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Swedish Radiation Safety Authority

Research

Recent Research on electromagnetic fields and Health Risk, twentieth report from SSM's Scientific Council on Electromagnetic Fields, 2025

2026:03

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SSM perspektiv

Bakgrund

Strålsäkerhetsmyndighetens (SSM) vetenskapliga råd om elektromagnetiska fält följer den aktuella forskningen 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 prövning är nödvändig. Rådet ska varje år 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. Rapportens främsta syfte är att sammanfatta föregående års forskning inom området elektromagnetiska fält (EMF) och hälsa och att sätta denna forskning i ett sammanhang med befintlig kunskap. Rapporten ger myndigheten en överblick och utgör ett viktigt underlag för riskbedömning.

Resultat

Denna rapport går igenom studier om elektromagnetiska fält (EMF) och hälsorisker som publicerades från januari 2024 till och med december 2024. Rapporten är den tjugonde i en serie årliga vetenskapliga översikter som fortlöpande diskuterar och bedömer relevanta nya studier och placerar dem i sitt kunskapssammanhang. Rapporten omfattar olika typer av EMF (statiska fält, lågfrekventa fält, intermediärfrekventa fält och radiofrekventa fält) samt olika typer av studier såsom biologiska studier, humanstudier och epidemiologiska studier. Resultatet är en successivt framväxande hälsoriskbedömning av exponering för EMF.

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

De studier som presenteras i rapporten löser inte frågan om huruvida 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 forskning som i huvudsak antyder frånvaro av risk. Sköldkörteln är potentiellt kraftigt exponerad vid mobilsamtal, men hittills har få studier om sköldkörtelcancer genomförts.

Vad 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 rapporterats i tidigare SSM-rapporter, fortsätter att förekomma, 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 till följd av svag radiovågsexponering kan påverka människors hälsa återstår att undersöka.

Relevans

Resultaten från forskningsöversikten ger inget skäl att ändra några referensvärden eller rekommendationer inom området. Däremot visar de biologiska effekter som rapporterats i vissa djurstudier vid svag radiovågsexponering tydligt vikten av att upprätthålla försiktighetsprincipen enligt miljöbalken.

SSM:s rekommendation om att använda handsfree vid mobiltelefonsamtal kvarstår, även om trender avseende förekomsten av gliom inte ger stöd för en ökad risk orsakad av radiovågor från mobiltelefoner. Observerade biologiska effekter 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. De svenska myndigheternas rekommendation 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 hittills har kunnat påvisas 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 radiovågsexponering och oxidativ stress som observerats i djurstudier, samt att fastställa om ett sådant samband även förekommer hos människor och i så fall i vilken omfattning 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 frekvensområden som används för 5G. Myndigheten uppmuntrar forskare att initiera epidemiologiska studier inom detta område. Exempelvis finns idag mycket få studier i 26 GHz-bandet.

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

Trots den ökande användningen av tillämpningar inom det intermediära frekvensområdet (300 Hz–10 MHz) är den vetenskapliga utvärderingen av potentiella hälsorisker fortfarande begränsad. De få studier som rådet identifierat inom detta område har inte visat några hälsoeffekter under gällande referensnivåer. Årsrapporten innehåller också ett avsnitt där studier som bedömts ha otillräcklig kvalitet listas. Liksom föregående år har många studier exkluderats 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

Contact person SSM: Karl Herlin

Reference: SSM2025-10822 / 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. This 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 2024 up to and including December 2024. The report is the twentieth 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.

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: SSM2025-10822 / 4530606

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Executive summary

Static Fields

Epidemiological Studies

One study published in 2024 evaluated geomagnetic activity due to solar activity in connection with Mini Mental State Examination, a screening tool for dementia. Participants scored worse in times with higher solar and geomagnetic activity. The mechanism how this could cause lower scores in the test is unclear. In addition, it is an exposure that cannot be changed or prevented.

Human Studies

In 2024, no experimental studies on the potential effects of static fields on humans have been published, so no new conclusions can be drawn.

Animal Studies

The findings of *in vivo* studies on the biological effects of SMF and SEF (in some cases higher than ICNIRP exposure limits) suggest potential therapeutic applications, such as liver damage treatment and adipose metabolism regulation, while others raise concerns about long-term effects (at very high levels of SMF, up to 27 T), particularly on embryonic development.

Cell studies

The majority of *in vitro* studies on the effects of static magnetic fields published in 2024 focused on therapeutic strategies and were thus not included in this report. However, one study investigated the impact of SMF on cytokine production and the viability of peripheral blood mononuclear cells. The findings indicate that SMF influences cytokine production in T cells activated by dendritic cells, with the effects varying based on the orientation and intensity of the static magnetic field.

