median exposure. Using Mann-Whitney and regression models the authors observed no association with progression rate or age at onset. The authors conclude: "Our findings suggest that electromagnetic fields do not modify the ALS phenotype or progression".
It is unclear which exact frequency ranges were included in the study. Additionally, occupational and previous residential exposures were not taken into account. Counting half the participants as exposed will likely have left only a very small proportion of the exposed group with any potentially relevant exposure making the study conclusions unfounded.

2.1.5 Other outcomes

Kosek et al. [36] performed a cross-sectional study among 143 secretaries of different departments at Balcalı Hospital (Adana, Turkey). The authors used questionnaires to ask about age, sex, daily working hours, distance to screens, etc.; and to fill in a questionnaire regarding a Computer Vision Syndrome scale and an Ocular Surface Disease Index. Examinations by ophthalmologists served to assess visual acuity, eye pressure, anterior segment and fundus, as well as dry eyes (Schirmer test). Magnetic field exposure was measured in a square of 30 and 60 cm distance around the workplaces with a 6010 Gauss/Teslameter (American Bell, Milwaukie, OR, USA), and average values were used to express exposure. The authors report higher magnetic field exposure among secretaries with Computer Vision Syndrome as compared to secretaries without the condition.
It is not reported when the study was performed. Apparently, the total number of secretaries was 290, which would bring the response rate to about 49%. It is not reported over how long the measurements were performed, and under which conditions (e.g. all devices emitting magnetic fields in use or not). The reported exposure values are unrealistically high with 1457 vs 1545 μT (higher than the current occupational exposure limit guidelines). Such values are not realistic to occur, as previous reports have reported average exposure of office workers that would be much lower (more likely around 0.1-0.2 μT; Bowman et al 2007). All in all, this makes it unclear what was done and how to interpret the results.

Mansourian et al. [37] reported performing a systematic review and meta-analysis of EMF exposure and indices of heart rate variability. The authors initially identified 45 studies and after excluding 25, extracted information from 15 studies, leaving 5 studies unaccounted for. Before-after studies and case-control studies were mixed, as were studies addressing ELF-MF exposures and RF-EMF exposures. Meta-analyses combining such different study designs are unlikely to result in any meaningful summary estimates. Also, the combination of ELF-MF and RF-EMF into meta-analyses (with very different underlying interaction with human bodies) means that the summary estimates from the meta-analysis cannot be interpreted.

Khosravipour et al. [38] (2023b) investigated the association between liver function enzyme levels and three-way interactions between occupational noise, ELF-MF and shift work. 296 male workers were recruited in 2016/17 from the thermal power plant industry and followed up until 2020. Each worker had at least 2 measurements (n=1032 observations in total). Data were collected during annual mandatory check-ups. Workers were divided in four groups for exposures, with exposure to noise and ELF-MF based on a quantitative job-exposure matrix (JEM). The JEM was based on measurements converted to 8-hour time weighted averages. The study included a large amount of regression models, nearly all showing statistically significant results in relation to noise, shiftwork and ELF-MF, and their two-way and three-way interactions. Given the effect sizes, sample size and methodology this seems implausible and may indicate residual confounding particularly since potentially important confounders such as alcohol consumption was not accounted for. The statistically significant ELF-MF associations disappeared after adjustment for noise exposure. Two 3-way interactions including ELF-MF are reported, but the study seems underpowered to analyse these, particularly as exposures are based on assumptions that all workers in a job have the same exposure (i.e. the JEM approach), known to have measurement error.

2.1.6 Conclusions on ELF epidemiological studies

An Australian family-based case-control study on occupational ELF-MF exposure and follicular lymphoma did not provide clear evidence of presence or absence of risk.

An Italian case-control study on exposure from overhead power lines and distance to transformer stations and childhood leukaemia reported risk estimates that were not conflicting with previous reports, but that also did not elucidate possible underlying explanations for the results.

A register-based Californian study on proximity to power lines and childhood leukaemia reported that pesticide exposure could be an independent risk factor for the disease, but was unlikely to have confounded previous reports on the association with magnetic field exposures.

Somewhat perplexing, several systematic reviews published during the reporting period mixed different exposures (ELF-MF and RF-EMF) and also different exposure assessment methods and types of outcomes together. Quantitative results from such efforts are not interpretable (Table 2.1).

Table 2.1: Epidemiological studies investigating ELF fields.

Endpoints	Reference	Exposure assessment	Study design, Population	Results
Childhood cancer	Zagar (2023)	Efficient model to assign ELF-MF exposure from 110-400kV overhead power lines and 110kV underground cables to residences.	Registry based study on childhood cancer in Slovenia	Study not informative for childhood cancer as there were too few exposed cases.
Childhood leukaemia	Malagoli (2023)	Distance to power line and field measurements	Case-control study	Proximity to power lines associated with leukemia risk. Few exposed cases and large statistical uncertainty.

Childhood leukaemia	Malavolti (2023)	Residential proximity to transformer stations	Case-control study	No overall association with leukaemia, indications among children > 5 years.. Very few exposed cases and large statistical uncertainty.
Liver enzyme levels	Khosravipour (2023a)	Assessment of long-term exposure to noise, extremely low-frequency electromagnetic fields (ELF-EMF), and shift work	Occupational cohort study	No significant correlations observed between ELF-EMF exposure and liver enzyme levels after adjusting for noise exposure.
follicular lymphoma	Odutola (2023)	Occupational exposure to ELF-MF assessed using a modified INTEROCC job exposure matrix (JEM) based on self-reported job history.	case-control study	No statistically significant association between ELF-MF exposure and follicular lymphoma.
Childhood leukaemia	Nguyen (2023)	Proximity of residence at birth to power line.	Registry-based case-control study.	Previous reported associations with power lines not likely to be confounded by pesticide exposure from plant nurseries.
Reproduction/ birth outcomes	Irani (2023)	ELF and RF mixed	Meta-analysis	Not informative due to mixing of different exposures in the same analyses.
Adverse birth outcomes	Zhou (2023)	ELF-MF exposure assessment with different approaches combined.	Meta-analysis	Combined quantitative analysis of different exposure assessment approaches and different outcomes. Not seen as informative.
Neurodegenerative outcomes	Duan (2023)	Depending on original study.	Meta-analysis	Study tried to map genetic and environmental risk factors for ALS. Unclear how environmental and occupational exposure was combined. Study not informative regarding shocks vs magnetic fields and quantitative results.

ALS onset and progression	Vasta (2023)	Power lines and repeater antenna around residence	Cohort	No observed association. Exposure was dichotomized at the median why most “exposed” are unlikely to have had potentially relevant exposure.
	Mansourian (2023)	ELF-MF and RF-EMF combined from different studies.	Meta-analysis	Not informative.
	Kosek (2023)	Spot measurements 30 and 60cm from devices. Unclear which scenario and how long. Reported exposure unrealistically high (above occupational limits).	Survey among secretaries in a hospital.	Lack of detail and uncertainty around exposure make it unclear how to interpret the results of this study.
Liver hormone levels	Khosravipour (2023b)	JEM based on ELF-MF spot measurements	occupational cohort of male thermal power plant workers	No statistically significant correlations for ELF-MF exposure after adjustment for noise exposure.

2.2 Human Studies

In the last year´s report it was concluded that study participants required a longer exposure time to reach a specific level of precision in a subjective vertical perception task under ELF-MF exposure compared to AC stimulation. In addition, it was reported that combinations of very low field strengths of AC and DC electric fields (e.g. 1kV/m each) were reliably perceived by at least one participant. Finally, detection thresholds were significantly lower with increased AC EF strength, which would highlight the role of AC in human perception of hybrid EFs.

There were two systematic reviews published in 2023, one on possible effects of ELF and mobile phone RF-EMF (Mansourian et al. [37]) and one on biological effects of magnetic storms and ELF magnetic fields (Sarimov et al. 2023 [39]). Since the systematic review of Mansourian er al. (2023) has several methodological flaws, it was briefly summarized under epidemiological studies and not further considered here. In the systematic review of Sarimov et al. (2023) on biological effects of magnetic storms and ELF magnetic fields reported on 96 different studies, most of them cell, animal and epidemiological studies, and only two experimental human studies. Both experimental studies have already been discussed in the SSM report 2021, and due to the lack of further human studies this systematic review did not bring any new insight into the topic.

Navarro and Navarro-Modes [40] (2023) republished their results from Navarro et al. [41] (2016) of the effects of audio frequency magnetic fields (2 kHz and approximately 0.1 µT) on short-term memory (see also SSM report 2017). The data presented in the current publication does not reveal any new insight, authors applied slight changes in the statistical approach (non-parametric vs. parametric) and presentation of the results (no vs. 3 decimal places). The study has some shortcomings that were already discussed in the SSM report 2017, like an (unbalanced) parallel group design.

2.2.1 Conclusions on ELF human studies

In conclusion, the re-publication of a study on audio frequency magnetic fields did not contribute any new findings. The authors reported again a small but negative effect of audio frequency magnetic fields on some parts of the reaction process when conducting a working memory task. It should be mentioned that the design of the study is not suitable to investigate very small effects that can be expected for this type of stimulation. One of the two systematic reviews did not provide new insights regarding ELF human studies, the other systematic review was excluded due to methodological shortcomings (Table 2.2).

Table 2.2: Human studies investigating ELF fields.

Endpoints	Reference	Exposure condition	Sample	Results
Sternberg working memory task	Navarro and Navarro-Modesto 2023	double-blind; randomly applied: Audio frequency magnetic fields (20 Hz - 20 kHz) Sham-exposure duration = 11min each	65 healthy male volunteers Parallel group design: 31 sham exposed: mean age ± SD: 23.6 ± 2.3 years 34 ELF exposed: mean age ± SD: 22.8 ± 2.5 years	No effect on accuracy (mistakes, omissions); no effect on total reaction time; significant changes in part of reaction time
Perception threshold of AC and DC EF	Kursawe et al. (2023)	AC and DC	49 healthy participants	Please refer to Table Static fields

2.3 Animal Studies

Last year’s report on animal studies and ELF exposure reported some adverse effects, in particular related to behavioural effects, development and oxidative stress. These data are in agreement with the previous Council reports.

2.3.1 Rodents

Behavior and Oxidative Stress

In the study by Klimek et al. [42], stress responses to 50 Hz B-field exposure were investigated. A total of 179 adult male Wistar rats were utilized for the study. Two different exposure levels were examined: 1 mT and 7 mT. The animals were exposed for three periods every 3 weeks, with each period consisting of 7-day exposure for 1 hour each day. Following each exposure period, a subset of rats from each group was sacrificed. In the second set of experiments, rats were exposed to a stress factor (open-field (OF) stress) after the exposure to ELF B-field with the same exposure protocol of the previous experiment. All groups (n = 10) had their sham control group for a total of 18 groups. To analyze stress responses, hormone concentrations and the abundance of receptor mRNA transcripts were measured in the hypothalamic pituitary-adrenal (HPA) axis. The results of this study showed that, in the investigated conditions, ELF-B-field exposure activated HPA axis variables in a dose-dependent manner. Additionally, OF stress factor modified HPA axis hormone concentrations and the relative mRNA transcript abundance of their receptors. However, in groups exposed to the B-field, the release of hormones stimulated by OF stress was reduced. This reduction was most notable in the 7 mT EMF group, where the concentrations of all HPA axis hormones induced by OF stress were several times lower than their respective "basal" concentrations.

Kantar et al. [43] examined the effects of 50 Hz E-field exposure (10 kV/m) for 1 hour on stressed Wistar albino rats. Eight different groups (n = 8 each) were investigated: (1) control group, (2) stress group, (3) E-field exposed group, (4) stress and E-field exposed group, (5) 5-HT2CR agonist applied group, (6) 5-HT2CR and E-field exposed group, (7) stress and 5-HT2CR agonist applied group, (8) stress, 5-HT2CR agonist and E-field exposed group. The 5-Hydroxytryptamine, 5HT (5-HT2CR) agonist is a drug activating 5-HT2CR receptor involved in the serotonergic regulation of anxiety. Both behavioral tests and measurements of some stress related physiological parameters were performed such as the measurements of the Loudness Dependence of Auditory Evoked Potential (LDAEP) that is inversely correlated with serotonergic activity. The elevated plus maze (EPM) test evidenced a decrease in open area entries percentage in the stress group successfully reversed with the application of the E-field. The anxiogenic effects of the 5-HT2CR agonist was assessed, but even in this case the exposure to E-fields ameliorated anxiety-like behavior in the group (8) respect the group (7). However, when compared to the group (4), this ameliorative effect was counteracted by the co-administration of the 5-HT2CR agonist suggesting that the anxiolytic effect of E-field exposure is mediated by the inhibition of 5-HT2CR receptor. The social interaction test demonstrated that the E-field exposure did not potentiate the social interaction in stressed and 5-HT2CR agonist applied groups. Contrary, the E-field exposure reinforced the stress induced decrement in social interaction. Through the measurement of the LDAEP this study observed: an attenuation of the stress induced increment of LDAEP by E-field application that also decreased the 5-HT2CR agonist effect, indicating that E-field exposure increased serotonergic tone in stressed rats. Biochemical analyses were performed by measurement of serotonin and glucocorticoid levels: the E-field exposure reversed the stress, induced attenuation in the serotonin level and prevented the 5-HT2CR agonist induced decrement of serotonin. In contrast, E-field exposure attenuated the increment of glucocorticoid level in stressed rats, and even in this case prevented the enhancement of glucocorticoid level in 5-HT2CR agonist applied stressed rats.

Hosseini et al. [44] investigated the effect of ELF B-field exposure (50 Hz, 100 µT) on prenatal stress. A total of 24 female Wistar rats were divided into four groups (n = 6 for each group), namely sham, chronic stress exposure, B-field exposure, and chronic stress plus B-field exposure. The exposure protocol consisted of 21 days of exposure for 4 hours per day before mating and an additional 21 days of exposure for 4 hours per day after mating. Behavioral tests and immunohistochemistry analyses were performed on the offspring. The EPM test showed anxiety-like behavior in all treatment groups compared to the sham group. Moreover, the group simultaneously exposed to chronic stress and B-field exhibited a statistically significant effect compared to the group exposed only to stress. In the OF stress test, the number of center square entries was reduced in both the B-field exposed group and the chronic stress group compared to the sham group. Leaning behavior in the stress group and in the B-field plus stress exposed group was higher than in the B-field exposed group. Immunohistochemistry analyses were performed to examine the expression of synaptic plasticity-associated proteins such as the brain-derived neurotrophic factor (BDNF), GAP-43 (that is a presynaptic secreted protein) and the neural apoptotic factor (cas-3). All treatment groups showed increased expression of cas-3 compared to the sham group and decreased expression of GAP-43 and BDNF. A significant decrease in the number of neurons in the hippocampus was found in all treated groups. In these conditions, the presence of the B-field seemed to increase neurodegeneration and exacerbate the effects of prenatal stress.

Reproduction

Karbalay-Doust et al. [45] studied the effects of 50 Hz 100 µT exposure on the male reproductive system of Sprague-Dawley rats. A total of 60 animals were divided into eight experimental groups, each exposed for different durations: 1 h/d for 52 days, 4 h/d for 52 days, 1 h/d for 5 days, and 4 h/d for 5 days. Each exposed group had its corresponding sham group. A significant decrease was observed in the sperm count and motility in animals exposed for 4 h/d for 52 days, 1 h/d for 52 days, and 4 h/d for 5 days compared to their respective control groups. In the group exposed for 4 h/d for 5 days compared to its sham group, significant reductions were evident in serum testosterone levels, volume of the seminiferous tubules, seminiferous tubule epithelium, and interstitial tissue, along with an 18% reduction in tubule length. No differences were found in the other investigated endpoints.

Cancer

Ji et al. [46] investigated whether B-field exposure can affect breast cancer metastasis *in vivo*. Female BALB/c (nu/nu) nude mice were injected with 5×10^6 MDA-MB231 cells into their tail veins to develop a breast cancer cell metastasis mouse model. The mice were divided into three groups ($n = 12$ for each group) and exposed to a B-field at 4.2 Hz, with sham, 0.1-T, or 0.4-T exposure for 6 h/d, for 136 days. To confirm the health status of the animals, multiple behavioral tests, including the balance beam test, grip test, and OF test, were performed. These tests showed that B-field exposure could improve the motor coordination, muscular strength, and exploratory activity of MDA-MB231–bearing mice. Mice survival was prolonged by 31.5% and 46% in mice exposed to 0.1 T and 0.4 T, respectively. Both 0.1-T and 0.4-T B-field exposures could reduce lung metastasis in a dose-dependent manner, as analyzed with HE (hematoxylin and eosin) and Ki-67 staining, a commonly used marker for cell proliferation in cancer. Additionally, three additional cancer markers, including proliferating cell nuclear antigen and epidermal growth factor receptor, were analyzed, confirming that B-field exposure could inhibit breast cancer metastasis in lung tissues. All the evidenced effects seemed to be dose-response effects.

Immune system

In the study by Gholamian-Hamadan et al. [47], the effects of B-field exposure at 50 Hz at various exposure levels on the humoral immune system in rats were investigated. A total of eighty adult male Wistar rats were equally divided into a sham group and four groups receiving B-field exposure at 1, 100, 500, and 2000 µT. The exposure protocol consisted of 2 hours per day for 60 days. To stimulate the humoral immune response, the rats were immunized with human serum albumin on days 31, 44, and 58 of exposure. Analyses were conducted before immunization and at the end of the exposure period, following immunization. The results of the study indicated that only exposure at 1 µT reduced the expression of the AID gene. Additionally, serum IL-6 levels post-immunization were increased after exposure to 500 µT (no change in serum IL-6 was observed in the pre-immunization phase). However, B-field exposure did not affect the expression of Bcl-6.

2.3.2 Other animal species

Behavior and Oxidative Stress

In Guo et al. [48], the effect of 50 Hz B-field exposure on the spontaneous movement of zebrafish larvae was studied. In this research, embryos were collected at 3 hours post-fertilization (hpf) and exposed to four B-field levels (100, 200, 400, and 800 µT) as well as a sham exposure for either 1 hour or 24 hours every day for 5 days. At 24 hpf, six live embryos from each group were randomly selected to count the occurrences of spontaneous movement. The experiment was repeated at least three times. At 120 hpf, a total of 12 healthy larvae randomly selected from each group were transferred into 96-well plates, and their spontaneous movements were observed. Additionally, after the exposures, 20 embryos from each group were collected and analyzed to evaluate synapsin 2a (syn2a) transcription and expression, as well as the level of reactive oxygen species (ROS). Results indicated that B-field exposure seemed to not affect the basic developmental parameters; only the 200 µT exposed group exhibited significantly induced hypoactivity in zebrafish larvae's spontaneous movement. Analyses of syn2a transcription and expression, and ROS levels were solely conducted on the 200 µT exposure group. The findings revealed an inhibition of syn2a transcription and expression, along with an increase in ROS levels.