Extremely low frequency (ELF) fields

Epidemiological Studies

Three studies were published in 2024 that addressed exposure to ELF-MF fields and childhood leukaemia or lymphoma. Of these, one study assessed distance to overhead power lines, one study evaluated exposure from in-built transformer stations and the third study did not directly assess ELF-MF exposure, but rather performed a cluster analysis. All three studies reported findings in line with previous assessments that there could be a slightly increased risk of childhood leukaemia with higher exposures to magnetic fields. However, none of the studies contribute to the understanding of why such an association could occur. None of the studies produced statistically significant results.

Adults cancers were evaluated in an interesting study from Finland, analysing possible risks of persons who had ever lived close to an in-built transformer

station. The study only observed increased risks of gallbladder cancer, which may represent a chance finding.

A study in an occupational setting did not identify reduced DNA integrity in ELF-MF exposed workers.

Several reviews were published that analysed a large list of possible risk factors or associations of ELF-MF exposure and health outcomes. No very strong or clear increased risks were reported for people exposed to ELF-MF, although some associations were noted, especially for childhood leukaemia and neurodegenerative disease, as was the absence of associations for example for Parkinson's disease and reproductive outcomes.

Human Studies

Of studies published in 2024, two reviews on the effects of ELF on humans did not meet the inclusion criteria. All experimental human studies focused on therapeutic applications and were therefore not considered further.

Animal studies

The animal studies of 2024 underscore the diverse and context-dependent biological effects of ELF-MF exposure. While some studies suggest potential risks, particularly at higher intensities or in combination with other stressors, others indicate possible beneficial effects on cellular function and adaptation.

Cell studies

The 2024 cell studies on ELF-MF exposure suggest its potential to influence cellular and molecular processes, including tumorigenicity, proliferation, epigenetic regulation, neuronal activity, and oxidative stress. While some studies indicate increased cell growth, changes in epigenetic markers, and altered calcium oscillations, others report no significant impact on cell viability or DNA integrity. These biological effects are often transient and vary depending on exposure parameters, cell type, and duration. Overall, the interpretation of ELF exposure effects remains challenging due to inconsistencies across studies and the complexity of biological responses.

Intermediate frequency (IF) fields

Epidemiological Studies

No observational studies in humans regarding intermediate frequency fields were found in this reporting period.

Human Studies

As in 2023, no new releases were found.

Animal studies

In 2024, only one paper addressing *in vivo* IF field exposure was published. The results of this study indicated that IF magnetic field exposure (90 kHz, 0.6 ± 0.4 mT, 2 hours/day for 2, 4, and 8 weeks) had no significant impact on the cognitive function of mice. The patch-clamp assays revealed that IF exposure significantly reduced K⁺ outflow in granular neurons of the hippocampal dentate gyrus, lowering the threshold for action potential triggering and enhanced neuronal excitability in the hippocampal region.

Cell studies

No *in vitro* studies on intermediate frequency were included. Further two studies were excluded from the analysis due to methodological issues.

Radio frequency (RF) fields

Epidemiological Studies

The prospective COSMOS cohort found no association between cumulative amount of mobile phone use and the risk of developing glioma, meningioma, or acoustic neuroma. In the same cohort, an association with headaches was reported, likely related to phone use rather than RF-EMF per se. Similarly, a systematic review suggested that greater mobile phone use may be linked to poorer mental health in children and adolescents and a UK-biobank study found associations with cardiovascular disease. In both cases the authors considered mechanisms other than a direct effect of RF-EMF as likely explanations. These results highlight the challenge of disentangling RF-EMF effects from other effects of mobile phone use when exposure is measured in terms of mobile phone use rather than actual RF-EMF exposure. Two Mendelian randomization studies reported associations between mobile phone use and migraine or glaucoma. However, because genetic influences on mobile phone use likely act through complex traits such as lifestyle or personality, this method cannot reliably isolate the effect of mobile phone use from other risk factors associated with these traits.

This year, WHO-commissioned reviews were published on leukemia, non-Hodgkin lymphoma, thyroid cancer, glioma, meningioma, acoustic neuroma, pituitary and salivary gland tumors, as well as pediatric brain tumors and leukemias, cognition, symptoms, and male and female reproduction. For cancer endpoints, the evidence suggested no associations. The quality of evidence was rated as moderate for mobile phone use and tumors of the brain or salivary glands, and for far-field exposure and childhood leukemia risk. For all other cancer outcomes, the quality of evidence was rated as low. A positive association was reported for small-for-gestational-age; however, the authors emphasized that the supporting evidence was of low quality. For all other evaluated endpoints, the conclusion was that current data do not suggest associations at exposure levels below existing guidelines, the quality of evidence was consistently rated as low.

Human Studies

An experimental study, whose initial results on electroencephalography (EEG) in 2023 showed no effects of exposure to a 3.5 GHz far-field antenna, reported slight changes in some parameters of skin temperature and electrodermal activity that were within the normal physiological range. A pilot study showed a deterioration in subjective sleep quality in individual participants exposed to a baby monitor (2.45 GHz) and slight changes in some of the EEG power spectra investigated. Due to shortcomings in the study design, the results are not informative.