Froidevaux et al. [49] performed an observational study on the effects of the presence of very high voltage transmission lines on insectivorous bat activity and foraging intensity. The study employed a paired sampling design, monitoring bats over two years at 25 pairs of sites: a “treatment” site consisting of a forest edge near high voltage transmission lines and a control site consisting of a forest edge nearby (with a minimum distance between sites of 1000 m). According to the provided information, the exposure to high voltage transmission lines was assessed at 3.16 and 4 µT at 30 m from a 220 kV and a 400 kV transmission line, respectively. Bat activity and foraging intensity in foraging habitats seemed to be influenced by the presence of very high voltage transmission lines. Overall, relative humidity mediated the effects of power lines on bats. It was observed that bats were attracted to power lines at high relative humidity levels (i.e., when corona discharges occurred), while they avoided power lines at low relative humidity levels (i.e., when no corona discharges were expected). The authors argued that the increased activity with increasing humidity in powerline sites could be explained by insect aggregation, increasing bat foraging intensity, due to the light emitted by the transmission lines owing to corona discharges while the lower activity in powerline sites compared to control sites might be owing to the physical presence of pylons/cables at foraging height and/or because of the presence of magnetic field. The authors conclude that noise, light, and high-frequency electromagnetic fields resulting from corona discharges appeared to play no role in explaining bats' avoidance of power lines. They do however note that the data do not allow conclusions as to whether the observed activity patterns are due to direct effects on the bats or due to altered insect activity. Also, though the authors endeavored to ensure comparability of powerline and control sites it can not be ruled out that the sites may have differed in other aspects e.g. botanical diversity, which could influence bat or insect activity patterns.

In the study by Montenegro et al. [50], the effects of exposure to a 50 Hz B-field produced by voltage transmission lines on the behavior and other physiological parameters of honeybees were examined. The paper utilized two different exposure conditions: 1) open site exposure, using an area with three active voltage transmission lines as the exposure area and another with three inactive transmission lines as the sham area; 2) B-field and sham exposures in the laboratory, by using a solenoid. For the open site exposure, the hives were exposed for 15 minutes to an active B-field (5 µT at 50 m from the transmission lines). In the solenoid, the B-field was 7.8 ± 0.51 µT, with exposures lasting either 10 seconds or 180 seconds. The study highlighted a significant increase in the heat shock protein (Hsp70) expression levels in honeybees exposed in both open site and the solenoid compared to those sham exposed. For honeybees exposed in the solenoid, the expression of 14 behavioral and stress-response genes was evaluated: significant differential expression was observed for 12 of the 14 evaluated genes between unexposed and exposed honeybees. Additionally, at the open site, it was possible to analyze the behavior of honeybees; it was found that the presence of the B-field impaired the honeybees' flower visiting activity and, consequently, their pollination services to plants.

2.3.3 Summary and conclusions on ELF animal studies

In 2023, 9 papers were published concerning the study of health effects related to *in vivo* exposure to MF or EF at ELF. Except for a single paper addressing exposure to 4.2 Hz magnetic fields [36], the others involved medium- or long-term exposure to MF or EF at 50 Hz. Six studies focused on experiments conducted on rodents, observing various endpoints: behavior and oxidative stress (3 papers), reproduction, cancer, and immune system (one article each). Regarding the effects on behavior and oxidative stress, exposure to EF at 10 kV/m appears to reduce anxiety behavior alongside an increase in serotonin levels and a decrease in cortisol levels. Conversely, exposure to MF appears to increase anxious behavior in exposed animals.

Only one paper concerned the study of MF exposure at 100 µT on the reproductive system of rats: in the examined conditions the ELF-MF exposure seemed to reduce spermatocyte count and motility and to induce structural changes in testicular tissue.

Only one study investigated the effect of 4.2 Hz MF exposure on mice injected with 5×10^6 MDA-MB231 cells to develop a breast cancer cell metastasis mouse model. Mice survival was prolonged by 31.5% and 46% in mice exposed to 0.1 T and 0.4 T, respectively (dose-response effect), Moreover both exposure levels could reduce lung metastasis in a dose-dependent manner.

The effect on humoral immune system of ELF-MF exposure (from 1 µT up to 2000 µT) was analyzed: The exposure to a B-field of 1 µT seemed to significantly decrease the expression of AID gene at in contrast the MF exposure at 500 µT could increase serum IL-6 and activate the differentiation of B cells to plasma cells enhancing humoral responses.

Regarding other animal species, the conducted studies have shown that 50 Hz MF exposure appears to influence the normal behavior of zebrafish, bats, and honeybees, with sporadic increases in ROS levels and ↑ Hsp70 expression levels.

Summarizing, the very different animal models describing dissimilar effects following ELF-MF exposure in the 7 mT range and below demonstrates again the absence of knowledge on biological-relevant effects of ELF-MF, except on oxidative stress and behavior (Table 2.3).

Table 2.3: Animal studies investigating ELF fields.

Endpoint	Reference	Exposure ELF MF/EF	Exposure Duration & Species	Effect of ELF exposure
Rodent Studies				
Behavior & Oxidative Stress	Klimek et al [32]	50 Hz 1 mT and 7 mT	1 h/d for 7 days Three exposure periods every three weeks Male adult Winstar rats	Dose dependent effects on the hormone concentrations and receptor mRNA abundance of the HPA axis. The effect depends on the number of exposures also.
	Kantar et al [33]	50 Hz 10 kV/m	1 hour Wistar rats	↓anxiety behavior and attenuated the LDAEP responses in stress and/or 5-HT2CR receptor agonist applied groups. ↑serotonin levels ↓glucocorticoid levels
	Hosseini et al [34]	50 Hz 100 μT	4 h/d for 21 days before mating 4 h/d for 21 days after mating Wistar rats	↑anxiety-like behavior in all treatment groups ↑neurodegeneration hippocampus. The presence of the B-field exposure exacerbates the effects of the prenatal stress.
Reproduction	Karbalay-Doust et al [35]	50 Hz 100 μT	1h/d for 52 days 4h/d for 5 days 1h/d for 5 days 4h/d for 52 days Male Sprague Dawley rats	↓ Both count and motility of sperms in the groups exposed 1h/d and 4 h/d for 52 days and 4h/d for 5 days. In the group exposed for 4 h/day for 5 days: ↓Serum testosterone levels, ↓The volume of the seminiferous tubules, seminiferous tubules epithelium and interstitial tissue, ↓Tubules length.
Cancer	Ji et al [36]	4.2 Hz 0.1 T 0.4 T	6 h/d for 136 days Female BALB/c nude mice	↑ survival in exposed groups ↓Lung metastasis
Immune system	Gholamian-Hamadan [37]	50 Hz 1 μT 100 μT 500 μT 2000 μT	4 h/d for 60 days Wistar male adult rats	↓expression of the gene AID @ 1 μT. ↑ serum IL-6 at the post immunization @ 500 μT. no change in serum IL-6 was observed in the pre-immunization phase. Unchanged the expression of Bcl-6
Other Species				
Behavior and Oxidative Stress	Guo et al [38]	50 Hz 100 μT 200 μT 400 μT 800 μT	1 h/d for 5 days 24 h/d for 5 days Zebrafish embryo	No effects on development. Inhibition of spontaneous movement at 200 μT.

				Downregulation of some neurodevelopment-related genes @ 200 μT. ↑ ROS level
	Froidevaux et al [39]	Exposure to very high voltage transmission line (3.16 – 4.3 μT @ 30 m from the line)	117 detector nights over two years. Bat	Bat activity and foraging intensity are affected by the presence of high voltage transmission lines. Bat attraction to power lines at high relative humidity levels and avoidance of power lines by bats at low relative humidity levels.
	Montenegro et al [40]	Open site exposure: 5 μT @ 50 m from voltage transmission lines Solenoid exposure: 7.8 ± 0.5 μT	Open site exposure: 15 min Solenoid exposure: 10 s and 180 s Honeybees	↑ Hsp70 expression levels in exposed honeybees (both open site and solenoid exposure). ↓Exposed honeybee flower visits. Effects on natural pollination.

Abbreviations: ↑=increase(d); ↓=decrease(d); HPA: hypothalamic-pituitary-adrenal; LDAEP: Loudness Dependence of Auditory Evoked Potential; 5-HT2CR: 5-Hydroxytryptamine, 5HT; AID: Activation-Induced-Deaminase; Bcl-6: B-cell lymphoma 6; ROS: Reactive Oxygen Species; Hsp70: Heat shock protein 70

2.4 Cell Studies

One study highlighted the influence of ELF-EMF exposure during early pregnancy on molecular markers within the porcine myometrium. Two separate studies conducted on various human cell types shed light on the biological impacts of exposure to ELF-EMF on DNA damage, gene expression, proteomic profiles and oxidative stress response. The differentiation of B-cells from hematopoietic stem/progenitor cells was achieved in the context of childhood leukemia. In comparison to the previous Council report, a lower number of publications was identified for the reporting year 2023.

2.4.1 Epigenetic

Previous findings from by the same research group (Drzewiecka et al. [51]) suggested that exposure to an extremely low-frequency magnetic field (ELF-MF) triggers molecular changes in the porcine myometrium (middle layer of the uterine wall). The hypothesis was that this field could influence the epigenetic control of gene expression in the myometrium. In this present investigation, slices of porcine myometrium taken on days 15-16 of pregnancy (peri-implantation period) were subjected to *in vitro* exposure to ELF-MF (50 Hz, 8 mT, 2 h) or not (n=4) (Franczak et al., 2023). The study aimed to explore whether ELF-EMF exposure affects: 1) the expression of enzymes involved in DNA methylation (DNA (cytosine-5)-methyltransferase 1 (DNMT1) and DNA (cytosine-5)-methyltransferase 3a (DNMT3a)), 2) the levels of genomic DNA methylation, and 3) the amplification levels of methylated and unmethylated variants of promoter regions of specific genes with altered expression due to ELF-MF exposure. The results revealed that ELF-MF treatment led to an increase in DNMT1 expression, a decrease in DNMT3a mRNA transcript and protein abundance, and an elevation in genomic DNA methylation levels. Changes in the amplification levels of methylated and unmethylated variants of selected gene promoter regions, including prodynorphin (PDYN), interleukin 15 (IL15), signal transducer and activator of transcription 5A (STAT5A), and tumor necrosis factor (TNF), as well as down-regulated genes such as early growth response 2 (EGR2), hyaluronan and proteoglycan link protein 1 (HAPLN1), and uteroferrin associated basic protein-2 (UABP2), largely aligned with alterations in their transcriptional activity, as evaluated in a previous study. According to the authors, ELF-MF radiation disrupts epigenetic mechanisms, potentially contributing to ELF-MF-related changes in gene expression in the myometrium.

2.4.2 Proteomic

The study of Lazzarini et al. [52] examined the effects of ELF-EMF exposure (50 Hz, 1 mT for 4 h) on cell viability, cellular morphology, oxidative stress response, and proteomic profiles in breast cancer cells (MDA-MB-231), with non-tumorigenic human breast cells (MCF-10A) serving as controls. Analysis were done 4 days after exposure on triplicate, repeated 3 times. Results showed that ELF-MF exposure increased the viability and live cell count of MDA-MB-231 breast cancer cells, along with exhibiting higher density and length of filopodia compared to unexposed cells. Moreover, ELF-MF induced elevated levels of mitochondrial reactive oxygen species (ROS) and altered mitochondrial morphology. Proteomic analysis revealed alterations in the expression of 328 proteins in MDA-MB-231 cells and 242 proteins in MCF-10A cells upon ELF-MF exposure. Gene Ontology term enrichment analysis highlighted upregulation of genes associated with "focal adhesion" and "mitochondrion" in both cell lines following ELF-MF exposure. Furthermore, ELF-MF exposure reduced the adhesive properties of MDA-MB-231 cells while enhancing their migration and invasion abilities. Proteomic analysis, corroborated by Real Time PCR, indicated upregulation of transcription factors linked to cellular reprogramming in MDA-MB-231 cells and downregulation in MCF-10A cells post-ELF-MF exposure.

2.4.3 Genotoxicity

Nguyen et al. [53] aimed to investigate the impact of long-term *in vitro* ELF-MF exposure on three specific endpoints: cell viability, genetic damage, and susceptibility to damage induced by known mutagens, using the human B lymphoblastoid cell line (TK6). The cells underwent exposure to 50 Hz MF at three distinct magnetic flux densities (10, 100, and 500 μT) for varying periods, ranging from 96 h up to 6 weeks. Cell viability post-exposure was gauged through an ATP-based assay (n= 3), while the alkaline comet assay (n= 4) and cytokinesis block micronucleus assay (CBMN) (n= 3) were employed to assess MF exposure effects on genetic damage and sensitivity to mutagen-induced damage, respectively. Results indicated a significant increase in TK6 cell viability following exposure up to 96 h to 50 Hz MF at all tested flux densities compared to non-exposed control cells. However, no discernible impact on cell genetic damage was observed with long-term MF exposure, and prior MF exposure did not alter cell sensitivity to damage induced by known mutagens (ethyl methanesulfonate (EMS; 0.25 mM) in the comet assay and methyl methanesulfonate (MMS; 2 μg/ml) in the CBMN assay). While statistically significant discrepancies in genotoxicity test outcomes were noted between MF-exposed cells and controls at specific time points, these findings could not be consistently replicated in repeat experiments, suggesting they may lack biological significance.

2.4.4 B-cell differentiation

Acute B-lymphoblastic leukemia, the most prevalent form of childhood leukemia, arises from abnormal B-cell proliferation during early differentiation. In this study, Takahashi & Furuya [54] focused on understanding the impact of 50 Hz MF exposure on B-cell early differentiation. Initially, the authors refined an in vitro differentiation protocol for human hematopoietic stem/progenitor cells (HSPCs) into B-cell lineages. After confirming the protocol's responsiveness to additional stimuli (lipopolysaccharide LPS or interleukin type-7 IL-7 treatment) and ensuring consistent experimental conditions, human HSPCs were subjected to continuous exposure to 300 mT of 50 Hz MF over a 35-day differentiation period (except for twice weekly medium changes). These experiments were conducted in a blinded fashion. The proportions and differentiation stages of myeloid and lymphoid cells, ranging from pro-B to immature-B cells, in the MF-exposed group exhibited no significant differences compared to those in the control group (n=6). Additionally, the expression levels of recombination-activating genes 1 (RAG1) and RAG2 (contributing to genetic diversification of the immunoglobulin genes) in B cells mirrored those of the control group (n=6). These findings suggest that exposure to 50 Hz MF at 300 mT does not influence early B-cell differentiation from HSPCs in humans.

2.4.5 Conclusions on ELF cell studies

The report incorporates findings from four in vitro studies examining the impact of ELF-EMF exposure. Specifically, it reveals that ELF-EMF exposure disrupts epigenetic processes in the porcine myometrium, alters the expression of DNA methylation-related enzymes, correlates with changes in gene expression, and triggers proteomic alterations along with an increase in cell viability. Furthermore, it indicates no significant effects on differentiation stages or gene expression in B cells. These findings enhance our understanding of potential impacts from ELF-MF exposure across various cellular contexts (Table 2.4).

Table 2.4: Cell studies investigating ELF fields.

Cell type	Endpoint	Exposure conditions	Effect	References
Porcine myometrium slices n=4	Epigenetic	50 Hz, 8 mT, 2 h	Disruption of epigenetic mechanisms	Franczak et al, 2023
Breast cancer cells (MDA-MB-231), non-tumorigenic human breast cells (MCF-10A) Triplicate, repeated 3 times	Cell viability, morphology, oxidative stress	50 Hz, 1 mT, 4 h	Alterations in proteomic profiles, changes in cell viability, morphology, oxidative stress response, adhesion, migration, and invasion abilities in MDA-MB-231 breast cancer cells.	Lazzarini et al., 2023
Human B lymphoblastoid cell line (TK6) n=3	Cell viability, genetic damage, and susceptibility to damage induced by known mutagens	50 Hz, 10, 100, and 500 µT, 96 h up to 6 weeks	Significant increase in cell viability following exposure up to 96 h to 50 Hz MF at all tested flux densities. No	Nguyen et al., 2023

			impact on cell genetic damage, and prior MF exposure did not alter cell sensitivity to damage induced by known mutagens	
Human hematopoietic stem/progenitor cells (HSPCs) n=6	B-cell early differentiation	50 Hz, 300 mT, 35 days	No influence on early B-cell differentiation from HSPCs in humans.	Takahashi & Furuya, 2023

3 Intermediate frequency Fields

3.1 Epidemiological Studies

The previous reports stated that given the very scarce scientific literature on exposure to IF-MF and possible health effects, no conclusions could be drawn. Last year, no study was identified and therefore the same conclusion applied.

Sato et al. [55] analysed if using induction heating cookers during pregnancy affected gestational age at birth or birth weight of their offspring. The study was performed in Japan between 2020 and 2021 among 8920 pregnant members who had agreed to participate in market research panels for an internet company. Post-partum follow-up surveys were performed between 2020 and 2022. In the baseline questionnaire, details about induction cookers and their usage were asked; also gestational age and birth weight, as well as a range of potential confounders, such as maternal age, smoking status, alcohol intake, educational level and recurrent foetal loss. The authors describe that there are three usual induction cooker types available in Japan: In-built, stationary, and tabletop, all types use similar power levels and work in the 20-90 kHz range. Postpartum questionnaires (61% participation rate) inquired about hypertensive disorders during pregnancy, gestational diabetes, foetal growth restriction, delivery method, gestational age at delivery, child sex and birth weight. From these, 5022 women with a singleton birth were included into the final analysis. Logistic regression analysis was used to analyse associations between gestational age at birth (<37 vs >=37 weeks) and low birth weight (<2500g vs >=2500g) and induction cooker use, adjusted for the above listed potential confounders. Both outcomes were reported by roughly 8% of the mothers. Results were presented unadjusted and stratified by trimester and by induction cooker type. Because for two of the induction cooker types (stationary and tabletop), there appeared to be associations with gestational age at birth during the first and second trimester, these associations were further explored in logistic regression analyses. OR were elevated for induction cooker use for these two types of cookers, and for first and second trimester use; OR varied between 1.27-1.44 and were all statistically significant.
It is unclear why the authors separated all analyses by cooker type, and in how far the analysed cooker types actually translated into different exposure levels of users. The shown tables make it unclear which population was used as the comparator between the different cooker types, and if women not using any of the cooker types were the only ones in the unexposed group. While the initial tables showed data by amount of usage of the respective cooker types, such an analysis was not used for the adjusted logistic regression analysis. It would have been of interest to also show adjusted odds ratios for birth weight, even though these were likely not statistically significant. Strength of the study include that the exposure was assessed during pregnancy (before women knew about the respective outcome), and the follow up on gestational age and low birth weight, as well as the availability of a range of potentially confounding variables. Weaknesses of the study include a relatively large proportion of dropouts between the baseline and post-partum questionnaire, which could relate to birth outcome and also to exposure, if IF influences foetal development. Further limitations included self-reported outcome data, lack of true exposure data available, and the question if results are generalisable to the general public. The authors conclude that in light of all considerations, the increased odds ratios did not indicate increased risks of premature births. This conclusion in itself is somewhat surprising, as the authors present reasoning, but no data, of residual confounding or other biases that could be underlying the reported risks. Given the relatively high foetal exposures (due to the position in the body) during the use of induction cooking, as well as the

general scarcity of epidemiological studies addressing intermediate frequency exposures, the observation reported here remains of interest.