Two WHO-commissioned systematic reviews and meta-analyses showed no significant effects of RF-EMF exposure on non-specific symptoms and on cognitive performance in experimental human studies. Another systematic review and meta-analysis reported evidence of changes in the alpha frequency band of the resting EEG with eyes open during 2G exposure. The authors recommended that future studies should use standardized protocols to eliminate inconsistencies in EEG results, which are most likely due to methodological differences.

Animal studies

The included experimental animal studies show a variety of effects after exposure to RF-EMF. However, due to the heterogeneous study designs, the variety of assessed outcomes, and a low number of animals per group in many of the studies, it is difficult to draw conclusions. In several systematic reviews, effects of RF EMF exposure on cancer in co-exposure studies, oxidative stress and the male reproductive system were analysed. Co-exposure to RF-EMF and a carcinogenic agent resulted in small increases for liver, kidney and benign lung tumours. The strength of the evidence was moderate. However, the authors considered the risk as not being conclusive. No substantial evidence that RF-EMF exposure induces oxidative stress *in vivo* was found in a systematic review commissioned by WHO. In another WHO-commissioned systematic review, there were adverse effects observed on pregnancy rate and sperm count with moderate or low certainty, but most studies evaluated exposure levels that were higher than the limits set in international guidelines.

Cell studies

For the year 2024, nine *in vitro* studies were considered, addressing the effect of RF-EMF exposure on apoptosis, cell cycle, viability, gene and protein expression and DNA damage. In two of them, the effect of combined exposures was also considered. In studies where gene and protein expression was investigated, slight changes were detected in exposed samples compared to sham controls. For the other investigated endpoints, no effect of RF EMF exposure was recorded.

Sammanfattning

Statiska fält

Epidemiologiska studier

En studie som publicerades 2024 utvärderade geomagnetisk aktivitet till följd av solaktivitet i relation till Mini Mental State Examination, ett screeningverktyg för demens. Deltagarna fick sämre resultat under perioder med högre sol- och geomagnetisk aktivitet. Mekanismen bakom hur detta skulle kunna påverka testresultaten är oklar. Dessutom är det en exponering som inte kan förändras eller förhindras.

Humanstudier

Under 2024 publicerades inga experimentella studier om potentiella effekter av statiska fält på människor, så inga nya slutsatser kan dras.

Cellstudier

De flesta in vitro-studier om effekter av statiska magnetfält som publicerades 2024 fokuserade på terapeutiska tillämpningar och inkluderades därför inte i denna rapport. En studie undersökte dock påverkan av statiska magnetfält på cytokinproduktion och viabilitet hos perifera mononukleära blodceller. Resultaten indikerar att statiska magnetfält påverkar cytokinproduktion i T-celler aktiverade av dendritiska celler, med effekter som varierar beroende på orientering och intensitet av det statiska magnetfältet.

Djurstudier

Resultaten från in vivo-studier om biologiska effekter av statiska magnetfält och statiska elektriska fält (i vissa fall högre än ICNIRP:s exponeringsgränser) tyder på potentiella terapeutiska tillämpningar, såsom behandling av leverskador och reglering av fettvävsmetabolism. Andra studier väcker oro för långtidseffekter vid mycket höga nivåer av statiska magnetfält, upp till 27 T, särskilt på embryonal utveckling.

Extremt lågfrekventa fält (ELF)

Epidemiologiska studier

Tre studier publicerades 2024 som behandlade exponering för ELF-magnetfält och barndomsleukemi eller lymfom. En av dessa studier bedömde avstånd till luftledning, en annan exponeringsnivå från inbyggda transformatorstationer och den tredje bedömde inte direkt ELF-exponering utan genomförde en klusteranalys. Alla tre rapporterade resultat i linje med tidigare bedömningar, nämligen att det kan finnas en svagt ökad risk för barndomsleukemi vid högre exponering för magnetfält. Ingen av studierna bidrar dock till förståelsen av varför ett sådant samband skulle kunna finnas. Ingen av studierna gav statistiskt signifikanta resultat.

Cancer hos vuxna utvärderades i en studie från Finland, som analyserade eventuella risker för personer som någon gång bott nära en inbyggd transformatorstation. Endast en ökad risk för gallblåsecancer observerades, vilket kan vara ett slumpfynd.

En studie i yrkesmiljö identifierade inte minskad DNA-integritet hos ELF-exponerade arbetare.

Flera översikter publicerades som analyserade en lång rad möjliga riskfaktorer eller samband mellan ELF-exponering och olika hälsoutfall. Inga starka eller tydliga riskökningar rapporterades för personer exponerade för ELF, även om vissa samband noterades, särskilt för barndomsleukemi och neurodegenerativa sjukdomar, och frånvaro av samband exempelvis för Parkinsons sjukdom och reproduktionsutfall.