3.1.1 Conclusions on IF epidemiological studies

This year, one study from Japan investigated whether exposure of pregnant women to induction cooking could affect birth outcomes, in particular gestational age and low birth weight. While the authors concluded that the increased odds ratios observed in their study did not indicate increased risks of premature birth, the observations reported here remain of interest. This is because of the relatively high exposures experienced by the foetus, and the scarcity of epidemiological studies on the matter (Table 3.1).

Table 3.1: Epidemiological studies investigating IF fields.

Endpoints	Reference	Exposure assessment	Study design, Population	Results
Premature birth	Sato et al 2023	Exposure from induction cookers	8920 pregnant women participating in market research panel. Follow-up surveys to assess birth outcomes.	Elevated odds ratios for 1st and 2nd trimester use of stationary and tabletop induction cookers were observed which the authors interpreted as no indication of increased risks.

3.2 Human Studies

As for the previous reporting periods, there was no human experimental study in the intermediate frequency range.

3.2.1 Conclusions on ELF human studies

No study on intermediate fields was published in 2023.

3.3 Animal Studies

Last year only one study was reviewed in the section animal studies and IF exposure . In this study in rats, exposure to 150 kHz (0.3 V/cm) resulted in slight adverse effects on some fertility parameters and alteration of hormonal balance.

3.3.1 Rodents

Physiology & Pathophysiology

In the study by Othani et al. [56] the *in vivo* genotoxic effects on mice exposed to an electric field (EF) of 87 V/m at 82.3 kHz were investigated. C57BL/6JJ mice were exposed 90 seconds per day for either 1 day or 7 days. Different endpoints were considered: the micronucleus (MN) test and the *gpt* assay in the mice germ cells and the MN test and the *Pig-a* assay on the mice hematopoietic cells. The number of mice in each analyzed group was always ≤ 6. Under these conditions no genotoxic effects were observed in the IF field exposed groups compared with the sham-exposed groups.

Sundaran et al. [57] investigated the effects of IF field exposure (150 kHz) on the vital organs of female Sprague Dawley rats. A total of 20 rats were divided in two groups (*n* = 10 for each group): a sham exposed group and an IF field exposed group at 65 ± 15 μW/cm^2, 24 h/d for two months. Hematological, histochemical and histopathological profiles of all major organs of all animals were performed. The results of this study showed that all major organs showed no significant effects across the examined biological endpoints, in either the sham or exposed groups. Only liver and lung showed inflammatory changes without significant biochemical/hematological manifestations. Only a significant increase in serum sodium level and a decrease in serum urea level were observed in the exposed group (Table 3.3).

Table 3.3: Animal studies investigating IF fields.

Endpoint	Reference	Exposure IF Fields	Exposure Duration & Species	Effect of the exposure to IF fields
Rodent Studies				
Physiology & Pathophysiology	Ohtani et al. [56]	87 V/m @ 82.3 kHz	90 s/d for 1 day or 10 days C57BL/6JJ mice	No *in vivo* genotoxic effects
	Sundaran et al. [57]	65 ± 15 μW/cm^2 @ 150 kHz	24 h/d for two months Female Sprague Dawley rats	↑ in serum sodium level. ↓ in serum urea level. The exposure seemed to trigger changes in the liver and lungs, but it was not sufficient to cause clinical and functional manifestations.

Abbreviations: ↓=decrease; ↑=increased;

3.4 Cell Studies

As for the previous reporting period, no *in vitro* studies on intermediate frequency range were found.

4 Radio Frequency Fields

4.1 Epidemiological Studies

Last year, two large studies reported a few associations between different aspects of mobile phone use and some semen quality parameters, although the majority of analyses did not indicate increased risks. It was concluded that this might represent chance findings due to the high number of analyses, but needed follow-up investigations.

A prospective cohort study from the Netherlands indicated that EHS was not a very stable attribution and often changed over time, even if the overall proportion in the population may remained constant.

An Iranian study found a decrease of blood pressure in relation to mobile phone use in women but not in men. Given the lack of mechanism and lack of supporting data from other studies, this may have been a chance finding or due to residual confounding.

4.1.1 Adult cancer

Shapira et al. [58] investigated RF-EMF exposure and malignancy risk in Israeli Army (IDF) members. They included all 4157 soldiers serving in air defence units between 2009 and 2018 and sampled a comparison group (n=12113) of other members of the IDF. The groups differed in a range of aspects including proportion serving in combat units, length of education and gender composition. Therefore a 1:1 matched control population was sampled from among these persons. The authors state that the control group was selected to not have occupational non-ionizing radiation exposure and to have similar exposure to chemicals including fuels and solvents. It is unclear how this was ensured. RF-exposure was not qualified except to state that IDF uses radar frequencies in the 2-300 GHz range, regulated to stay within ICNIRP guidelines. With an average follow-up time of around 4.7 years, participants were followed up for cancer in a national cancer registry until 2018 yielding a total of 41 cancers, 13 in the exposed group. Logistic regression showed no statistically significant differences between those considered exposed and the full or the matched control group for total cancer or for specific tumour groups. The authors conclude: "In this study, occupational exposure to non-ionizing radiation did not increase the risk for cancer in young adults during the 9-year follow-up, as compared with unexposed individuals."
Study limitations include few cancer cases, short follow-up, and insufficient exposure assessment. It is unclear how many of the "exposed" groups were relevantly exposed and it is unclear how they might differ regarding other potential exposures. These limitations could obscure associations and would make it difficult interpret associations, had they been seen.

Gao et al. [59] conducted a Mendelian randomization study to identify modifiable risk factors for benign salivary gland neoplasms (BSGN). That is, they identified specific genotypes (Single nucleotide polymorphisms, SNPs) that were more frequent in people with each of the behavioural risk factors they investigated and then they tested if people with these genotypes were more likely to develop BSGN. In theory this method eliminates the possibility of reverse causation as the genotypes are constant since conception and therefore not influenced by lifestyle. The genotypes associated with each investigated factor were identified from large publicly available databases. For mobile phone use, self-reported data from UK-biobank on years of using a mobile phone >1 week (<1,2-4,5-8,9+ years) were used. The associations of the identified genotypes and BSGN was investigated in the Finish FinnGen data with 2445 BSGN cases and 340,054 controls. The authors

found smoking and BMI to be associated with BSGN, whereas they found no association for years of mobile phone usage, radiation related skin damage, alcohol consumption or periodontitis. The authors conclude: "In summary, our study supported the independent causal role of lifetime smoking index (long-term heavy smoking) and BMI in BSGNs risk but found no evidence of an association between length of mobile phone use, radiation-related skin disorders, alcohol consumption, periodontitis, and BSGN risk.
Mendelian randomization studies have three main assumptions 1: that the identified genotypes are associated with the exposure of interest. 2: the genotypes are not associated with confounders of the exposure outcome relationship. 3: the genotypes are only associated with the outcome via the exposure under investigation. It seems unlikely that any particular genotype will specifically code for early mobile phone usage. More likely certain genotypes will be associated with lifestyles that increase likelihood of early mobile phone usage and it seems plausible that such lifestyle could also affect other aspects of BSGN risk. The assumptions of the Mendelian randomization study may thus have been violated. Additionally, the use of years since first use as exposure metric, without also considering intensity of use, is likely to have reduced the study's power to detect any association. A final possible concern relates to UK-biobank data. This is a volunteer cohort, that is not genetically representative of the general UK population. This has been demonstrated to influence results of mendelian randomization studies [60]. This issue may even be aggravated when the information is applied to the genetically distinct Fins.

Zhang et al. (2023a) [61] used UK-Biobank data to investigate the association of mobile phone use with cancer in people aged 38-73 at enrolment (2006-2010). At enrolment, participants (n=431 861) provided data on age, Townsend deprivation index, race, educational levels, BMI, smoking status, alcohol drinking, healthy diet scores, physical activity, sedentary behaviour, total mental health complaints, comorbidity, family history of cancer, use of NSAIDs, use of dietary supplement, menopausal status, age at menarche, number of live births, oral contraceptive pill use, and hormone replacement therapy use. As well as skin colour, skin reaction to sun exposure, hair colour, sun or UV protection use, and solarium use. Participants also answered if they used a mobile phone at least weekly (n=367 033 defined as regular use), and if so, how much time they talked on it and for how many years (<=1, 2-4, 5-8, 9+ years). Participants were followed up for cancer in mortality, hospitalization, and cancer registers until an unprovided date, but with a median follow up time was 10.7 years. During this time 35,401 and 30,865 primary cancers were diagnosed in males and females respectively. Using Cox regression models with adjustment for abovementioned factors, they investigated overall cancer as well as glioma and the 25 most common cancer sites in each sex. Compared to non-users (<1 call/week), mobile phone users (≥1 call /week) had higher HR for overall cancer, 1.09 (95%CI: 1.06-1.12) and 1.03 (1.00-1.06) In men and women respectively. Non-melanoma skin cancer was also associated with mobile phone use in both men and women. Prostate cancer was associated in men and vulva cancer in women. Urinary tract cancer risk was elevated in men but with no evidence of elevated risk in women. In analyses restricted to mobile phone users, years of use showed positive dose response for overall cancer and non-melanoma skin cancer in both sexes and prostate cancer but not urinary tract or vulva cancer. In analysis of length of calls, use of hands-free devise or side of head when using a phone, the only association was for right sided use and risk of non-melanoma skin cancer in men, but not women. The authors argue that the skin is the first organ to be exposed to radiation from a mobile phone and that the prostate is close to phone carried in a pocket and that duration of use may be more important than dose, since they see no association with total length of calls. The authors conclude: "there was a positive dose-response relationship between length of mobile phone use and risk of incident NMSC in both men and women and prostate cancer in men. The potential association of mobile phone use with the risk of urinary tract cancer in men and vulva cancer in women needs to be further verified."

The study investigated a selection of tumours chosen for frequency and not due á priori hypotheses about association with mobile phones. For some of these tumours, associations were observed even when simply comparing non-users and users (>=1 call/week) where of many may not have plausibly relevant exposure levels. Some chance findings are to be expected when performing this many analyses. Furthermore, despite the impressive array of confounders, residual confounding may have influenced the results. Confounders and use of mobile phones were only assessed at baseline and in relatively crude categories and users were different from non-users in several lifestyle parameters and a possible explanation for the apparent dose response could therefore be if year of first mobile phone use was associated with lifestyle factors not sufficiently accounted for in the analysis. For overall cancer and non-melanoma skin cancer, adjusted risk estimates where closer to the null than unadjusted, indicating confounding, and it cannot be ruled out that residual confounding may be affecting the results. For vulva cancer, there was little effect of confounders included but the absence of any dose response indicates that mobile phones are not causal. A possible cause for the observed association might be HPV infection which was not adjusted for but could conceivably be associated with a lifestyle associated with earlier use of mobile phones as indicated by the higher use of oral contraceptives among mobile phone users. For prostate cancer there was apparent dose response with years since first use. Lifestyle factors are the primary causes for prostate cancer and additionally prostate cancer may go undetected for a long time, meaning that if early mobile phone users were more likely to be diagnosed this would appear as an association in data. Regarding potential confounders, it should also be noted that the UK-biobank is a self-selected cohort and that the association of mobile phone use with potential confounders may be skewed if both factors are associated with likelihood of participating in UK-biobank. It is unclear why urinary tract cancer is singled out in the conclusion. The association was only seen in men and with no evidence of an exposure -response relationship. This, as well as the other associations in this study, seems unlikely to be a causal association.

Vijayan et al. [62] performed a meta-analysis of the risk for salivary gland tumours in mobile phone users. They identified seven retrospective case-control studies, with a total of 1247 cases and 8935 controls. In meta-analysis the combined OR was 1.06 (95%CI: 0.86-1.32) with no evidence of publication bias. There were also no statistically significant association in analyses stratified by malignant or benign tumours, analogue or digital phones, ipsi- or contra-lateral use, or years of usage. The authors conclude "This meta-analysis found no significant association between mobile phone usage and salivary gland tumours. However, these results were susceptible to selection and recall bias, and were predicated on poor exposure assessment, precluding firm conclusions from being drawn. Instead, this warrants well-designed prospective studies with correct exposure assessment investigating the long-term effect of mobile phone use."

Moon [63] compared age standardized brain tumour incidence rates (ASIR) in the period 1999-2018 and number of mobile phone subscriptions in South Korea in the period 1985-2019. Cancer data were obtained from a national register, while subscription rates were obtained from operator data. South Korea, like other countries, saw a significant rise in subscription holders over the study period. The ASIR of benign CNS tumours increased over the study period, as did the ASIR for brain tumours situated in cerebrum, frontal lobes, or temporal lobe. Tumours of the spinal cord, cranial nerves, and other parts of the CNS (C72) also increased over the study period. For meningioma and unspecified tumours of the brain the ASIR decreased over time. Together all tumours of the brain showed no increase over time. In general, tumour groups with increasing ASIR where positively correlated with mobile phones and tumours with decreasing ASIR were negatively correlated. The exception was C72, where the change in ASIR was very small and there was no correlation.

The authors suggest that improved diagnostics may explain the rise in benign tumours, but not malignant ones, since the latter would eventually be detected due to their growth. They propose the increase of tumours in areas most exposed to phone radiation supports a possible association with use of mobile phones.
Overall, the incidence trends in this study agree with what has been observed in previous incidence trend studies, which have in general been interpreted to indicate a lack of a strong or general association with mobile phones. As pointed out by de Vocht 2023, the authors argument that increased surveillance and improved diagnostics and classification cannot explain the increase malignant tumours groups fail to consider that these factors could change and improve classification of tumours. This effect is also indicated by the present results where the decreasing incidence of unclassified brain tumours match the increase in other sites leading to a constant ASIR for brain tumours in total. A general limitation of incidence tend studies is the inability to detect small risk increases or risks restricted to small subgroups of the total population. Apart from the general caveat that correlation does not equal causation, the analysis of subscriptions data is limited by the lack of details on age or sex of users.

Kadeh [64] investigated buccal mucosa micronuclei in 50 Iranian mobile phone users aged 20-38. While the method of participant recruitment is not specified, it is noted that individuals were screened to exclude alcohol or tobacco use, oral mucosa lesions, systemic diseases, occupational chemical exposure, or radiation exposure within the past two months. Data on participants' age, gender, BMI, and mobile phone usage patterns (years of use, weekly hours of use, use of headphones, and preferential side of head use) were collected via a questionnaire. Buccal mucosa cells were sampled from both cheeks of all participants, with the cheek corresponding to the side of the head used for mobile phone calls considered as the exposed side. Individuals who reported equal usage of both ears when using a mobile phone were excluded from the analysis. Using two different staining methods, the researchers found no statistically significant differences in the mean number of micronuclei based on various mobile phone usage characteristics. The authors conclude “This study showed that cell phone use does not cause genotoxic effects in the buccal mucosa in the oral cavity.”
It is noteworthy that in all comparisons, the standard deviation of the mean was either larger or similar in size to the mean itself. This suggests a high degree of variability within the data. Therefore, if the association with mobile phone use was only weak, larger study populations would be necessary to reliably detect such an association.

4.1.2 Childhood cancer

Lim et al. [65] performed a systematic review of health effects of RF-EMF in children. They identified 13 studies on cancer, 8 on birth outcomes, 19 on neurocognitive development, and 11 on behavioural problems. They found no conclusive evidence associating these endpoints with near (mobile phones) or far field (antennae) exposure and caution that studies “should be interpreted with caution due to the possibility of reverse causality, confounding or mediation of behavioural/environmental factors, and exposure misclassification.” The authors particularly highlight the need for better exposure assessment in future studies.

Kojimahara et al. [66] investigated mobile phones and risk of brain tumours in 118 cases and 236 matched controls, aged 10-24, from South Korea and Japan. The study was based on the MOBI-kids study but included all intracranial tumours of the brain or meninges, including also the deeper and therefore unexposed regions of the brain, to compensate for very low number of cases. Cases were recruited from 15 Korean (52 case) and 31 Japanese (66 cases) hospitals. The exact tumour location within the brain was established from 3D models. For each case, two controls, post hoc matched on age, sex and area of residence, were selected from patients hospitalized with appendicitis in the same hospitals. Use of mobile phones until one year prior to diagnosis was obtained from computer assisted interviews and location specific RF energy absorption (J/kg) was established with the MOBI-kids algorithm; modified to better reflect Korean and Japanese conditions. The model considers cumulative call time, phone type, mobile phone technology and other factors such as adaptive power control. The algorithm did not include information on use of headsets, occupational exposures, or exposure from DECT phones. Mobile phone use was more common in Korea than Japan (95% vs 70%) and Korean users made far more calls than Japanese. Conditional logistic regression models, controlling for country and maternal education, were used to compare tertiles of cumulative call time, and energy absorption in relevant brain hemisphere, at site of the tumour and at centre of gravity of the tumour. There was no indication of association for exposure by hemisphere or at the tumour centre of gravity. Being in the highest tertile of exposure for cumulative call time (258-18,760 minutes) or for energy absorption in the tumour (energy levels not provided), was associated with ORs of 1.61 (95%CI: 0.72-3.60) and 1.33 (95%CI: 0.61-2.89), respectively. In all cases confidence limits were wide and there was no significant trend across exposure categories.
Looking specifically at the 46 glioma cases and their controls, higher exposure tended to be associated with lower risk estimates with significant negative trends for centre of gravity and hemisphere absorption. The authors conclude "our findings suggested that mobile phone use does not greatly impact the development of brain tumours".
As acknowledged by the authors, the low number of cases is a major limitation wherefore, they included also tumours from unexposed regions of the brain. In the MOBI-kids study, sub-analyses revealed potential biases relating to participation and recall. These are general limitations of case-control studies and are likely to have affected this study as well, but participation rates or other data to evaluate this are not reported.

Morales-Suarez-Varela et al. [67] published a study entitled "Relationship between parental exposure to radiofrequency electromagnetic fields and primarily hematopoietic neoplasms (lymphoma, leukaemia) and tumours in the central nervous system in children: a systematic review." They performed a systematic literature search, and identified 13 case control studies, 2 cohort studies and 2 meta-analyses published in English between 1990 and 2021. These were narratively summarized, and the authors conclude that the body of evidence does not allow a conclusion about the relationship between parental exposure and the occurrence of childhood tumours.

4.1.3 Fertility, reproduction and child development

Kashani [68] systematically reviewed and meta-analysed studies regarding parental exposure to extremely-low frequency, radiofrequency fields, and ionizing radiation (x-ray examination during pregnancy), and a wide range of foetal and childhood developmental disorders and risk of cancer. Overall, 14 studies published between 2001-2019 were included. The authors presented meta-analysed results stratified by frequency range/technology (but still combining very different exposures e.g. mobile phone use (near field) and broadcast (far field)) for any health outcome. For most exposures, it remains unclear if parental exposure also included paternal, or only maternal exposures, and how these differences were handled when combining studies. In addition, when presenting results per health outcome, exposure was combined across all exposure groups. Given very different underlying mechanisms, the quantitative results of the meta-analyses unfortunately are not informative.

Rahban et al. [69] conducted a cross-sectional study in Switzerland to evaluate associations between mobile phone use and male fertility in the general population. All Swiss men aged 18-22 are evaluated for conscription and during the years 2005-2018, 2886 men were recruited (3.1% of those originally invited). Study participants, regardless of whether they passed the conscription fitness tests, delivered a semen sample to a nearby andrology laboratory where they also underwent a physical examination by a trained urologist and weight and height were measured. Sperm concentration, total sperm count, and sperm motility were recorded. Participants also answered a questionnaire on health and lifestyle. The questionnaire also covered frequency of mobile phone use (as <1 per week, 1-5 per day, 5-10 per day, 10-20 per day, and >20 times per day) and where the phone was kept when not in use (not kept at body, kept in jacket pocket, kept in trousers pocket). Multivariable logistic and linear regression models were adjusted for BMI, alcohol consumption, smoking, educational level, maternal smoking during pregnancy, cryptorchidism, varicocele, abstinence, recruitment center, year, and season, as well as 'time before motility analysis' for sperm motility models. Missing data were imputed using MICE.
The researchers reported that compared to using the phone 1-5 times / day, highest frequency of mobile phone use (>20 times per day) was associated with lower sperm concentration, but this did not reach statistical significance (-0.152; 95% confidence interval: -0.316; 0.011). However, this association was statistically significant when analysed as a dose-response association per 10 times/day use (-0.062; 95%CI -0.118; -0.005). Highest frequency of mobile phone use (>20 times per day) was also associated with decreased total sperm count (-0.271; 95% confidence interval: -0.515; -0.027). These findings translate to a 30% and 21% increased risk for sperm concentration and total sperm count to be below the World Health Organization reference values for fertile men, respectively. The inverse association was most pronounced in 2005–2007 and gradually decreased over the 2008–2011 and 2012–2018 periods, which the authors argue is consistent with a move from 2G to 3/4G. No consistent associations were observed between mobile phone use and sperm motility or sperm morphology. Keeping a mobile phone in the pants pocket was not found to be associated with lower semen parameters.
This was a well-conducted study but has limitations in that it was cross-sectional, and relied on self-reported phone use frequency data without information about type of phone use (calling, texting, apps) such data only provide a crude indication of actual exposure. It should also be noted that the heavy mobile phone users had less healthy lifestyles and had higher BMI. The authors argue that the limited effect of adjusting for the included confounders indicate limited potential for residual confounding. It could, however, also be an indication that the relevant confounders were not captured or not captured in sufficient detail. In the same vein, the authors ascribe the observed stronger associations in the earlier years to higher output power from earlier phone technologies. Residual confounding would, however, be an alternative explanation since the men using their phone 20+ times / week will be a more selected group in earlier years when 56.5% of participants used their phones less than once a week, whereas only 5% used it so infrequently late in the study period. Further studies will be needed to confirm the observed associations and to resolve what might be the cause.

4.1.4 Self-reported electromagnetic hypersensitivity (EHS) and symptoms

Eicher [70] performed a survey in Switzerland to assess self-reported sleep quality in EHS persons. Between 2017 and 2018, 2040 participants aged 18-30 were recruited via social media and flyers at several universities in Switzerland. Participants filled in questionnaires about self-reported sensitivity to EMF, attribution of health complaints to EMF, and self-reported sleep quality. In addition, saliva samples were collected for genotyping of three functional variants of CACNA1C. Mobile phone calling (<1h, 1-2, >2h/week) without headphones was used as a proxy for RF-EMF exposure. The authors report that self-rated sleep was worse in EHS individuals or persons attributing health complaints to EMF, but that this effect was independent of RF-EMF exposure.
It is somewhat unclear in how far the question of EHS/attribution (referring to any EMF) also matches the evaluated exposure to RF-EMF, which could have introduced a mismatch between EHS/attribution and exposure. Also, people with sleep problems may change their phone habits, and it is unclear if that could have affected the results. Overall, the results of the study are more informative regarding the question whether self-reported sleep quality was worse or different among EHS/attributers as compared to people who don't report EHS or attribution of symptoms to EMF. The analysis regarding mobile phone calling as a proxy for "true" RF-EMF exposure is less informative, but also does not suggest a health problem.

Eeftens [71] investigated short-term associations of phone use and cognitive performance, health-related quality of life and sleep among 121 volunteers aged 18-70 from France and Switzerland. Each participant was followed for a 10-day period between 2019 and 2021. Participants recruited via advertising and among acquaintances of the researchers completed a baseline questionnaire including age, sex, education, preferred side of head when using a phone etc. Wrist devices monitored sleep quality. Each evening, participants filled in a short questionnaire on use of cordless phones, mobile phones, and mobile phone screen time during the past 4 hours. As well as coffee and alcohol consumption, time spent outdoors, sleep duration, stress, fatigue, and mood. Finally, they completed gamified cognitive performance tests: three verbal tests (Digit Span, Double Trouble and Grammatical Reasoning), and three visuo-spatial tests (Odd One Out, Rotations and Spatial Span). The association of mobile phone use in the 4 hours preceding answering the daily questionnaire and each outcome was analysed linearly with mixed effect models.
None of the exposure metrics were associated with sleep. Mobile phone screen time was associated with borderline reduced fatigue and mood and elevated stress. Screen time was not associated with performance in any cognitive test when looking at all participants. Nor when looking at right- (n=39) or left-hand (n=17) phone users. In those using both hands equally (n=45), screen time was associated with improved performance in all visuo-spatial tests combined, driven by associations in the Double Trouble and Rotations test.
For mobile phone use some positive associations were reported in relation to the gamified tests, but there was little consistency with respect to preferred side of using the mobile phone.
The authors note that the observed cognitive associations were inconsistent across tests and mention chance findings due to multiple testing as a likely cause. The association of screen time with stress, mood and fatigue is proposed to not be due to RF-EMF, as surfing is associated with low exposure compared to phone calls, where no association was observed. The authors conclude "The study did not find associations between short-term RF-EMF markers and cognitive performance, health related quality of life or sleep duration or quality."
The repeated measurement design and the simultaneous in-home collection of exposure and

outcome information are strengths of the study. Limitations include low power and generalizability due to few participants. The relatively crude RF-ELF assessment may have driven the results towards the null. Finally, the results may be influenced by lack of accounting for a range of factors potentially associated with both mobile phone use and outcomes such as for example workload, social interaction or physical exercise.

Gaya (2023) [72] undertook a cross sectional study on correlation of sleep with use of electronic devices and social media in adolescents aged 12 to 17. The participants were recruited from three schools in the Spanish Valle de Ricote region in 2021. Participants were required to not be exempt from physical education class and not be undergoing pharmacological treatment. The participants answered a questionnaire on hours a day spent using mobile phones, computers, TV, video games, Instagram, and WhatsApp. Participants were also asked about sleep length and quality, participation in organized sports (Y/N), adherence to the mediterranean diet (MD), socioeconomic indicators and psychosocial health. BMI was measured for all participants. After excluding 277 children with missing data on one or more parameters, 1101 children remained for analysis. Sleep problems were analysed separately by sex, in Poisson regression models, whereas sleep duration was analysed for both sexes combined in linear regression models. The different types of media and device use were analysed separately. In adjusted models sleep duration was negatively associated with use of cell phones, computers, Instagram, and WhatsApp. Results are not presented for TV or videogames. Sleep problems were assessed with a validated scale and grouped into either no or one or more sleep related problems. Having sleep problems were associated with mobile phone use and video games in both boys and girls. With use of WhatsApp and Instagram in girls and with use of computers in boys. Results are not presented for TV or Instagram. The exposures not included in tables appear to be those that were not statistically significantly associated with endpoints. The authors conclude "Our results suggest a relationship between cell phones, video games, and social networks with sleep-related problems and time."
Apart from the limitations inherent to cross sectional questionnaire studies, it is a limitation that the different exposures were only analysed separately, and no information is provided on how the different activities correlate and to what extent time spend using cell phones is actually the same as the time spend gaming or on social media. It is therefore not possible to determine if the associations for mobile phone use are due to using the mobile phone per se or are due to using the phone for social media or gaming. But it seems unlikely that RF exposure of the head is a primary causal mechanism as the mean daily time spend by participants using mobile phones is 3.6 h (SD: 1.1) and very few people will be using their phone for talking and even less holding their phone to the head for so long time in a day.

Besset et al. (2023) [73] analysed RF-EMF exposure and sleep in 29 preterm hospitalized neonates, 18 girls and 11 boys. Children were included into the study at the Amiens University Medical Center in France. Exposimeter (EME SPY 200) measurements were taken at a fixed location 30cm from the child's head every 2 minutes for the first 21 days. Analysis used the median and the 99th percentile of the total time, and of the day a sleep recording was made: Three weeks after birth, a polysomnographic reading was taken between 8pm and 8am. As sleep outcomes, the authors analysed sleep period time (SPT), beginning at the first sleep onset and ending at the last awakening; the frequency, mean duration, and proportion of wakefulness after sleep onset (WASO), expressed as a percentage of the SPT; total sleep time (TST), defined as the difference between SPT and WASO durations; and the frequency, mean duration, and proportion of the different sleep states, expressed as a percentage of TST. In addition, they analysed wakefulness, REM (rapid eye movement) and NREM (non- rapid eye movement) sleep as well indeterminate sleep (IS), if

criteria were not met for either REM or NREM sleep. RF-EMF exposure levels were correlated with sleep outcomes. Exposure levels were rather low: median exposures were 0.03 (SD 0.01 V/m) and 99th percentiles of exposure was 0.24 V.m (SD 0.11) for the 21 days. Levels recorded during the polysomnographic measurement night were in a similar range. Bonferroni correction was applied, with a resulting p-value of 0.0007 to reach statistical significance. None of the presented correlations reached this level of statistical significance. The authors nevertheless highlighted correlations between 21-day exposure and IR and REM sleep. Exposure on the day of the reading correlated with sleep period time and proportion wakefulness after sleep onset.
Using a Bonferroni correction, none of the results remained statistically significant. The authors concluded that chronic exposure to low RF-EMF levels did not disrupt sleep structure despite some discrete alterations such as increased IS and sleep fragmentation. While no potential confounding was considered or taken into account in the analysis, it also remains unclear which factors could be associated with the RF-EMF exposure levels described here. In addition, exposure levels appear to be remarkably low, roughly a factor of 10-250 lower as compared to usually encountered average exposure levels (Loizeau et al 2023, Birks et al 2018, Ramirez-Velasquez et al 2023). In addition, no mechanism exists to explain any effect from such low exposure levels on sleep.

Roosli [74] performed a systematic review on RF-EMF exposure and tinnitus, headache, migraine, sleep disorders and a composite symptoms score. Cohort and case-control studies - studies with a longitudinal design - were included. Overall, 13 publications were reviewed that reported results from 8 individual cohort and one case-control study. All included publications summarised European studies. Risk of Bias was assessed with a specific tool adapted to the topic, effects were summarised using random effects meta-analyses. Three publications assessed tinnitus, one migraine, six headaches, and five each assessed sleep disturbance and symptom scores. For the outcomes with more than one study, meta-analyses did not suggest that RF-EMF was underlying these conditions, but the evidence was rated as very uncertain. Low certainty was discussed to be caused by the low number of studies, possible risk of bias in some studies, inconsistencies, indirectness, and imprecision.
This is one of the long-awaited systematic reviews commissioned by the World Health Organization. This is a high-quality assessment of the available evidence. While no association between exposure and these conditions was reported, the authors highlighted the particular challenges inherent of this type of research. A particular problem is the difficulty to disentangle biophysical effects from the exposure and behavioural aspects that are related to exposure. An example would be extensive use of wireless communication devices that could compete with healthy behaviours such as sleep or physical activity. The authors also highlight that as long as no better exposure assessment approaches become available that are able to deal with this challenge, no better evidence will be generated. The topic likely remains of relevance, given the high prevalence of both exposure and the outcomes.

4.1.5 Other outcomes

Zhang (2023b) [75] investigated the association of mobile phone use and new-onset chronic kidney disease (CKD) in UK-biobank participants. They included 408,743 (81%) UK biobank participants with complete information on mobile phone use and without CKD at enrolment. Participants answered the biobank questionnaire between 2006 and 2010 with details on mobile phone usage, age, sex, ethnicity, education, income, alcohol consumption and smoking as well as use of antihypertensive, cholesterol lowering or glucose lowering drugs. Area level socio-economic position, BMI, and prevalent diabetes at baseline were also established. Participants were divided

into tertiles based on their genetic risk score (GRS) for CKD, established from 263 nucleotide polymorphisms. Median follow-up time is stated as 12.1 years, but it is not specified what data sources were used for follow-up or what year follow-up ended. In Cox-models, mobile phone users, defined as people with at least weekly use, had higher risk of CKD than non-users HR: 1.07 (CI: 1.02-1.13) after adjustment for other covariates. In analyses restricted to users (n=348,602), risk did not increase with years of use, but hours of weekly usage was positively associated with risk, also after adjustment for use of handsfree devices.
The authors note that among weekly mobile phone users, the highest point estimate was seen for those with high usage and high GRS (HR: 1.22, CI: 1.12-1.33) when compared to low users with low GRS scores. There was, however, no significant interaction between GRS and usage (p=0.6) indicating that the association of CKD with use of mobile phones was not stronger among those with high genetic susceptibility. A propensity scores analysis produced similar result as the main analysis.
The authors argue that sleep disturbances or mental health are not likely to be causal, as adjustment for these factors did not affect their results. They propose as a possible causal pathway that the static arm position when holding the phone to the ear call may lead to temporary increased blood pressure or that oxidative stress, inflammation and DNA damage and elevated blood creatinine levels which has been observed in some animal studies, may be involved. The authors conclude: "mobile phone use was significantly associated with a higher risk of new-onset CKD, especially in those with longer weekly usage time of mobile phones making or receiving calls, among the general population. Of note, there is no established biological mechanism for the results. Our findings and the underlying mechanisms should be further investigated in more studies".
Strengths of the study include the large cohort size with biological measurements available at baseline. A limitation was that use of mobile phones was also only assessed at baseline and usage patterns before or after this point were not available. The study does not provide information about how participants were followed-up for CKD, but the fact that they specify ICD codes suggest that follow-up may have been through something like hospital discharge registers. CKD is often detected from routine blood or urine tests but can go undetected for a long time. Therefore, a potential non-causal explanation for the observed association could relate to an association between heavier use and being registered in this unknown register e.g. if use in all or many users were associated with more doctor visits or urine/blood samples. As stated by the authors, further studies will be needed to establish if the association can be confirmed and if so whether the causal pathways relate to RF-radiation or some other aspect of mobile phone use.

4.1.6 Conclusions on epidemiological studies

Last year, two studies reported a few associations between different aspects of mobile phone use and some semen quality parameters. This was likely chance findings due to the number of analyses. This year one cross sectional study also found an association between mobile phone use and total sperm count and concentration, this could however also be due to chance findings or residual confounding e.g. from lifestyle.

Yet another incidence trend study found no overall increase in brain tumours, indicating that mobile phones are not a major driver of brain tumour risk.

This year we saw the first of the long awaited WHO reviews published which highlighted difficulty to disentangle biophysical effects from the exposure and behavioural aspects that are related to exposure. A number of other new systematic reviews and meta-analyses that were published this year did not provide additional insights, either because too few primary studies of decent quality were available or because vastly different exposure and/or outcomes were combined in single meta-analyses. Such pooling is not informative, especially if rationale or justification for the pooling is not provided (Table 4.1).

Table 4.1: Epidemiological studies investigating RF fields.

Endpoints	Reference	Exposure assessment	Study design, Population	Results
Cancer in adults	Shapira (2023)	Exposed: Serving in Israeli air defence Units Unexposed serving in other military units	.Cohort study	No association between air defence service and cancer. Study limited by small size, few cases insufficient exposure assessment
Benign salivary gland neoplasms	Gao (2023)	Single nucleotide polymorphisms associated with self reported years of mobile phone use	Mendelian randomization study using data from Finish and UK biobanks	No association between genotypes associated with mobile phone use and benign salivary gland neoplasm The Mendelian randomization design may be inappropriate and its assumptions may have been violated
Cancer: overall, the 25 most common sites and glioma	Zhang (2023a)	Duration of self reported mobile phone usage	UK-biobank	Positive relationship non-melanoma skin cancer in both men and women, prostate cancer in men and vulva cancer in women. Likely residual confounding and surveillance bias.
Brain tumour incidence trends	Moon (2023)	Mobile phone subscriptions in Korea	Korean incidence trends	Incidence trends increased for specific tumors correlating with increased usage of mobile phones. Simultaneous decrease in unspecified tumours suggests changes and improvements in surveillance, diagnosis and classification
Salivary gland tumours	Vijayan (2023)	Mobile phone use	Meta-analysis	No association with salivary gland tumours. Included studies susceptible to selection and recall bias and suffering from poor exposure assessment

Buccal mucosa micronuclei	Kadeh (2023)	Self reported mobile phone use	Cross sectional study of 50 mobile phone users	No association between mobile phone use and micronuclei of buccal mucosa. Study likely underpowered.
Childhood cancer	Kojimahara (2023)	Site specific RF energy absorption estimated from self reported mobile phone usage and MOBI-kids algorithm	Case control study	
Cancer, birth outcomes, neurocognitive development, and behavioural problems	Lim (2023)	RF-EMF from mobile phones and antennae	Systematic review	No conclusive associations. Reverse causation, confounding and quality of exposure assessment was highlighted as a potential limitations of included studies
Childhood lymphoma and leukaemia	Morales-Suarez-Varela (2023)	Parental occupation exposure in original studies	Systematic review	Available data does not allow conclusions on associations
Fertility, reproduction, child development	Kashani (2023)	ELF-MF, RF-EMF and ionizing radiation from medical assessments (x-ray)	Meta-analysis	Quantitative results, not informative.
Male fertility	Rahban (2023)	Self-reported mobile phone use frequency and phone placement (pocket, jacket, etc.).	Cross-sectional study	
Cognitive performance, health-related quality of life and sleep	Eeftens (2023)	Daily questionniares	Cohort	No associations with cognitive performance, health related quality of life or sleep duration or quality. Small sample
Sleep	Gaya (2023)	Self reported use of electronic devices and social media	Cross sectional	Possible relationship between cell phones, video games, and social networks with sleep-related problems. Analyses do not allow separation of

				associations due to RF-emf exposure specifically
	Besset (2023)	Measured RF-EMF levels in 29 hospitalized neonates.	Survey	No associations with sleep from the very low observed exposure levels.
	Roosli (2023)	RF-EMF	Systematic review and meta-analysis	No association between exposure and tinnitus, migraine, sleep, symptom scores. Challenges of the underlying studies include to disentangle biophysical effects from exposure from behavioural aspects of device use that may correlate with exposure.
	Eicher (2023)	Self-reported calling with a phone without headphone use.	Survey	Self-rated sleep worse in self-reported EHS persons, but this effect was independent of phone use behaviours. Likely analysis on exposure not informative.
New-onset chronic kidney disease	Zhang (2023b)	Self reported mobile phone use	Cohort study - UK-biobank	mobile phone use was associated with chronic kidney disease. Possible surveillance bias

4.2 Human Studies

Last year, a systematic review reported insufficient evidence on the effects of cell phone exposure on brain activity and cognition in children and adolescents. Another systematic review found no differences in the impact of 5G compared to previous generations of mobile communications. An experimental study showed no exposure effects of LTE on brain connectivity and dynamic functional networks. Symptoms reported by individuals with self-reported idiopathic intolerance due to EMF were not related to RF-EMF in another experimental study. Finally, one study observed an association between cell phone exposure and food intake and energy homeostasis in the brain, a finding that bears repeating due to several methodological shortcomings.