Humanstudier

Av de studier som publicerades 2024 exkluderades två översikter om effekter av ELF på människor eftersom de inte uppfyllde inklusionskriterierna. Alla experimentella humanstudier fokuserade på terapeutiska tillämpningar och beaktades därför inte.

Djurstudier

Djurstudierna från 2024 betonar de varierande och kontextberoende biologiska effekterna av ELF-exponering. Vissa studier antyder potentiella risker, särskilt vid högre intensiteter eller i kombination med andra stressorer, medan andra indikerar möjliga positiva effekter på cellulär funktion och anpassning.

Cellstudier

Cellstudierna från 2024 om ELF-exponering antyder att den kan påverka cellulära och molekylära processer som tumörbildning, proliferation, epigenetisk reglering, neuronal aktivitet och oxidativ stress. Vissa studier visar ökad celltillväxt, förändringar i epigenetiska markörer och ändrade kalciumoscillationer, medan andra inte rapporterar någon påverkan på cellviabilitet eller DNA-integritet. Dessa biologiska effekter är ofta övergående och varierar beroende på exponeringsparametrar, celltyp och exponeringstid. Sammantaget är tolkningen av ELF-effekter utmanande på grund av inkonsekvenser och den komplexa naturen hos biologiska responser.

Intermediärfrekventa fält (IF)

Epidemiologiska studier

Inga observationsstudier berörande människor om intermediärfrekventa fält identifierades under denna rapportperiod.

Humanstudier

Som under 2023 hittades inga nya studier.

Djurstudier

Endast en in vivo-studie om IF-exponering publicerades 2024. Resultaten visar att exponering för IF-magnetfält (90 kHz, 0.6 ± 0.4 mT, 2 timmar per dag i 2, 4 eller 8 veckor) inte hade någon signifikant påverkan på kognitiv funktion hos möss. Patch-clamp-analyser visade däremot att IF-exponering minskade K⁺-utflödet i granulära neuroner i hippocampus dentate gyrus, vilket sänkte tröskeln för aktionspotential och ökade neuronernas excitabilitet.

Cellstudier

Inga in vitro-studier om intermediärfrekventa fält inkluderades. Ytterligare två studier exkluderades på grund av metodologiska brister.

Radiofrekventa fält (RF)

Epidemiologiska studier

Den prospektiva COSMOS-kohorten fann inget samband mellan kumulativ mobiltelefonanvändning och risken att utveckla gliom, meningiom eller akustikusneurinom. I samma kohort rapporterades ett samband med huvudvärk, sannolikt relaterat till mobilanvändning snarare än RF-EMF i sig. En systematisk översikt antydde att högre mobiltelefonanvändning kan hänga samman med sämre mental hälsa hos barn och ungdomar, och en UK Biobank-studie fann samband med hjärt-kärlsjukdom. I båda fallen ansåg författarna att mekanismer andra än direkta RF-effekter var sannolika förklaringar. Dessa resultat illustrerar svårigheten att särskilja RF-effekter från andra effekter av mobilanvändning när exponeringen mäts som användning snarare än faktiska RF-nivåer.

Två Mendelska randomiseringsstudier rapporterade samband mellan mobilanvändning och migrän eller glaukom. Eftersom genetiska influenser på mobilanvändning sannolikt verkar via komplexa egenskaper som livsstil eller personlighet kan denna metod inte isolera effekten av mobilanvändning från andra riskfaktorer kopplade till dessa egenskaper.

I år publicerades WHO-beställda översikter om leukemi, non-Hodgkin-lymfom, sköldkörtelcancer, gliom, meningiom, akustikusneurinom, hypofys- och spottkörteltumörer samt pediatrika hjärntumörer och leukemier, kognition, symtom och reproduktion hos män och kvinnor. För cancerutfall visade evidensen inga samband. Evidenskvaliteten bedömdes som måttlig för mobiltelefonanvändning och tumörer i hjärna eller spottkörtlar och för fjärrfältsexponering och risken för barndomsleukemi. För övriga cancerutfall bedömdes evidenskvaliteten som låg. Ett positivt samband rapporterades för liten för gestationsåldern, men evidenskvaliteten var låg. För alla andra utvärderade utfall var slutsatsen att nuvarande data inte tyder på några samband vid exponeringsnivåer under rådande riktlinjer, och evidenskvaliteten bedömdes genomgående som låg.

Humanstudier

En experimentell studie vars initiala resultat om EEG från 2023 inte visade några effekter av exponering för en 3.5 GHz fjärrfältantenn, rapporterade 2024 små

förändringar i vissa parametrar för hudtemperatur och elektrodermal aktivitet som låg inom det normala fysiologiska intervallet. En pilotstudie visade försämrad subjektiv sömnkvalitet hos vissa deltagare som exponerades för en babyvakt (2.45 GHz) samt små förändringar i vissa EEG-frekvensband. På grund av brister i studiedesignen är resultaten inte informativa.