In 2023, Mansourian et al. [37] published a systematic review and meta-analysis of man-made EMF on heart rate variability parameters in healthy participants. (2023). As mentioned in the ELF chapter, this systematic review was briefly summarized under epidemiological studies but excluded here due to methodological shortcomings.

The number of original studies on high-frequency electromagnetic fields is still larger than in any other type of non-ionising fields. The main endpoint in the studies published in 2023 remains human brain activity while awake, measured with electroencephalography (EEG), and with particular attention to the eye state during recording, i.e. eyes open or eyes closed.

Jamal et al. [76] analysed power spectral densities of the wake EEG (alpha, beta, theta, delta) before, during and after a far-field 5G mobile communication exposure at 3.5 GHz, pulse-modulated (577 µs/ 4.6 ms) condition. The study design was triple-blinded, counterbalanced and sham controlled. Thirty-four healthy volunteers (17 females, 17 males; mean age ± SD: 26.6 ± 4.7 years) took part in two separate sessions, scheduled at a maximum of one week apart at the same time of day for each individual. Experiments were conducted in an electrically shielded room and exposure was realised with a far-field antenna, placed 1.2 m and 45 degrees to the right of the participant. During a 17 min pre- and post exposure condition as well as during the 26 min exposure/sham condition, EEG was recorded for 2 x 3 min runs eyes open and eyes closed. EDA was measured at the beginning of each run for 2.5 min each. Overall, repeated ANOVA indicated no significant changes in all spectra, except for single electrodes in the alpha, theta, and delta spectra. The increase and decrease in power spectra occurred in response to the eyes open and eyes closed condition and did not survive correction for multiple comparisons. The authors concluded that 5G exposure within the regulatory levels does not affect brain activity in healthy young adults.

In their latest publication Wallace et al. [77], who had conducted several studies on possible effects of EMF on brain activity, that were reported in the SSM report 2022, investigated effects of RF-EMF of a GSM 900 MHz mobile phone signal on EEG power spectra in healthy young volunteers. The study is part of the previously published study, and the experimental procedure is described in detail in the SSM report 2022 (Wallace et al. 2022). The study followed a double-blind, randomised and counterbalanced cross-over design and participants were exposed to sham or a pulse-modulated (217 Hz) 900 MHz GSM signal (mean power of 250 mW; peak power of 2 W; max SAR1g = 0.70 W/kg). Twenty-one thoroughly screened healthy volunteers underwent a baseline condition, followed by an exposure and a post exposure condition, all periods lasting approximately 25 min. The EEG was recorded during all periods, the MEG only during the baseline and the post exposure condition. Power spectra for 74 electrode positions were calculated by applying fast Fourier transformation considering beta (12-20 Hz), theta (4-8 Hz), and delta (1-4 Hz) frequency bands. Log-transformed power values were separately averaged for each frequency band, electrode, exposure condition and for eyes open and eyes closed, respectively. Baseline corrected values were used. Three-way repeated ANOVA to measure effects of period (baseline, exposure), eyes condition (open, closed) and exposure (sham, GSM 900) and interactions were run, followed by subsequent one-way ANOVAs on frequency band with two exposure conditions. Data was post-hoc corrected for multiple comparisons. While delta and beta rhythms remained unaffected, power in the theta band decreased statistically significantly during real compared to sham exposure in the eyes open conditions, and increased statistically significantly when eyes were closed. The results are consistent with a previous MEG study by Wallace et al. (2021), which indicated a different effect of exposure on the alpha frequency band depending on the condition of the eyes. The results are in contrast to the findings on the alpha frequency in the same study, which were neither effect in the eyes open nor eyes closed condition under RF-EMF exposure (Wallace et al. [78])

Another study on possible effects of RF-EMF on the EEG in healthy volunteers was published by van de Meer et al. 2023. The aim of that study was to control for experimental and environmental factors that might have affected results in other earlier studies. Altogether 32 healthy participants (mean age ± SD: 23.6 ± 7.3 years; 21 females and 11 males) were assessed in a double-blind crossover counterbalanced design in a shielded room with reduced background radiation levels in one single session. Exposure was applied by four conventional GSM antennas (frequency range: 824 - 2170 MHz; pulsation frequency 217 Hz), placed in a rectangular configuration to deliver homogenous EMF to the volunteer´s head. EEG was recorded from 63 electrodes during two 15-min sham/real exposure sessions with alternating 1.5 min blocks of eyes open and eyes closed. A 15-minute rest/washout period was performed before and after the first exposure condition. Between the eyes open and eyes closed blocks, volunteers made self-paced breaks for on average of 6 to 60 s, but also longer breaks occurred with up to more than 100s. EEG data underwent several adjustments for artifact detection and elimination. Power spectra from the cleaned EEG were calculated for six brain regions (frontal, left/right temporal, central, parietal, occipital) and for four conditions of the combinations of eyes open and eyes closed, each under sham and GSM exposure condition. The authors used Bayesian statistics with different models as well as t-tests for the comparability with results of other studies to analyse the individual power spectra contrasts between the exposure and non-exposure conditions. The results show a subtle increase in EEG power in the frequency band between 6 and 10 Hz in the eyes open condition only. The authors concluded that the brain is more susceptible to EMF effects when the eyes are open, although they argue that changes could also have occurred when eyes are closed, but were probably less easy to detect.

The technical and analytical approach is a strength of the study. There are some limitations that should be mentioned: For instance, age and gender might have not been adequately balanced in the order of conditions or at least no further information was provided. No information on the control of the menstrual cycle was reported. Like discussed in earlier SSM reports, the menstrual cycle affects the human EEG. Furthermore, the time of day should be kept constant, at least at the individual level, since circadian changes in brain activity should be controlled for. It remains unclear whether the state/activity of volunteers during the various breaks prior were standardised, at least the self-paced durations were not. For a more detailed discussion on factors affecting the human EEG, please refer to the publications Wallace and Selmaoui (2019) and Danker-Hopfe et al. (2019). Nevertheless, as the authors suggest, their protocol might be useful for future research in that area - with regard to the technical aspects.

4.2.1 Conclusions on radiofrequency human studies

Like already elaborated in the last SSM report, results concerning RF-EMF effects on the human EEG continue to be inconsistent. Whereas none of the frequency bands of the wake EEG was affected in the eyes open and closed condition in a study on RF-EMF of 5G mobile communication far field, two GSM studies reported modulations in dependence of the eye condition, one in the theta frequency band, and the other in a frequency range that represents part of the theta and the alpha band in the eyes open condition only. Differences in methods might still be the main reason for the different results (Table 4.2).

Table 4.2: Human studies investigating RF fields.

Endpoints	Reference	Exposure condition	Sample	Results
Waking state EEG	Jamal et al. 2023	2 exposure conditions: Real exposure: 3.5G pulse-modulated; EMF far-field antenna-emitted; in electrically shielded room Sham exposure Exposure duration approx.. 26min each, pre- and post-exposure condition of 17min during each period: 2x3min eyes open, 2x3min eyes closed randomised; triple-blinded; counterbalanced; sham-controlled	34 healthy volunteers (17 females, 17 males) Mean age ± SD: 26.6 ± 4.7 years	Overall non-significant change in all spectra; except for single electrodes (alpha, theta, delta); increase/decrease in response to eyes open/eyes closed condition No effect on brain activity in young adults.
	Van der Meer et al. 2023	double-blinded; cross-over, counterbalanced 4 GSM antenna positioned in a rectangular formation for delivery of homogenous EMF to the brain 2 exposure conditions: sham and real for 18 min each EEG: Power spectra from 63 electrodes / 6 brain regions	32 healthy participants (21 females, 11 males) Mean age ± SD: 23.6 ± 7.3 years	EMF effect in the alpha band power density in the eyes open condition only

	Wallace et al. 2023	Pulse-modulated (217 Hz) 900 MHz GSM signal, mean power 250 mW, peak power 2W; max SAR 1g = 0.70 W/kg and sham exposure	21 healthy volunteers (10 females, 11 males) Mean age ± SD: 25.1 ± 3.6 years	RF-EMF exposure modulates the spectral power of the theta band, depending on the eyes condition (eyes open: increased power, eyes closed: decreased power)

4.3 Animal Studies

This year, as in previous years, a variety of endpoints was investigated, including effects on the brain and on behaviour, reproductive system, development, oxidative stress and temperature changes. In the last year's report, most studies reported effects of RF-EMF exposure, but because of the variable exposure parameters, it was difficult to draw general conclusions.

4.3.1 Rodents & other non-human mammals

Behavior and effects on brain

Bodin et al. [79] exposed pregnant Sprague Dawley rats (n=7 per group) from gestational day (GD) 8 until postnatal day (PND) 21 to 3.5 GHz fields (continuous wave, CW) for 22 h per day at a whole-body SAR of 0.07 W/kg. After birth, litters were adjusted to 6 pubs (3 male and 3 female) by adoption or reduction. On PND 3, all rats underwent the neonatal test on righting and gripping, on PND 7 on righting, gripping and negative geotaxis. Two rats per litter (one male, one female) were sacrificed at PND 9 (no test), PND 21 and PND 43 (after open-field (OF) test). Regarding physical development, no effects of exposure were seen for weight and water intake of mothers, size of litters, sex ratio, pubs born alive, weight and body length of pubs, ear detachment or eye opening. Incisor eruption was delayed in exposed groups of both males and females (PND 10) compared to the sham-exposed group (PND 9). Neonatal reflexes tested on PND 3 and PND 7 were not modified by exposure compared to sham-exposure in both males and females. Regarding activity in the open field tested on PND 21 and 43, adolescent females showed statistically significantly less stereotyped movements (− 70%), while adolescent males showed statistically significantly more stereotyped movements (+ 50%) compared to the sham-exposed adolescent rats. Stereotyped movements were defined as repetitive motor responses that are invariant and have no purpose or goal. No effects of exposure on activity in the OF were seen in the adult mothers.

Hao et al. [80] investigated the effects of RF-EMF exposure on neuronal activity and neural circuit in mice. Therefore, they exposed transgenic or wild-type C57BL/6N male mice (n = 3-12) to 2856 MHz pulsed fields for 900 seconds. The peak power density was 200 mW/cm² and the average power density was 8 mW/cm². RF exposure had an adverse effect on the hippocampus (HPC-)dependent spatial and place memory ability (both long-term and short-term) and novelty-seeking behavior in mice. As the HPC serves a critical function in memory, navigation and cognition, additional experiments on the dorsal HPC (dHPC) were performed. In the dHPC CA1 region, RF-EMF exposure caused a statistically significant decline in dopamine release, and led to enhanced activity of pyramidal neurons in the first 100 s after exposure start with rectal temperature increase of only 0.1°C and recovery to pre-treatment levels within 300 s after exposure termination. No long-lasting effects were identified at 6 h, 3 d and 7 d post exposure. Furthermore, the decline of dHPC dopamine release by RFR exposure was due to decreased density of dopaminergic projections from the locus coeruleus to dHPC, and artificial activation of dopamine axon terminals or D1 receptors in dHPC CA1 improved memory damage in mice exposed to RFR.

Qin et al. [81] exposed male C57BL/6 mice (n = 3-12 per group) to 4.9 GHz RF-EMF and/or electromagnetic pulse (EMP) exposure. The average PD for the 4.9 GHz exposure was 50 +/- 2.5 W/m², and the electric field intensity for EMP exposure was 650 kV/m with 1000 pulses in total. Animals were exposed for 1 week either alone or combined to 4.9 GHz fields for 1 h per day and/or EMP for 10 min per day. The group with combined exposure showed a statistically significantly decreased locomotor activity and anxiety-like behavior, while no effects were observed on spatial learning and memory ability or depression-like behavior in any group. Protein expression analyses of hippocampus tissue (n = 3 per group) revealed enrichment of Glutamatergic and GABAergic synapse in the combined exposure group compared to the sham group. However, histological alterations and autophagy-related cell death were observed only in amygdala but not in hippocampus of mice in all single and combined exposed groups. Important information was missing in the description of the exposure setup (including modulation of 4.9 GHz signal, location of PD measurement), which makes the results less informative.

Spandole-Dinu et al. [82] exposed male BALB/c mice (age not given) to 2.45 GHz RF-EMF (OFDM-modulated) continuously for 16 weeks (n = 10 per group). The source of RF fields was either a household WiFi-Router device or a laboratory radiofrequency generator. The mice were able to move freely and were randomly subjected to different field intensities and different polarizations. The worst-case scenario resulted in a maximum local SAR of 0.01786 W/kg. Before and after the exposure period, all mice underwent behavioral tests, including the open-field test and Y-maze test. At the end of the experiment, mice were sacrificed and brains were removed for evaluation of global DNA methylation (5-methylcytosine) and histological analysis of brain tissue. Similar behavioral performances were observed for all groups before start of exposure, while at end of exposure, mice in both exposed groups showed statistically significantly higher locomotor activity compared to sham-exposed mice. Moreover, the group exposed to the laboratory device exhibited statistically significantly higher locomotor activity than the WiFi-exposed group. In contrast, anxiety-like behavior and working memory were not affected by both exposure types. In addition, no histological changes were found in the analyzed brain regions (cortex, hippocampus, cerebellum) but global DNA methylation was statistically significantly lower in the WiFi-exposed group compared to sham-exposed animals.

In the study by Wang et al. [83], male Wistar rats were exposed to 1.5 GHz pulsed RF-EMF for 6 min at power densities (PD) of 5, 30 or 50 mW/cm². The calculated average brain SARs were 1.85, 11.1 or 18.5 W/kg, respectively. Exposure led to a temperature rise of less than 1°C, but only rectal temperature and surface temperature and not brain temperature were measured. Changes in spatial learning and memory, EEG activity, hippocampal structure, and N-methyl D-aspartate receptor (NMDAR) signaling pathway molecules were analysed (n = 3 to 10 rats per group). All exposed groups showed statistically significantly impaired spatial learning compared to the sham exposed group 6 h, 1 d and 2 d after exposure, but not 3, 7 or 14 d after exposure. In the EEG, changes in α, δ, and θ wave power were observed in the 30 and 50 mW/cm² exposed groups 6 h after exposure, while 7 d after exposure only the 50 mW/cm² exposed group showed statistically significant changes compared to the sham group. In the histopathological examination, increased hippocampal injury was detected with increasing PD levels until 7 d after exposure. Thereafter, hippocampal structure recovered at day 14 and returned back to normal until 28 d after exposure in the 50 mW/cm² exposed group. The dentate gyrus region and neurons in the CA3 region seemed to be most affected. Regarding NMDAR subunits and downstream signaling molecules, there were several statistically significant changes in the levels of proteins in the exposed groups but only 6 h and not 7 d after exposure.

In another study by the same working group, Lai et al. [84] investigated effects of combined exposure to 1.5 GHz pulsed RF-EMF and electromagnetic pulses (EMP) on male Wistar rats (age not given). Animals (n = 3-10 per group) were exposed to RF EMF (PD = 30 mW/cm², SAR = 10.57 W/kg, 15 min) or EMP (peak E-field in rats = 11.65 kV/m, 400 pulses) alone or in combination and effects on learning and memory ability, alterations in brain electrophysiological activity, as well as microstructural damage, ferroptosis and oxidative stress markers in hippocampus were analysed at 6 h to 14 d after end of exposure. Rectum temperature was measured before and immediately after exposure and statistically significant elevations were observed. However, apart from a figure the exact temperature changes are not indicated and rats seemed to have high temperatures above 40°C after RFR-exposure alone. Compared with the sham group, all exposure groups showed impairment of learning and memory ability and a decreased α wave power in the EEG at 1 d after exposure. No effects were seen after 7 or 14 days and β, θ, and δ waves were not affected at any time point. Microstructural injury in the dentate gyrus region of the hippocampus was observed in all exposure groups compared to the sham group. Moreover, alterations in ferroptosis hallmarks, including increased levels of iron, lipid peroxidation, and prostaglandin-endoperoxide synthase 2 (PTGS2) mRNA, as well as downregulation of glutathione peroxidase 4 (GPX4) protein in the rat hippocampus were observed in all exposed groups.

Singh et al. (7) [85] exposed male Wistar rats (n = 13 per group) to 2115 MHz fields (digital modulation (16 QAM)) for 8 h at head average SAR of 1.51 W/kg. Out of thirteen rats from each group, four were used to study oxidative stress parameters (one hemisphere) and comet assay (another hemisphere), and three rats for cresyl violet (CV) staining to study neuronal morphology. Six rats from each group were injected with 5-Bromo-2′ -deoxyuridine (BrdU) intraperitoneally (300 mg/kg) at the end of exposure time and sacrificed 2 h or 24 h post-injection (n = 3) to study hippocampal neurogenesis. RF-EMF exposure caused a statistically significant increase in oxidative stress markers and DNA damage in cells in the cortex and hippocampus of rats compared to the sham exposed group. BrdU-positive cells were statistically significantly reduced in dented gyrus (subregion of hippocampus) at both time points indicating interference of cell cycle progression by RFR exposure. CV staining indicated neuronal damage in the dented gyrus but not in the cerebral cortex and other subregions of the hippocampus (CA3 or CA1).

Cancer

Pinto et al. [86] conducted a systematic review to provide an update of the current scientific knowledge on the link between RF-EMF and cancer in experimental animal studies in the frequency range 100 kHz-300 GHz. The systematic review only included studies that investigated carcinogenesis, while studies on co-carcinogenesis will be dealt with in another article. All criteria for eligible papers, the review design and analysis procedures were described in a published protocol beforehand. For each study, the risk of bias (RoB) and quality of evidence (NTP OHAT) were evaluated. From a total of 294 articles, 27 were considered eligible for the evaluation of tumor incidence and 23 were included in the meta-analysis. Based on the RoB assessment, the studies were of overall good quality, with 16 studies being of high, nine studies of moderate and only two studies of low quality.

Most risk estimates from the meta-analysis were not statistically significant (n = 34 out of a total of n = 41 results). For malignant tumours, a statistically significant increased risk was observed for the central nervous system (CNS), brain and heart, whereas a statistically significantly decreased risk was found for the intestine. For benign tumours, a statistically significantly increased risk was found for CNS/brain, and a statistically significantly decreased risk for male urogenital system and kidney. For brain, the detailed analyses by tumour-type revealed a RR of 2.63 (95% CI: 1.69-4.11) for glia tumours and a RR of 1.6 (95% CI: 1.05-2.45) for meninges tumours. For malignant spinal cord tumours, a statistically non-significant increased risk was observed.

To evaluate the quality of evidence (i.e. the confidence in the estimates of observed effects) the authors primarily applied the guidance from NTP-OHAT. They started from a "high quality" grade, and six items were considered to degrade this quality of evidence: (i) experimental design, (ii) Risk of Bias, (iii) inconsistency, (iv), indirectness of evidence, (v) imprecision and (vi) publication bias. Two items, consistency between species and dose response, were considered to upgrade the evidence. The quality was classified according to the OHAT categories as high, moderate, low or very low. Finally, the evidence of health effects was evaluated according to the same tool.

Overall, there was no high or very high certainty in the evidence for an increased risk for malignant or benign tumors for any organ. For the statistically significant results observed in CNS, brain, heart and intestine, the quality of the evidence was low to very low. For the statistically significant results observed for benign tumors, the quality of evidence was moderate to very low. These confidence ratings resulted in either low or inadequate health evidence for an association between RF-EMF exposure and carcinogenesis *in vivo*. The authors recognized that the number of sham animals was always much lower than the number of exposed animals, because in several studies, exposed groups shared the same sham group. Although very common in animal studies, this can lead to overestimations of events/no-events in the sham group ultimately resulting in unreliable results in meta-analyses aimed at assessing the risk of rare events.

The authors conclude that the insufficient health evidence does not warrant additional recommendations to current regulatory frameworks and emphasize the need of appropriate experimental design in future studies that takes into account the animal number and the sample number used for the sham exposed group.

Reproductive system

Gautam et al. [87] exposed male Wistar rats (n = 6 per group) to 2350 MHz fields (CW) for 2 h per day for 56 days. Effects of exposure on male reproductive system, liver, kidney, and on hematological parameters were investigated. The average SAR was 0.0625 W/kg. Exposure statistically significantly decreased sperm viability and alkaline phosphatase levels in liver, and statistically significantly increased hemoglobin, red blood cells, and packed cell volume in exposed animals compared to sham-exposed. Regarding histopathology of organs, alterations were reported in exposed animals in liver, kidney, testis and other reproductive organs, but the number of animals with alterations is not indicated. No significant effects of exposure were found for several additional liver and kidney functional markers and sperm parameters, including sperm count, sperm morphology, sperm mitochondrial activity or markers of oxidative stress in sperms.

The systematic review by Cordelli et al. [88] is one of the 10 systematic reviews commissioned by the WHO aimed at assessing potential health effects of exposure to RF-EMF in the general and working population. Cordelli et al. evaluated the effect of *in utero* exposure on fecundity, adverse effects on the offspring health at birth and delayed effects on the offspring health in non-human mammals. All criteria for literature search, eligible papers, review design and analysis procedures were described in a published protocol beforehand. The authors followed the guidelines for systematic reviews, which included a RoB assessment (NTP OHAT) and the assessment of the certainty of evidence using the Grading of Recommendations, Assessment, Development and Evaluations (GRADE) approach. In terms of the RoB assessment, most included studies were evaluated as "some concern", followed by "high concern" and only a very low number of studies as "low concern".

Of the 14 outcomes evaluated, 7 showed statistically significant results in the meta-analysis when based only on studies with low or some concern. This includes a significant increase of resorbed or dead fetuses, a small decrease of fetal weight, a moderate decrease in length at birth, an increase in the percentage of fetuses with malformations, a decrease in the endurance capacity in the motor activity test (based on 1 paper) and an increase of the magnitude of the startle response to stimuli (based on 1 papers). The average whole-body SAR levels applied were between 2 W/kg and 20.26 W/kg.

To base the assessment of possible RF-EMF exposure impact on the most solid set of data, the certainty of evidence assessment was only based on studies with low or some concern. A moderate certainty to the evidence of a small detrimental effect was attributed on fetal weight while for all other statistically significant results the certainty of evidence was rated as low to very low. Additionally, there was high certainty of evidence that RF-EMF does not influence litter size and a moderate certainty of evidence for a lack of delayed effects on the offspring brain weight. For all other endpoints assessed by the meta-analyses the evidence was attributed a low or very low certainty.

There were several limitations in the evidence including the heterogeneity of the endpoints employed to evaluate RF-EMF effects on pregnancy and the quality of the studies. Another limitation were the high SAR values applied in the included studies, which were well above the recommended human whole-body exposure limit value for the general public. The authors therefore conclude that the possible impact of *in utero* RF-EMF exposure remains uncertain. For future studies they recommend higher quality design and implementation and the use of several exposure levels, including those comparable to human exposure.

Adipose tissue

Maalouf et al. [89] exposed male C57BL/6J mice (n = 6 per group) to 900 MHz CW fields for 1 hour twice a day for 3 or 7 consecutive days at a whole-body SAR of 0.1 or 0.4 W/kg. Adipose tissue was dissected and brown and white adipose tissue analyzed separately. Changes in mRNA expression levels of genes coding for thermoregulation and mitochondrial signaling pathways were found in both exposure groups compared to sham-exposure at both time points. No effects were observed, at both time points, on mitochondrial DNA copy numbers.

Bone and muscle

Bektas et al. [90] exposed healthy and diabetic male Wistar Albino rats (n = 7 per group) to RF-EMF (900, 1800 or 2100 MHz, GSM-modulated) at average wbSAR values of 0.026 W/kg (900 MHz), 0.164 W/kg (1800 MHz) or 0.173 W/kg (2100 MHz), respectively, for 2 h per day, 5 days per week for 30 days. To create animal models of Type I diabetes, rats were injected with streptozotocin capable of destroying pancreatic islet β-cells. After exposure, catalase (CAT) activity, glutathione (GSH), malondialdehyde (MDA) and ischemia-modified albumin (IMA) levels were measured in muscle tissue, and biomechanical quality (three-point bending test) as well as thickness of cortex and medulla of right tibia bones were evaluated. In general, exposed healthy rats had lower GSH and CAT levels and higher IMA and MDA levels than healthy sham-exposed groups, while the levels in diabetic rats were lower than those of healthy rats. However, the authors did not statistically compare the levels of CAT, IMA and MDA of sham and exposed diabetic rats and those levels do not appear to differ greatly in most exposure groups. There were several statistically significantly different values for biochemical quality and thickness of tibia bones between exposed and sham-exposed animals, that the authors interpreted as adverse effects of exposure on tibia bone health.

Thermophysiology

In the first study by Ijima et al. [91], effects of quasi-millimeter wave (qMMW) exposure on local temperatures and skin blood flow were analyzed. Therefore, male Sprague Dawley rats were exposed to 28 GHz qMMW (CW) from the dorsal side at absorbed PDs of 0 W/m² (n = 8), 122 W/m² (n = 11) or 237 W/m² (n = 12) for 40 min. First, temperature changes in three regions (dorsal and tail skin, and rectum) and blood flow in the dorsal and tail skin were measured simultaneously using fiber-optic probes. Dorsal skin temperature increased immediately after exposure, whereas there was a delay of 46 s or more in the rectum and tail skin. These differences were reflected in the elapsed time during which a statistically significant increase in temperature was detected compared to the sham-exposed group. Temperature increases persisted until the end of exposure and were then approximately twice as large in the tail skin as in the dorsal skin. Dorsal skin blood flow showed no changes with exposure. In contrast, tail skin blood flow increased linearly throughout the exposure phase. Second, it was shown the temperature changes in all three regions had a significant relationship with the exposure intensity in each period, and the relationships were indicated as linear regression models. Using these models, exposure intensities necessary to induce 1°C or 5°C of temperature increase in each region were estimated. As previous studies suggested that heat accumulated in the body is dissipated through the tail, in a third step the authors had a closer look on the relationship between local temperature increases and blood flow in the tail. They observed that the tail skin blood flow increased in proportion to rectal temperature change and that the tail skin temperature rose in proportion to the change in tail skin BF. According to the authors, these results suggest that qMMW exposure drives thermoregulation to transport and dissipate heat generated on the exposed body surface through the tail.

In a second study by the same group, Ijima et al. [92] exposed male Sprague Dawley rats (n = 6-15) this time to 26.5 GHz (CW) at 5 different absorbed PDs (0, 125, 250, 370, 500 W/m²) for 18 min. Temperatures at four sites (rectum and three dorsal skin sites) were measured in real time using fiber-optic thermometers. One dorsal site (P1) was defined as the target site, to which exposure was applied, while the other two sides were 1 cm (P2) or 2 cm (P3) in front of P1. Temperature data were collected over 30 min, beginning 6 min prior to exposure and ending 6 min after end of exposure. Skin temperatures rose immediately after start of exposure and decreased immediately after the end of exposure. In the beginning, temperature rise was limited to the P1 area but spread over a larger area with advanced exposure. The temperature rise at P1 was proportionally to the qMMW intensity but less proportionally for P2 and P3. In the rectum, temperature began to rise at 4 min after start of exposure and increased linearly with exposure time, but only at 370 and 500 W/m². The authors then estimated the temperature change in rat skin when exposed to

200 W/m². This value was established by ICNIRP as limit value that will restrict local temperature rise at frequencies >6 GHz to below the operational adverse health effect thresholds for Type-1 (5°C) and Type-2 tissues (2°C), but this was derived only empirically without considering physiological responses, like thermoregulation (15). Using a linear regression model obtained from the relationship between the values of dorsal skin temperature change at P1 and absorbed PD, the skin temperature rise at P1 was estimated to be approximately 4.32°C when exposed to 200 W/m². Therefore, according to the authors, the validity of the limit value was confirmed in rats under the respective experimental conditions of this study.

4.3.2 Insects

Biological effects

Thill et al. [93] performed a systematic review and meta-analysis to examine the biological effects (altered behaviour, reduced reproductive capacity, DNA damage, oxidative stress, etc.) of LF and RF fields on insects. Only studies in the non-thermal range were included, based on provided tissue temperature measurements, or on the declared power densities used in experiments, if they were below ICNIRP limits. Meta-analyses were performed separately for single exposure sources but not for certain outcome domains except for reproductive outcomes in fruit flies. The meta-analysis of all endpoints combined revealed statistically significant negative effects for the exposure sources mobile phones, DECT phones, signal generators and coil systems, but not for base stations. The results of the meta-analysis for all experiments finding reproductive toxicity in fruit flies were also statistically significant at all three exposure levels examined. The overall conclusion of the authors is, that the majority of studies found effects, which were predominantly harmful, with RF fields being more harmful than LF fields.

Although the authors described their publication as a systematic review, there is no information that a study protocol documenting the methods used was published in advance or registered in an online database. Quality of included studies was assessed using the review criteria checklist published by the Task Force of Academic Medicine and the GEA-RIME Committee that was developed as guideline for reviewing manuscripts submitted for publication but not for systematic reviews. As recommended by PRISMA, risk of bias and certainty of evidence were not assessed (17). Therefore, important study quality aspects like randomization, blinding and quality of the exposure were not considered. The meta-analyses for the different exposure sources combined data from studies with very different endpoints and species leading to high heterogeneity (I^2 typically >90 %) and therefore unreliable results. Unfortunately, these limitations make the results of this systematic review uninformative.

Development

In a pilot study, de Paepe et al. [94] exposed pupae of the Blue Bottle Fly (*Calliphora vomitoria*, CV). Numerical, electromagnetic simulations with 3D anatomically accurate models of CV in the intrapuparial period, obtained using micro-CT scanning, were used. The pupae (n = 200 per group) were exposed for 48 h in a TEM cell to 5.4 GHz fields (modulation not given) at two different input power levels resulting in whole-body SAR of 0.028 W/kg or 0.23 W/kg, respectively. A sham-exposed group was included and all three groups had a concurrent control group that never entered the TEM cell. All groups showed similar masses, lengths and diameters during their development. The total rate of pupal emergence was reduced in the group exposed at 0.028 W/kg compared to its concurrent control. There was also a delay in emergence of flies from pupae in this group (+8 hours), while exposure at 0.23 W/kg resulted in a faster emergence (-8 hours) when compared to the concurrent control groups. However, also the sham condition resulted in a delayed emergence of flies (+4 hours) compared to its concurrent control group. Temperature measurements during exposure were not performed in that study.

4.3.3 Conclusions

As in previous years, effects on brain and behavior are the endpoints most often investigated. Other endpoints are rare and include effects on cancer, thermophysiology, reproductive system and other tissues and organs. This year, all included studies showed effects of exposure. However, within a study, effects were seen mostly on some but not all of the analyzed endpoints or only at specific time points. The exposure parameters, such as frequency, duration and exposure level, again vary considerably between studies.

A major limitation is the use of a very small number of animals per group in 11 of 13 experimental studies (excluding systematic reviews). In 5 studies, the sample size was only 3 animals in some of the experiments performed. In some publications, it is unclear how animals of each group were selected for the different experiments. A small sample size can lead to false-positive as well as to false-negative results (*see section on effects in animal studies*).

Two comprehensive systematic reviews were published on cancer and reproduction that showed either low to inadequate or uncertain evidence for health effects that did not allow to inform decisions at a regulatory level.

It is of concern that, similar to previous reports, a high number of studies had to be excluded because of insufficient or missing exposure description and/or dosimetry, but also due to other shortcomings (see appendix).

Overall, it is therefore difficult to draw a conclusion other than that under certain circumstances some effects from RF-EMF exposure are observed in experimental animals. It is striking, however, that most of the included experimental studies in this and the last year's report only examined male animals (Table 4.3).

Table 4.3: Animal studies investigating RF fields.

Endpoint	Reference	Exposure RF	Exposure Duration & Species	Effect
Rodents & other non-human mammals				
Behavior & effects on brain	Bodin et al. [78]	3500 MHz 0.07 W/kg (mother)	22 h/d for 7 days GD 8 until PND 21 Male & female Sprague Dawley rats (offspring)	Incisor eruption delayed in treatment groups of both sexes. Stereotyped movements in females ↓ and in males ↑. No other effects on physical development.
	Hao et al. [79]	2856 MHz pulsed Peak PD: 200 mW/cm²; average PD: 8 mW/cm²	900 s transgenic or WT Male C57BL/6N mice	↓ dopamine release in dHPC CA1 region. ↓ spatial learning and memory ability. ↑ activity of pyramidal neurons in dHPC CA1.

Endpoint	Reference	Exposure RF	Exposure Duration & Species	Effect
				No long lasting effects.
	Qin et al. [80]	4900 MHz ± EMP Average PD: 50 ± 2.5 W/m²; Electric field 650 kV/m; pulse repetition rate 2/s	4900 MHz: 1 h/d EMP: 10 min/d 1 week Male C57BL/6 mice	↓ locomotor activity and anxiety-like behavior. ↑ Glutamatergic and GABAergic synapse in hippocampus. Histological alterations in amygdala.
	Spandole-Dinu et al. [81]	2450 MHz WiFi router or laboratory RF generator Max local SAR: 17.86 mW/kg	16 weeks continuously Male BALB/c mice	↑ locomotor activity (higher in RF generator group than WiFi group). ↓ global DNA methylation in WiFi group. No histological changes.
	Wang et al. [82]	1500 MHz PD 5, 30, 50 mW/cm²	6 min Male Wistar rats	↓ spatial learning in all treatment groups. Changes in EEG at PD 30 and 50 after 6 h or 7 d. ↑ hippocampal injury with increasing PD until 7 d after exposure then recovery. Expression ↑ or ↓ of NMDAR proteins.
	Lai et al. [83]	1500 MHz ± EMP Average PD: 30 mW/cm²; Peak electric field strength: 400 ± 25 kV/m; pulse repetition frequency: 1 Hz	1500 MHz: 15 min EMP: 400 pulses Male Wistar rats	↓ Learning and memory ability. ↓ α wave power in EEG. Microstructural injury in hippocampus in all treatment groups. ↑ or ↓ expression of biomarkers of ferroptosis.
	Singh et al. [84]	2115 MHz Average head SAR: 1.51 W/kg	8 h Male Wistar rats	↑ oxidative stress and DNA damage in cortex and hippocampus. ↓ neurogenesis in dented gyrus. Neuronal damage in dented gyrus region but not cerebral cortex.
Cancer	Pinto et al. [85]	Systematic review 100 kHz-300 GHz	Rodents	Malignant tumours: ↑ in risk for CNS, brain, heart. ↓ in risk for intestine. CoE was low to very low resulting in low or inadequate health evidence.
Reproductive system	Gautam et al. [86]	2350 MHz 0.0625 W/kg	2 h/d for 56 days Male Wistar rats	↓ sperm viability. ↓ alkaline phosphatase in liver. ↑ of 3 hematological parameters. Alterations in tissue morphology of several organs.
	Cordelli et al. [87]	Systematic review 100 kHz-300 GHz	Non-human mammals exposed exclusively *in utero*	↑ resorbed or dead fetuses, percentage of fetuses with

Endpoint	Reference	Exposure RF	Exposure Duration & Species	Effect
				malformations, magnitude of the startle response to stimuli. ↓ fetal weight, length at birth, endurance capacity. CoE was moderate to very low. Impact of *in utero* RF exposure remains uncertain.
Adipose tissue	Maalouf et al. [88]	900 MHz CW 0.1, 0.4 W/kg	1 h/d twice, for 3 or 7 days Male C57BL/6J mice	mRNA expression changes of genes coding for thermoregulation and mitochondrial signaling pathways. No effect on mitochondrial DNA copy number.
Bone and muscle	Bektas et al. [89]	900, 1800, and 2100 MHz 0.026, 0.164, and 0.173 W/kg	2 h/d for 1 month Male Wistar albino rats	Changes in markers of oxidative stress in muscle tissue and of bone biomechanical quality in healthy and diabetic rats.
Thermophysiology	Ijima et al. [90]	28 GHz Absorbed PD at dorsal skin: 122, 237 W/m²	40 min Male Sprague Dawley rats	Exposure intensity-dependent increase in local temperature of rectum, dorsal and tail skin accompanied by blood flow changes in tail skin. qMMW exposure induces thermoregulation.
	Ijima et al. [91]	26.5 GHz Absorbed PD at skin surface: 125, 250, 370, 500 W/m²	18 min Male Sprague Dawley rats	qMMW exposure induces localized temperature increases. At 200 W/m², skin temperature rise is less than 5°C.
Insects				
Biological effects	Thill et al. [92]	Systematic review LF and HF fields	Drosophila, Honeybee, Cockroach, Beetle Ant, Wasp, Locust Springtail, Other	Negative effects of mobile phones, DECT phones, signal generators, coil systems, but not base stations. Negative effect on fruit fly reproduction.
Development	De Paepe et al. [93]	5.4 GHz 0.028, 0.23 W/kg	48 h Blue Bottle Fly (Calliphora vomitoria)	↓ rate of pupal emergence at 0.028 W/kg. Emergence of flies delayed at 0.028 W/kg, faster at 0.23 W/kg. Sham group also delayed emergence.