Två WHO-beställda systematiska översikter och metaanalyser visade inga signifikanta effekter av RF-exponering på ospecifika symtom eller kognitiv funktion i experimentella humanstudier. En annan metaanalys rapporterade förändringar i alfafrekvensbandet i EEG i vila med öppna ögon under 2G-exponering. Författarna rekommenderade att framtida studier använder standardiserade protokoll för att eliminera inkonsekvenser som sannolikt beror på metodologiska skillnader.

Djurstudier

De inkluderade djurstudierna visar en rad olika effekter efter RF-exponering. På grund av heterogena studiedesigner, varierande utfallsmått och lågt antal djur per grupp är det svårt att dra slutsatser. Flera systematiska översikter analyserade effekter av RF-exponering på cancer i samexponeringsstudier, oxidativ stress och manlig reproduktion. Samexponering för RF och ett carcinogent ämne gav små öknningar av lever, njur- och godartade lunghinnetumörer. Evidensstyrkan var måttlig, men författarna bedömde risken som icke-säkerställd. En WHO-beställd översikt fann inget robust stöd för att RF-exponering inducerar oxidativ stress in vivo. I en annan WHO-beställd översikt rapporterades negativa effekter på graviditetsfrekvens och spermier, men med måttlig eller låg säkerhet, och de flesta studier använde exponeringsnivåer som var högre än de som anges i internationella riktlinjer.

Cellstudier

För 2024 inkluderades nio in vitro-studier som undersökte RF-exponeringens effekter på apoptos, cellcykel, viabilitet, gen- och proteinuttryck samt DNA-skador. I två av studierna analyserades även kombinerad exponering. I studier där gen- och proteinuttryck undersöktes observerades mindre förändringar i exponerade prover jämfört med sham-kontroller. För övriga utfall rapporterades inga effekter av RF-exponering.

Excursion: Systematic reviews commissioned by WHO

In 2018, the World Health Organization (WHO) performed a survey among scientists to evaluate the most pertinent questions regarding RF-EMF exposure and possible health effects. Based on this survey, a series of ten systematic reviews (and where possible meta analyses) were commissioned ([1]). During the past years, first the corresponding protocols outlining the approach of the systematic reviews were published, followed by the actual systematic reviews.

Reviews are summaries of existing scientific literature, so of studies that have been published in the peer-reviewed literature. Reviews exist in many different formats and shapes, such as narrative reviews (an overview over a specific topic), scoping reviews (systematic assessment of concepts, gaps and evidence), systematic reviews or umbrella reviews (a review of reviews). Of this list, systematic reviews are different in the sense that they should have a clear and pre-specified systematic approach that makes the methodology transparent and reproducible. By including systematic searches of the literature, the aim is to provide an overview of all existing knowledge on a topic, provided that the studies are included based on specified inclusion and exclusion criteria and that a pre-defined protocol is followed. A meta-analysis, or a quantitative summary of published results, is sometimes included, when several original studies were published on the same type of exposures and identical outcomes. Therefore, a meta-analysis is not always included in a systematic review.

In this years' report, the following reviews in this WHO-commissioned series were included:

- Karipidis et al. (2024): observational studies on glioma, meningioma, acoustic neuroma, pituitary, salivary gland tumours, paediatric brain tumours and leukaemia's.
- Rösli et al. (2024): observational studies and tinnitus, migraine and non-specific symptoms.
- Bosch-Capblanch et al. (2024): experimental studies and symptoms.
- Pophof et al. (2024): experimental studies and cognitive performance.
- Benke et al. (2024): human observational studies and cognition.
- Johnson et al. (2024): adverse female reproductive outcomes.
- Kenny et al. (2024): observational studies on male fertility.
- Cordelli et al. (2024): experimental studies on male fertility in nonhuman mammals and human sperm *in vitro*.
- Meyer et al. (2024): *in vivo* and *in vitro* studies on biomarkers of oxidative stress.
- Karipidis et al. (2025): observational studies on leukaemia, non-Hodgkin's lymphoma, thyroid cancer related to mobile phone use, cancers of the lymphohematopoietic system and oral cavity/pharynx cancer in occupational populations.

- Mevissen et al. (2025): Experimental studies on cancer in laboratory animals.

Please note that although the last two systematic reviews in this list (Karipidis et al 2025, Mevissen et al, 2025) fall outside of the reporting period of this years' SSM report, they were included here, in order to provide a more complete overview.

In addition, one of the systematic reviews was already published in 2023 and has been included in last year's SSM report [2]:

- Cordelli et al. (2023): experimental studies on pregnancy and birth outcomes in non-human mammals.

The series of systematic reviews commissioned by the WHO are unique in the sense that they were done in a harmonised way, pre-defined and published in the peer-reviewed literature the protocols beforehand, and that they included a rigorous risk of bias assessment. As such, the reviews provide an overview of the current state of knowledge regarding RF-EMF effects on health. An expected next step is for the WHO to provide an overview integrating this knowledge into a Monograph on RF-EMF within the Monograph Series ([3]).