Abbreviations: ↑ increase; ↓ decrease; GD: gestational day; PND: post-natal day; WT: wild-type; dHPC: dorsal hippocampus; PD: power density; EMP: electromagnetic pulse; CW: continuous wave; NMDAR: N-methyl D-aspartate receptor; EEG: Electroencephalography; CNS: central nervous system; CoE: Certainty of evidence; qMMW: quasi-millimeter wave.

4.4 Cell Studies

In the previous reporting period seven studies on the effect of RF exposure *in vitro* were recognized, and two of them also considered combined exposures to chemical agents. In the period of interest 19 papers were recognized but eleven of them have not been included in the analysis due to scanty quality of the research. The eight studies considered addressed the effect of exposure on apoptosis, cell cycle, neuronal activity, mitochondrial stress, inflammation, and DNA integrity, DNA methylation and oxidative stress. In four of them the effects of combined exposures were also considered. In most cases no effect of RF exposure alone was detected, while combined exposures resulted in a difference with respect to samples exposed to RF alone.

4.4.1 Cell proliferation, cell cycle, apoptosis, DNA damage and oxidative stress

An et al. [95] investigated the effects of RF exposure on embryonic neural stem cells. They applied a double blind procedure to exposed neuroectodermal stem cells (NE-4C cells) to a 1950 MHz, 2 W/kg SAR, for 48 h and measured cell proliferation, cell cycle progression and apoptosis. Protein content and mRNA expression was also evaluated. In three to four independent experiments no effect was detected by comparing sham exposed and RF exposed cultures, except for the content of some proteins involved in neurodevelopment or brain function that resulted significantly upregulated ($p<0.05$), although the expression of other genes directly related to neurodevelopment or brain function did not differ compared to sham samples. In addition, no significant pathway alterations in NE-4C cells were detected. [For RF exposure, it is not reported if a CW or a modulation was applied].

Non-genotoxic carcinogenesis epigenetic alterations can occur which can affect gene function, leading to cellular neoplastic transformation. DNA methylation (DNAm) is one of the main epigenetic modifications and aberrant DNAm of genomic repetitive elements (REs) may promote genomic instability .In a study carried out by Ravaioli et al. [96] the authors investigated whether exposure to RF affects DNA methylation (DNAm) of different classes of Res (Repetitive elements) whose deregulation has been implicated in carcinogenesis, such as long interspersed nuclear elements-1 (LINE-1), Alu short interspersed nuclear elements (SINEs) and the DNA sequences encoding RNA ribosomal (rDNA) alterations in the average DNAm level and of DNAm profile (epihaplotype).

To this purpose, an epithelial human cell line (HeLa) and two neuroblastoma human cell

lines, (Be(2)C and SH-SY5Y), were exposed blinded to 900 MHz, GSM modulated for 48 h at 1 W/kg SAR and the effect of RF was evaluated in terms of both alterations in the average DNAm level and in DNAm profile (epihaplotype) and distribution.

The results indicate that the exposure can induce changes in the DNAm epihaplotype diversity. In particular, by comparing exposed to sham-exposed cultures, an increase of LINE-1 DNAm was detected in HeLa and SH-SY5Y cells, whereas a decrease was recorded in rDNA DNAm in BE(2) C cells ($p<0.05$).

The authors concluded that such changes may indicate a dysfunction in the maintenance of epigenetic patterns, which can contribute to epigenetic instability, although the effect strongly depends on the cell type investigated. [In this study the authors stated that a larger number of observation are necessary to obtain more solid results, but they do not report the number of independent experiments performed].

Global DNA methylation changes were also investigated by Cantu et al. [97] following exposure of human epidermal keratinocytes (HEKa) to 900 MHz, CW, for 1 h at an estimated mean specific absorption rate lower than 0.01 W/kg. The experiments were carried out blinded and temperature was controlled and remained within 37 °C during the exposure period. The results of three independent experiments indicated that no effect on cell viability was induced by the exposure, but differences in DNA methylation patterns of exposed cells were detected compared to sham controls ($p<0.05$). In particular, 114 significant differentially methylated genes (DMGs) were identified, of which 48 were hypomethylated and 66 were hypermethylated.

Since modification of DNA methylation pattern can result in alteration of gene expression, the authors evaluated if the identified DMGs were differentially expressed in the exposed samples. The comparison analysis revealed only six genes in the exposed group that had a significant change in both DNA methylation and gene expression, with a positive correlation between DNA methylation and gene expression. These genes include targets involved in critical cell functions such as cell survival and response to damage.

According to the authors, the results of this study indicate that RF-induced changes in differential DNA methylation can elicit changes in gene expression.

In a study carried out by Sannino et al. [98] the cellular response to RF exposure, administered alone and in combination with mitomycin-C (MMC) was investigated.

Chinese hamster lung fibroblast (V79) cells were exposed/sham exposed 1950 MHz, long-term evolution (LTE) signal, in a waveguide-based system at 0.3 and 1.25 W/kg SAR for 3 or 20 h.

Chromosomal damage (micronuclei formation, MN), oxidative stress (reactive oxygen species [ROS] formation), and cell cycle progression were analysed after exposure and co-exposure. No differences between exposed samples and sham-controls were detected following RF exposure alone, for all the experimental conditions tested and biological endpoints investigated. MMC treatment also served as positive control.

When RF was followed by MMC treatment, 3h pre-exposure did not modify MMC-induced MN at both 0.3 and 1.25 W/kg. Same results were obtained following 20 h pre-exposure at 0.3W/kg, while 1.25W/kg resulted in a significant reduction of MMC-induced damage ($p<0.001$). Absence of effects was also detected when CW was used, at both SAR levels. MMC-induced ROS formation resulted significantly decreased at both SAR levels investigated ($p<0.001$), while cell proliferation and cell cycle progression were not affected by co-exposures. The results, obtained in 3 to 4 independent experiments carried out blinded, provide no evidence of direct effects of 1950 MHz, LTE signal. Moreover, they further support previous findings reported by the same research group on the capability of RF pre-exposure to induce protection from a subsequent toxic treatment, and the key role of the modulated signals and the experimental conditions adopted in eliciting the effect.

4.4.2 Mitochondrial integrity

Mitochondria are one of the most crucial intracellular organelles with a critical role in maintaining cellular homeostasis. Despite cell respiration and energy production, they also have a key role as regulator for calcium metabolism, including buffering of intracellular calcium ($[Ca2+]i$) levels by concentration of mitochondrial calcium ($[Ca2+]m$) uptake, when cytosolic levels are elevated.

Several diseases have been suggested to be related to [Ca2+]m overload, such as neurodegeneration, ischemia and cancer. The transmembrane protein mitochondrial calcium uniporter (MCU) is one of the primary sources of [Ca2+]m uptake, which allows the passage of calcium ions from the cytoplasm into mitochondria and treatments with Ruthenium 360 (RU360) inhibits the flow of calcium into mitochondria.

In a study carried out by Sun et al. [99] it was investigated whether inhibition of MCU in immortalized mouse embryonic fibroblasts (MEFs) exposed to 1800 MHz, 4 W/kg SAR, induces effects on DNA integrity, cell cycle, cell proliferation, cell viability and apoptosis. RF exposure was carried out in absence and in presence of RU360 or Carbonyl Cyanide m-Chlorophenylhydrazone (CCCP, an inhibitor of oxidative phosphorylation, affecting mitochondrial membrane potential) based on the parameter investigated. The exposures were blinded and for each parameter a positive control was provided. The results are obtained from three to six independent experiments.

RF exposure for 15 min had no effect on DNA damage, evaluated by applying the comet assay, while in cells treated with Ru360 a significant DNA damage was detected ($p<0.01$). For longer exposure duration (1 hour) DNA damage was detected in cells untreated and treated with Ru360 ($p<0.001$). In both cases the damage resulted reversible within 1 h from the end of the exposure. Cell cycle, proliferation and viability resulted unaffected by 15 min exposure, in presence and in absence of RU360. Apoptosis also resulted unaffected after 15 min and 1h exposure to RF alone but in cells treated with RU360 the exposure induced a significant increase ($p<0.05$).

Patrignoni et al. [100] investigated the effect of 5G-modulated 3.5 GHz on mitochondrial stress by evaluating viability, mitochondrial membrane potential (MMP), mitochondrial reactive species concentration (mitROS) and apoptosis in human fibroblasts (Xp6eb cells) and keratinocytes (KHAT cells) exposed for 24 h at 0.25, 1, and 4 W/kg SAR. Both cell types were also subjected to a co-exposure protocol with UV-B to evaluate combined effects. To this purpose, UV radiation was given before RF. In six independent experiments carried out blinded, viability, mitochondrial membrane potential (MMP) and apoptosis resulted unaffected in both cell types and for all the RF exposure and co-exposure protocols. On the contrary, mitROS concentration resulted significantly decreased in Xp6eb cells exposed to RF alone at 1 W/kg ($p<0.01$) but not in KHAT cells and increased in KHAT cells co-exposed to UV and RF at 0.25 and 1 W/Kg ($p<0.05$), but not in Xp6eb cells.

4.4.3 Other cellular endpoints

A study carried out by Canovi et al**.** [101] assessed the effects of RF exposure at 3.5 GHz, CW or 5G-modulated signals, on neuronal activity of primary cortical neurons isolated from the cortex of embryonic Sprague–Dawley rats. Spontaneous electrophysiological activities of neuronal networks were recorded by a multi-electrode array (MEA).To this purpose, neuronal cultures were exposed or sham-exposed for 15 min at SAR values of 1, 3, and 28 W/kg. The exposure protocol was divided into 5 phases of 15 min: two pre-exposure phases, the RF or sham exposure phase and two post-exposure phases and for all exposure conditions, the electrophysiological recordings of the RF-exposed phase were compared with the pre-exposure and the post-exposure recordings, according to four metrics, such as the mean bursting rate (MBR) (total number of bursts per minute collected over all active electrodes), the mean firing rate (MFR) (total number of spikes per second collected over all active electrodes) (MFR), the mean burst duration (MBD) (average burst duration calculated across all active electrodes), and the mean outside bursts firing rate (MOBFR) (total number of isolated spikes (occurring outside bursts) per second collected over all active electrodes.). At SAR values of 1 and 3 W/kg no differences were detected in CW experiments for all metrics considered while 5G modulated experiments showed a significant increase of MOBFR at 1 W/kg and of MFR at 3 W/kg ($p < 0.05$), although such an increase resulted reversible. On the contrary, CW and 5G-modulated signals elicited a clear decrease in bursting and total firing rates during RF exposure at high SAR levels (28 W/kg). To assess the role of the carrier frequency in eliciting the effect, the authors used the same setup to exposed neuronal cultures to a 1.8 GHz, CW, at a SAR of 28 W/kg and obtained similar results, demonstrating that such an effect is not related to the frequency. However, they stressed that the employed SAR exceeds the maximum SAR recommended by ICNIRP for human exposure.

Szilagyi et al. [102] investigated whether RF exposure (2422 MHz, Wi-Fi signal) given alone or in combination with UV radiation induce inflammation and photoaging in a 3D reconstructed human skin model composed by normal human-derived epidermal keratinocytes and normal human-derived dermal fibroblasts. To this purpose, cell viability and interleukins and the matrix metalloproteinase-1 enzyme (MMP-1, a fibroblast collagenase) production were evaluated.

Interleukins play a key role in pro- and anti-inflammatory functions; MMP-1 is an enzyme that degrade several components of extracellular matrix proteins, such as collagen, fibronectin, elastin, proteoglycans and is a regulator of photocarcinogenesis.

Cell cultures were exposed to 2422 MHz Wi-Fi RF field and UV radiation by applying two protocols named “additive protocol” (RF given immediately after UV radiation; UV+RF) and “adaptive protocol” (RF given before UV radiation; RF+UV). In both protocols the effect of RF exposure alone was also investigated. For RF exposure a wire patch cell was employed and cell cultures were exposed for 24 h. In the experiments carried out with the additive protocol the RF exposure was intermittent (20 min on/20 min off) at 4 W/kg SAR. UV exposure was carried out by using a solar lamp and the dose was 2 SED (Standard Erythemal Dose, corresponding to 100 Jm^{-2}) when the additive protocol was applied. For the adaptive protocol, 1.5 W/kg SAR and an UV dose of 4 SED were used.

Concerning experiments with RF alone, viability was measured only in cultures exposed at 4 W/kg and resulted unaffected by comparing exposed and sham exposed cultures. No effects were also detected when interleukin (IL-1α, IL-6 and IL-8) and MMP-1 concentration was measured.

In both combined protocols (UV+RF and RF+UV) no effects were detected, except for UV treatments in presence or in absence of RF ($p<0.005$), indicating no effects of combined exposures. For each condition three independent experiments were carried out. [In this study blind procedure was not applied].

4.4.4 Conclusions on RF cell studies

As in previous years, there is a large variety of endpoints, cell types and exposure parameters investigated with varying results. Therefore, although it is difficult to draw general conclusions, it should be noted that when RF is given alone, in most cases no effects are measured. The opposite is for combined exposures. The additional eleven studies recognized were not considered due to the scanty experimental quality (mainly lack of dosimetry and/or sham-controls). Thus, as for the previous years, quality remains one of the most important aspects to be improved in bioelectromagnetic research (Table 4.4).

Table 4.4: Cell studies investigating RF fields.

Cell type	Endpoint	Exposure conditions	Effect	References
Neuroectodermal stem (NE-4C) cells n = 3-4	Proliferation, cell cycle, apoptosis and protein content	1950 MHz 2 W/kg 48 h	No effect on proliferation, cell cycle, apoptosis; ↑ content of some proteins but not of gene expression involved in brain development or functions	An et al. (2023)
Epithelial human cell line (HeLa) Human neuroblastoma cell lines (SH-SY5Y; BE(2)C) n = not reported	DNAm level and profile	900 MHz, GSM 1 W/kg, 48 h	↑ or ↓ in DNAm profile depending on the cell type investigated.	Ravaioli et al. (2023)
Human epidermal keratinocytes (HEKa) n = 3	Proliferation, DNAm changes and gene expression	900 MHz, CW 0.01 W/kg 1 h	No effect on cell proliferation. Differences in DNAm patterns and gene expression	Cantu et al. (2023)
Chinese hamster lung fibroblast (V79) cells n = 3-4	MN frequency; ROS formation; cell cycle	1950 MHz, CW and LTE 0.3 and 1.25 W/kg 3 and 20 h Co-exposure to MMC (after RF)	No effect of LTE alone. No effect of CW RF exposure and co-exposure. ↓ of MMC-induced MN at 1.25 W/kg for 20h; ↓ of MMC-induced ROS at o.3 and 1.25 W/kg for 20h	Sannino et al. (2023)
Immortalized mouse embryonic fibroblasts (MEFs) n = 3-6	DNA damage, cell cycle, proliferation, viability and apoptosis	1800 MHz 4 W/kg 15’ and 1 h RF + RU360	RF alone: No effect, except for DNA damage after 1 h exposure. RF+RU360: reversible DNA damage after 15’ and 1h exposure; induction of apoptosis	Sun et al. (2023)
Human fibroblasts (Xp6eb cells) and keratinocytes (KHAT cells) n = 6	mitochondrial stress	3.5 GHz 5G mod. 0.21, 1, 4 W/kg 24 h Co-exposure to UV (before RF)	No effects on MMP and apoptosis in all cases. mitROS ↓ in Xp6eb cells exposed to RF alone at 1 W/kg and ↑ in KHAT cells co-exposed to UV and RF at 0.25 and 1 W/Kg	Patrignoni et al. (2023)

Primary cortical rat neurons n = 8	Neuronal activity	3.5 GHz CW, 5G mod. 1, 3, 28 W/kg 15 min 1.8 GHz CW 28 W/kg 15 min	CW: no effect 5G Mod: increase of MOBFR at 1 W/kg and of MFR at 3 W/kg. Reversible effect. ↓ at 28 W/kg Similar effect as 5G Mod	Canovi et al. (2023)
human skin model n = 3	Viability, Interleukins and MMP-1 production	2422 MHz, Wi-Fi UV+RF 2 SED; 4 W/kg 24 h, 20'on/20'off RF+UV 4 SED; 1.5 W/kg 24 h continuous	No effects of RF alone. No effects of co-exposures.	Szilagyi et al. (2023)

Abbreviations: ↓: decrease; ↑: increase; 5G-mod: 5G modulation; Ca++: Calcium ions; CW: Continuous wave; DNAm: DNA methylation; GSM: Global System for Mobile Communications; LTE: Long-Term Evolution; MBD: mean burst duration; MBR: mean bursting rate; MFR: mean firing rate; MMC: mitomycin-C; MMP: mitochondrial membrane potential; MN: micronuclei; MOBFR: total number of isolated spikes; mitROS: mitochondrial reactive oxygen species; ROS: reactive oxygen species; RU360: Ruthenium 360; Wi-Fi: Wireless Fidelity.

5 Studies Excluded from Analysis

5.1 Harmonised inclusion/exclusion criteria for report

5.1.1 General inclusion/exclusion criteria

In a first step, all articles that were not relevant for this report were discarded, i.e.:

1.a) Papers that did not study non-ionizing electromagnetic fields (i.e., static, extremely low frequency, intermediate frequency or radiofrequency EMF).