Exkurs: Systematiska översikter på uppdrag av WHO

År 2018 genomförde Världshälsoorganisationen (WHO) en enkät bland forskare för att utvärdera vilka frågor som var mest relevanta när det gäller exponering för RF-EMF och möjliga hälsoeffekter. Baserat på denna enkät beställdes en serie om tio systematiska översikter (och där det var möjligt även metaanalyser) ([1]). Under de senaste åren publicerades först motsvarande protokoll som beskriver tillvägagångssättet för de systematiska översikterna, följt av de faktiska systematiska översikterna.

Översikter är sammanfattningar av befintlig vetenskaplig litteratur, alltså studier som har publicerats i den peer review-granskade litteraturen. Översikter finns i många olika format och former, såsom narrativa översikter (en överblick över ett specifikt ämne), kartläggande översikter (systematisk bedömning av koncept, kunskapsluckor och evidens), systematiska översikter eller paraplyöversikter (en översikt av översikter). Av dessa typer skiljer sig systematiska översikter genom att de ska ha ett tydligt och i förväg fastställt systematiskt tillvägagångssätt som gör metodologin transparent och reproducerbar. Genom att inkludera systematiska litteratursökningar är målet att ge en överblick över all befintlig kunskap inom ett område, förutsatt att studierna inkluderas baserat på specifika inklusions- och exklusionskriterier och att ett förutbestämt protokoll följs. En metaanalys, eller en kvantitativ sammanfattning av publicerade resultat, ingår ibland när flera originalstudier har publicerats om samma typ av exponeringar och identiska utfall. Därför ingår inte alltid en metaanalys i en systematisk översikt.

I årets rapport ingick följande översikter i denna WHO-beställda serie:

- Karipidis et al. (2024): observationsstudier om gliom, meningiom, akustikusneurinom, hypofys- och spottkörteltumörer, pediatrika hjärntumörer och leukemier.
- Rösli et al. (2024): observationsstudier och tinnitus, migrän och ospecifika symtom.
- Bosch-Capblanch et al. (2024): experimentella studier och symtom.
- Pophof et al. (2024): experimentella studier och kognitiv prestation.
- Benke et al. (2024): humana observationsstudier och kognition.
- Johnson et al. (2024): negativa kvinnliga reproduktionsutfall.
- Kenny et al. (2024): observationsstudier om manlig fertilitet.
- Cordelli et al. (2024): experimentella studier om manlig fertilitet hos icke-humana däggdjur samt human sperma in vitro.
- Meyer et al. (2024): in vivo- och in vitro-studier om biomarkörer för oxidativ stress.
- Karipidis et al. (2025): observationsstudier om leukemi, non-Hodgkinlymfom, sköldkörtelcancer relaterad till mobiltelefonanvändning,

cancer i det lymfohematopoetiska systemet samt cancer i munhåla/svalg i yrkesmiljöer.

- Mevissen et al. (2025): experimentella studier om cancer i laboratoriedjur.

Observera att även om de två sista systematiska översikterna i listan (Karipidis et al. 2025, Mevissen et al. 2025) faller utanför rapporteringsperioden för årets SSM-rapport, inkluderades de här för att ge en mer komplett överblick.

Dessutom hade en av de systematiska översikterna redan publicerats 2023 och har inkluderats i förra årets SSM-rapport [2]:

- Cordelli et al. (2023): experimentella studier om graviditet och födelseutfall hos icke-humana däggdjur.

Serien av systematiska översikter som beställts av WHO är unik i den bemärkelsen att de utfördes på ett harmoniserat sätt, med i förväg definierade och publicerade protokoll i den peer review-granskade litteraturen, och att de inkluderade en rigorös risk-för-bias-bedömning. Som sådana ger översikterna en överblick av det aktuella kunskapsläget gällande RF-EMF:s effekter på hälsa. Ett förväntat nästa steg är att WHO integrerar denna kunskap i en monografi om RF-EMF inom Monografiserien ([3]).

1. Static fields

1.1 Epidemiological studies

Liddie et al. [4] analysed data from the Normative Aging Cohort, a longitudinal study starting in 1963 in the Greater Boston Area, US. In 1993, 1,131 of cohort participants also completed a battery of seven cognitive tests and 1,081 were included in the current analysis of the Mini Mental State Examination (MMSE). The MMSE is a screening tool for dementia. The authors assessed Sunspot Number (SSN) and Kp index, which quantifies geomagnetic activity on Earth driven by changes in solar activity. Moving averages of SSN and Kp index in the 28 days before MMSE tests of participants were calculated. Generalised Estimation Equations adjusted for a range of covariates were used to analyse the data to account for within-subject correlations between MMSE tests. Study participants were all male and on average 68 years old at the first visit. The authors observed an increased risk of a lower MMSE score (corresponding to a higher risk of dementia) associated with a higher solar and geomagnetic activity on the testing day. Risk estimates were consistently higher when only the first visit was analysed. There was heterogeneity (positive and negative associations with solar and geomagnetic activity) across the remaining seven cognitive tests that were performed.