1.b) Papers that did not study any health outcome and/or biological effect (including letters, commentaries etc.).

1.c) Papers that did not in any way study the association between radiofrequency fields and a health outcome and/or a biological effect (e.g., the use of text messages for self-management of diabetes).

1.d) Studies on using EMF as therapeutic interventions (e.g. diathermy, osteoporosis, bone healing, diabetes, schizophrenia, spinal cord injury,…).

1.e) Case-reports.

1.f) Not a peer-reviewed publication, or published in another language than English.

1.g) Studies published outside of the time frame of this report (online publication date).

1.h) Narrative reviews.

1.i) Duplicate reports, unless new additional analyses are presented (including the first original publication, and information from duplicate reports if new additional results were presented).

1.j) Insufficient or missing exposure description and/or dosimetry in human, animal and in vitro studies. This includes studies addressing exclusively exposure assessment methods which have been proven to be invalid such as self-estimated distance to mobile phone base stations.

EPIDEMIOLOGICAL STUDIES

Under “epidemiological studies”, observational studies in humans are summarized. In addition to the general exclusion criteria, the following criteria are applied:

2.a) Studies that did not include humans.
Note that studies of humans with an experimental design are included in the chapter “human studies”.

2.b) Study base not identified (e.g., self-selection of subjects in cross-sectional or case-control studies, the population intended for inclusion not described).

2.c) No comparison group or no exposure considered (either no unexposed group or lacking denominator for prevalence/incidence calculation in descriptive or incidence study), with the exception of incidence trend studies from registries applying a systematic data collection.

2.d) Studies on self-reported quality of life outcomes/psychological outcomes and media use if they do not explicitly mention EMF.

2.e) Statistics not described and/or confounders not adjusted for.

HUMAN STUDIES

Under "human studies", experimental design studies in humans are summarized. In addition to the general exclusion criteria, the following criteria are applied:

3.a) Studies that investigate technical devices to reduce exposure.

3.b) Studies with a parallel group design, in which differences in the investigated outcome parameters at baseline are not considered in the analysis.

3.c) No sham exposure condition.

3.d) No information on blinding.

3.e) No information on randomization or counter-balancing provided.

3.f) Studies that do not report statistics for exposure effects.

ANIMAL STUDIES

Under "animal studies", observational or experimental design studies in animals are summarized. Studies addressing human observational or experimental studies, or in vitro studies, were excluded from this chapter. In addition to the general exclusion criteria listed above, the following criteria are applied for this group:

4.a) Studies that did not include animals.

4.b) Studies on bacteria or viruses.

4.c) Animal studies reporting on geomagnetic field orientation and/or magnetoreception.

4.d) Papers that did not include a sham exposed group.

4.e) Insufficient description of animal experiment, e.g., strain and/or sex or age of exposed species not reported [1]). This includes a statement that ethical clearance has been obtained.

4.f) Studies that did not include at least 3 animals per group in experimental studies.

4.g) Studies that did not report statistics for exposure effects and/or studies that do not provide details of the statistical methods used for the analysis.

4.h) Studies using a commercial mobile phone as exposure source

IN VITRO (CELL) STUDIES

Under in vitro studies, only experimental studies using in-vitro designs are discussed. In addition to the general exclusion criteria, the following criteria were applied:

5.a) Studies that did not include at least 3 independent experiments with at least 2 different exposure conditions in which cells are treated completely identically, with the only exception in exposure.

5.b) Studies that did not provide a clear description of method to evaluate endpoint.

5.c) Temperature not controlled for in RF-EMF studies.

5.d) Studies that did not report statistics for exposure effects and/or studies that do not provide details of the statistical methods used for the analysis.

5.2 Epidemiological Studies

Reference	Reason for exclution
Jamshed et al. [103]	1.g
Addison et al. [104]	1.b
Aerts et al. [105]	1.b
Amiri et al. [106]	1.g
ANFR [107]	1.b
Arribas et al. [108]	1.b
Atanasova et al. [109]	1.b
Baliah et al. [110]	1.b
Banerjee et al. [111]	1.g
Ben Ishai et al. [112]	1.g
Berisha et al. [113]	1.b
Calvente et al. [114]	1.b
Chardon et al. [115]	1.b
Chartes et al. [116]	1.b
Chou et al. [117]	1.g
Chu KY et al. [118]	1.g
Chu Y et al. [119]	2.d
Costa et al. [69]	1.b
da L A Silva et al. [120]	1.b
Davis et al. [121]	1.b
de Vocht et al. [122]	1.b
de Vocht et al. [123]	1.g
Deschamps et al. [124]	1.b
Deshayes-Pincon et al. [125]	1.b
Eeftens et al. [71]	1.b
Emeksiz et al. [126]	1.b
Foster et al. [127]	1.b

Goiceanu et al. [128]	1.b
Hardell et al. [129]	1.e
Henderson et al. [130]	1.b
Hensinger et al. [131]	1.b
Hinrikus et al. [132]	1.b
Hoang et al. [133]	1.g
Lakovidis et al. [134]	1.g
Islam et al. [135]	1.b
Jakusova et al. [136]	1.g
Kaplan et al. [137]	1.b
Khalat et al. [138]	1.h
Kopacz et al. [139]	1.b
Lee et al. [140]	1.b
Leszczynski et al. [141]	1.b
Leszczynski et al. [142]	1.b
Levitt et al. [143]	1.g
Lin et al. [144]	1.g
Lin et al. [145]	1.b
Loizeau et al. [146]	1.b
Lopez et al. [147]	1.b
Mallik et al. [148]	1.g
Manassas et al. [149]	1.b
Martinez et al. [150]	1.b
Mazloum et al. [151]	1.b
McCredden et al. [152]	1.g
McCredden et al. [153]	1.b
McKenzie et al. [154]	1.b
Michalowska et al. [155]	1.b
Minoretti et al. [156]	1.e
Misek et al. [157]	1.b

Mulot et al. [158]	1.f
Nadolny et al. [159]	1.b
Nedelcu et al. [160]	1.b
Nedic et al. [161]	1.b
Nilsson et al. [162]	1.b
Nordin et al. [163]	1.b
Nyberg et al. [164]	1.b
Olorunsola et al. [165]	1.b
Onishi et al. [166]	1.b
Panagiotakopoulos et al. [167]	1.b
Paniagua-Sánchez et al. [168]	1.b
Park et al. [169]	1.b
Peleg et al. [170]	1.g
Petroulakis et al. [171]	1.b
Pophof et al. [172]	1.f
Pophof et al. [173]	1.f
Rajendran et al. [174]	1.b
Ramirez-Vazquez et al. [175]	1.g
Ramirez-Vazquez et al. [176]	1.b
Ramirez-Vazquez et al. [177]	1.b
Ramirez-Vazquez et al. [178]	1.b
Ramos et al. [179]	1.b
Raveendran et al. [180]	1.b
Razek et al. [181]	1.h
Reddy et al. [182]	1.b
Redmayne et al. [183]	1.h
Sarimov et al. [184]	1.h
Sarimov et al. [39]	1.h
SCHEER [185]	1.f
Shaheen et al. [186]	1.g

Sharma et al. [187]	1.g
Shirbandi et al. [188]	1.d
Singh et al. [189]	1.g
Song et al. [190]	1.b
Suarez et al. [191]	1.b
Suraweera et al. [192]	1.b
SwissNIS [193]	1.f
Tamim et al. [194]	1.b
Thamilselvan et al. [195]	1.g
Thulu et al. [196]	1.b
Turuban et al. [197]	1.b
Tyrakis et al. [198]	1.b
Ureta-Leones et al. [199]	1.b
Vecsei et al. [200]	1.b
Vijayalaxmi et al. [201]	1.h
Weller et al. [202]	1.b
Wersenyi et al. [203]	1.h
Wright et al. [204]	1.b
Wyszkowska et al. [205]	1.g
Yang et al. [206]	1.b

5.3 Human studies

Extremely Low Frequency (ELF) fields

Reference	Reason for exclusion
Markus et al. [207]	Therapeutic application of ELF in athletes (1.d)
Wennberg et al. [208]	No sham condition (MRI exposure vs. classroom condition) (3.c)

Radiofrequency fields (RF)

Reference	Reason for exclusion
Besset et al. [73]	Non-experimental; observational study on RF-EMF on sleep in newborns, no sham condition (3.c)
Geronikolou et al. [209]	RF-EMF exposure by cellular phone 3 min phone call of parent (1.j)
Liang et al. [210]	No information on blinding; parallel-group design without cross-over for four different conditions not suitable to evaluate EMF effects (3.b)
Parizek et al. [211]	no sham control, no information on blinding (experimentor present), no cross-over design (3.d)

5.4 Animal Studies

Excluded animal studies SF

Reference	Reason for exclusion
Liu *et al*. [212]	Non *in vivo* study (4.a)
Lv et al. [213]	Medical application (1.d)
Oliva et al. [214]	No proper sham group (4.c)
Pogson et al. [215]	It is not an *in vivo* study, it presents a numerical model (4.a)
Xiao et al. [216]	No proper sham group (4.c)
Zhang et al. [217]	Medical Application (1.d)
Zhao et al. [218]	Non *in vivo* study (4.a)

Excluded animal studies ELF fields

Reference	Reason for exclusion
Aydinbelge-Dizdar et al. [219]	No proper sham group (4.c)

Budak et al. [220]	No *in vivo* study (4.a)
Nakanishi et al. [221]	No proper sham group (4.c)
Salari et al. [222]	No proper sham group (4.c)
Şenol et al. [223]	Exposure level not indicated (1.j)
Tekam et al. [224]	Medical application (1.d)
Zhao et al. [225]	No *in vivo* study (4.a)

Excluded animal studies IF fields

Reference	Reason for exclusion
Alamsyah et al. [226]	Not approved for publication (1.g)

Reviews SF-ELF-IF

All these reviews were excluded because they are not systematic reviews

Reference	Reason for exclusion
Jangid et al. [227]	Not a systematic review (1.h)
Khalat et al. [138]	Not a systematic review (1.h)
Lee et al. [228]	Not a systematic review (1.h)
López-Martín et al. [229]	Not a systematic review (1.h)
Pophof et al. [172]	Not a systematic review (1.h)
Reategui-Inga et al [230]	Not a systematic review (1.h)
Tian et al. [231]	Not a systematic review (1.h)
Wei et al. [232]	Not a systematic review (1.h)
Zhang et al. [233]	Not a systematic review (1.h)

Excluded animal studies RF-EMF

Reference	Reason for exclusion
Akbari et al. [234]	Poor description of exposure conditions, no dosimetry, unclear if control was sham-exposed (1.j, 4.c and 4.d)
Akefe et al. [235]	No dosimetry, Mobile phone in cage (unclear if in silent mode when calls were made) (1.j)
Amiri et al. [236]	Poor description of exposure conditions, SAR calculated from external E-field, unclear if control was sham-exposed (1.j, 4.c)
Asci et al. [237]	Insufficient description of dosimetry, no information about SAR, unclear if real sham (1.j, 4.c)
Augustianath et al. [238]	Poor dosimetry and experimental setup (eggs are not equally distributed under mobile phone) (1.j)
Baňas et al. [239]	Excluded because no health outcome studied (only position) (1.b)
Bayat et al. [240]	Insufficient description of exposure conditions, unclear how PD and SAR were measured/calculated (1.j)
Bozok et al. [241]	Insufficient description of dosimetry, control group probably not sham exposed (1.j, 4.c)
Chang et al. [242]	Exposure with household microwave oven (1.j)
Coronado et al. [243]	No sham exposure (4.c)
DastAmooz et al. [244]	Exposure with WiFi modem during down and upload of "various files, SAR probably measured using external E-field (1.j)
Dehghani et al.	No detailed description of statistical analysis, incomplete dosimetry: no SAR, power density not measured at location of animals (1.j, 4.f)
Demirbağ B. et al. [245]	Environmental conditions not reported (temperature, humidity, light/dark cycle) (4.d)
Díaz-Del et al. [246]	Therapeutic instrument used for exposure without dosimetry (1.j)
El-Kafoury et al. [247]	Exposure using commercial cell phone and making calls; EMF measured using Gauss/Teslameter (1.j)
Goudarzi et al. [248]	Poor description of exposure system, no dosimetry, no age reported, no information about animal cages (1.j, 4.d)
Islam et al. [249]	Exposure using commercial mobile phone and making video call (1.j)
Khayat et al. [250]	Exposure conditions (cage, distance to antenna) not described, no dosimetry, unclear where PD was measured because unclear were cages with animals were positioned (1.j)
Kilic et al. [251]	Insufficient dosimetry: E-field measured below cage (not at position of animals), no PD or SAR (1.j)

Koohestanidehaghi et al. [252]	Exposure using commercial mobile phone in conversation mode (1.j)
Leberecht et al. [253]	Orientation of eurasian blackcaps. Not affected by RF noise in the frequency bands 140 to 150 MHz and 235 to 245 MHz (4.b)
Li D. et al. [254]	Exposure not sufficiently described, the position at which the provided PD value was evaluated is not specified, age of animals not reported (1.j, 4.d)
Li K. et al. [255]	Out of scope (heating of skin tissue) (1.b)
Luan et al. [256]	Out of scope (fillets bought in supermarket) (1.b)
Men et al. [257]	Exposure system not sufficiently described, no dosimetry, probably no sham (just "control") (1.j, 4.c)
Migdal et al. [258]	No mentioning of sham (just unexposed control), unclear if control was held under same conditions, housing conditions during exposure not given (4.c, 4.d)
Mohamed et al. [259]	Control probably not sham exposed and unclear if held under same environmental conditions as exposed, housing conditions not indicated (4.c, 4.d)
Muheim et al. [260]	Orientation of zebra finches. Affected in presence of low-level (~ 10 nT) Larmor-frequency RF fields but able to orient if trained in this condition (4.b)
Niu et al. [261]	No age or sex of mice given, no dosimetry, unclear at which position PD was measured (1.j, 4.d)
Pecoraro R. et al. [262]	No sham group (control “placed far from the antenna”) (4.c)
Saka et al. [263]	Commercial mobile phone for exposure (1.j)
Salameh et al. [264]	SAR probably not correctly measured (no simulation, external field), no sham control (mentioning of a “control”, but unclear if exposed to same environmental conditions with RF generator turned off), insufficient description of animal experiment (unclear how many embryos from each mouse were used and how those were selected) (1.j, 4.c, 4.d)
Sarapultseva et al. [265]	For sham group ("mock-treated") not specified when sham-exposure took place (1 to 5 or 6 to 10 days?) (4.d)
Savchenko et al. [266]	Unclear if control group was exposed to same environmental conditions or put into the GTEM cell as well (with power turned off) (4.c)
Savchenko et al. [267]	Unclear if control group was exposed to same environmental conditions or put into the GTEM cell as well (with power turned off) (4.c)
Sofrankova et al. [268]	Insufficient dosimetry: no measurement of PD or electric field at position of animals, no SAR, insufficient description of "apparatus" holding the ticks (1.j, 4.d)
Son et al. [269]	Therapeutic effects of RFR exposure in a mouse model of Alzheimer's disease (1.d)

Tarsaei M. et al. [270]	No ethics approval (just "followed guidelines"), insufficient dosimetry: PD not measured at position of animals, incomplete housing conditions (1.j, 4.d)
Treder et al. [271]	No real sham (controls placed at a distance of 5 m away from EMF colonies) (4.c)
Tripathi et al. [272]	Mobile phone in "switched on" mode (1.j)
Tüfekci et al. [273]	No dosimetry (just reference to paper, where it is also not indicated but again only reference to another paper and there again reference to another paper where young adult rats (not pubs) were analyzed), unclear where animals were exposed ("exposure system included an lead-coated insulated room" - other than room described in the beginning?), unclear if sham group was sham-exposed under same environmental conditions as exposed group (1.j, 4.c)
Vafaei et al. [274]	No/very little information on exposure and dosimetry (1.j)
Wang et al. [275]	No/very little information on exposure and dosimetry (1.j)
Wang Y. et al. [276]	Missing description of exposure system and dosimetry (1.j)
Wu et al. [277]	No dosimetry, no housing conditions (temp, humidity, light/dark cycle) (1.j, 4.d)
Yao et al. [278]	Age of animals not given, housing conditions not indicated, insufficient dosimetry: unclear how SAR was calculated for testicles (1.j, 4.d)
Yao et al. [279]	Housing conditions not indicated, unclear if sham group exposed at same conditions, dosimetry insufficient: position of PD measurement not indicated (1.j, 4.c, 4.d)
Yazdanpanahi et al. [280]	No ethical approval, no dosimetry and poor description of exposure (1.j, 4.d)
Zheng et al. [281]	Unclear how SAR was calculated (just reference to two papers using different methods but not specified how it was done in current study), probably using external E-field for measurement, unclear if ethics approval (1.j, 4.d)
Zufry et al. [282]	No/insufficient description of exposure system and dosimetry: No SAR, no power density, no housing conditions, no description of mobile phone used as exposure source (1.j, 4.d)

Excluded reviews on animal studies and RF-EMF

Jangid et al. [227]	Narrative review on ELF and RF exposure and female reproductive system and fertility in in vivo and in vitro studies (1.h)
Karipidis et al. [283]	A systematic map about all the available evidence on whether anthropogenic RF EMF has an effect on plants and animals in the environment (1.h)

Kaur et al. [284]	Narrative review on RF exposure and male reproductive system in in vivo and in vitro studies (1.h)
Pophof et al. [173]	The report summarizes the effects of anthropogenic radiofrequency electromagnetic fields with frequencies above 100 MHz on flora and fauna presented at an international workshop held on 5-7 November 2019 in Munich, Germany (1.h)
Reategui-Inga et al. [230]	Narrative review with focus on bees (1.h)
Vijayalaxmi & Foster et al. [201]	A review that summarizes the evolution of consensus guidelines for genotoxicity testing and highlights existing issues in the investigation of genotoxic effects (1.h)

5.5 Cell Studies

Cell studies excluded from analysis

Reference	Reason for exclusion
Benavides et al. [285]	No Sham control (4.d)
Bertuccio et al. [286]	No Sham control (4.d)
Byun et al. [287]	No Sham control; no dosimetry performed (4.d, 1.j)
Chu et al. [118]	Smartphone in talk-mode; no dosimetry performed (1.j)
Laksono et al. [288]	No Sham control; no dosimetry performed (4.d, 1.j)
Laksono et al. [289]	No Sham control; no dosimetry performed (4.d, 1.j)
Nowak-Terpiłowska et al. [290]	No Sham control (4.d)
Rana et al. [291]	No Sham control (4.d)
Saka et al. [263]	Cell phone in talk-mode (1.j)
Toledano-Macías et al. [292]	No Sham control; no dosimetry performed (4.d, 1.j)
Wang et al. [293]	No Sham control (4.d)

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