This is a longitudinal study in a cohort with repeated measurements and including over 1000 participants. It remains unclear why there is a strong consistent effect when analysing only the first visit. While the authors argue that the first visit may cause more anxiety in participants due to unknown procedures, it remains unclear why this would be such a strong confounder regarding solar and geomagnetic activity. The exposure followed a strong annual pattern with higher exposures approximately 1993 and 2002/2003, especially for Sunspot Number. Risk estimates for the first-time visits were overall higher for all exposure time windows as compared to taking all visits into account. It is not entirely clear why taking repeat visits into account as well introduced attenuation of risk estimates. The overall mechanism of how geomagnetic activity causes lower test scores of the MMSE test is unclear. In addition, it is an exposure that can't be prevented or changed and therefore, there are no obvious preventive measures that can be taken by affected individuals.

1.1.1 Conclusions on epidemiological studies

One study evaluated geomagnetic activity due to solar activity in connection with Mini Mental State Examination, a screening tool for dementia. Participants scored worse in times with higher solar and geomagnetic activity. The mechanism how this activity could cause lower scores in the test is unclear. In addition, it is an exposure that cannot be changed or prevented.

Table 1.1: Epidemiological studies investigating static fields.

Endpoints	Reference	Exposure assessment	Study design, Population	Results
Mini Mental State Examination (MMSE)	Liddie 2024	Geomagnetic and solar activity	Analysis of the normative aging cohort, US, including ~1000 participants in this analysis.	Slightly worse MMSE scores in years with high solar and geomagnetic activity. Mechanism unclear.

1.2 Human studies

In 2024, a study on electric field (EF) perception showed that perception thresholds were lower under hybrid EF exposure conditions than for exposure to alternating current (AC) and direct current (DC) alone. This year, no further experimental studies on the possible effects of static fields on humans were published. As no new publications are available, no new conclusions can be drawn.

1.3 Animal studies

Last year the results of fourteen studies investigating the health effects of *in vivo* exposure to static magnetic fields (SMF) or static electric fields (SEF) were summarized. Beneficial effects on behavioral endpoints in rodents were found, while no significant effects were observed in other species, except for a few sporadic exceptions.

1.3.1 Rodents

Chen et al. [5] investigated the effect of SMF (0.1 – 0.2 T) on mice livers damaged by N-acetyl-p-aminophenol (paracetamol, APAP) overdose. APAP is a common drug used for fever reduction and as a first-line treatment for various pain conditions. An accidental overdose of APAP can lead to acute liver failure, which, at an early stage, can be treated with the antioxidant N-acetylcysteine (NAC). Male C57BL/J6 adult mice were divided into six groups ($n = 10$ mice per group): control, sham, immediate magnetic field treatment (downward and upward) after APAP or placebo injection, and magnetic field treatment 3 hours after injection (post-downward and post-upward) groups. The first experiment lasted 11 days: an injection of placebo or APAP was performed every 72 hours, and mice were sacrificed 48 hours after the final injection. The results indicated that SMFs (early or late, in either upward or downward directions) significantly reduced the high-dose APAP-induced lethality. Moreover, at the end of the experiment, all mice in the downward SMF group were still alive. Histopathological analysis of the livers revealed necrosis induced by the high-dose APAP, which was reduced by approximately 50% following downward SMF exposure. Another experiment aimed to examine the efficacy of SMF pretreatment for 30 days prior to the injection of a sublethal single dose of APAP.

In this case, both upward and downward SMF exposures induced a significant reduction in liver necrosis and apoptosis. Moreover, in this experiment, the oxidative stress induced by the single dose of APAP was analyzed. Results showed that SMF exposure significantly reduced APAP-induced oxidative stress and free radicals, leading to a decrease in multiple oxidative stress markers and an increase in the antioxidant glutathione (GSH). A third experiment explored the efficacy of SMFs (pre-treatment exposure for 33 days), either independently or in combination with NAC, on damage induced by a single dose of APAP. NAC was administered 6 hours and 24 hours after the APAP overdose. Results showed that NAC lost its efficacy when administered 24 hours post-overdose, but when combined with SMF exposure, there was a significant improvement in APAP overdose-induced weight loss, AST increase, liver necrosis, apoptosis, and lipid accumulation, even when NAC was administered 24 hours after the APAP overdose

In the study by Dong et al., [6] the effects of SEF exposure (56.3 ± 1.4 kV/m for 28 days) on the spleen of ICR mice were investigated. Eighty-four male mice were divided into two groups: a sham group and an exposed group ($n = 42$ for each group). On the 7th day of exposure, the 28th day of exposure, and the 7th day after stopping the 28-day exposure, the levels of IL-10 and IFN- γ in the spleen and the proliferation of splenic lymphocytes were measured ($n = 10$ for each time point). On the 28th day of exposure, the content of ROS in splenic lymphocytes and oxidative stress markers in the spleen were tested ($n = 8$), and the ultrastructure of splenic lymphocytes was observed ($n = 4$). Results showed that the levels of IL-10 and IFN- γ , the proliferation of lymphocytes, and the content of intracellular ROS decreased significantly on the 28th day of SEF exposure, with complete recovery by the 7th day after the exposure period ended. Among the oxidative stress markers examined in the spleen, only the activity of Superoxide Dismutase (SOD) increased significantly.

Oktaviani et al. [7] investigated the effect of SMF exposure (2 mT, 1 hour/day for 2, 7, 14, and 21 days) on the browning process of white adipocytes in obese mice by assessing the Lee index (an indicator of obesity), the expression of *Tbx15* (a gene regulating thermogenesis and adipocyte browning) and *Ucp1* (a gene mediating thermogenic function), as well as adipose cell size in the inguinal adipose tissue of obese mice. A total of 24 male C57BL/6J mice were divided into six groups ($n = 4$ per group): control group (non-obese mice), sham group (obese mice without exposure), SMF/2days group (obese mice exposed to SMF for 2 days), SMF/7days group (obese mice exposed to SMF for 7 days), SMF/14days group (obese mice exposed to SMF for 14 days), and SMF/21days group (obese mice exposed to SMF for 21 days). The results showed that the Lee index was significantly reduced in the SMF/2days, SMF/7days, and SMF/14days groups compared to the sham group, as well as adipose cell size in the SMF/2days group. *Tbx15* expression was significantly higher in the SMF/2days and SMF/7days groups, while no significant differences were observed in the relative expression of *Ucp1* between SMF-exposed and non-exposed groups.

In the study by Wu et al. [8], the effect of SEF exposure (56.3 ± 1.4 kV/m, 24 hours/day for 7, 14, and 21 days) on white blood cell (WBC) count in peripheral blood and its underlying mechanism were explored by assessing total WBC count, differential WBC count, and hypothalamic–pituitary–adrenal (HPA) axis hormone levels. A total of 60 male ICR mice were divided into two groups (sham-exposed group and SEF-exposed group). Ten animals from each group were sacrificed after 7, 14, and 21 days of exposure to evaluate biological endpoints. The total WBC and lymphocyte count in the exposed group decreased significantly after 7 and 14 days of SEF exposure compared to the sham group, whereas no significant changes were observed after 21 days of SEF exposure. No significant differences were found in neutrophil, monocyte, eosinophil, or basophil counts. The HPA axis hormone levels in the exposed groups were significantly higher than those in the sham group after 7 and 14 days of SEF exposure, while a complete recovery was observed after 21 days.

1.3.2 Other species

In the study by Cheng et al. [9] the effects of ultra-high SMFs on early embryonic division and development in *Caenorhabditis elegans* (*C. elegans*) were investigated. *C. elegans* is a widely used multicellular model organism in developmental research due to its rapid life cycle, invariant cell number and development, and strong fertility. Young adult hermaphrodites containing fertilized eggs *in vivo* were exposed to SMFs at intensities of 4 T, 10 T, 14 T, and 27 T for three hours. Each exposed group ($n \geq 20$, average number of worms per group) had a corresponding sham group for comparison. The results indicated that SMFs at intensities ≥ 14 T significantly increased germ cell apoptosis in parental worms but had no significant effect on the germ cell cycle. Moreover, abnormalities in early embryonic development and hatching were observed for SMFs ≥ 10 T, and the developmental rate of early embryos was significantly decreased following exposure to 10 T, 14 T, and 27 T SMFs. Only the 27 T SMF exposure group showed a statistically significant decrease in embryo hatching rate. Exposure to SMFs ≥ 10 T during the embryonic stage significantly reduced the lifespan of worms; however, SMFs had no multigenerational effects on the developmental rate of *C. elegans*. Finally, exposure to SMFs at 14 T and 27 T significantly increased the proportion of multipolar spindle formation in early embryonic cells.

Tian et al. [10] investigated the effects of SMF exposure (a single exposure at a gradient of 16.8–22.0 T for two hours) on the development of zebrafish embryos. The exposure system consisted of a tube with three exposure volumes where a gradient SMF was present (two exposure volumes with average value: 16.8 T) and a central volume where the SMF was homogeneous at 22 T. A total of 200 embryos were divided into two groups: sham-exposed and SMF-exposed. The exposed embryos were placed in three different volumes (gradient SMF and homogeneous SMF). After exposure, the embryos were raised and observed for 10 days to evaluate the selected biological endpoints. The results indicated that exposure to high-intensity SMFs did not affect the general development of zebrafish embryos. However, the hatching rate was reduced in the gradient SMF

group but not in the homogeneous 22.0 T SMF group. Additionally, zebrafish locomotory behaviors were differentially affected by these ultra-high SMFs.

1.3.3 Conclusions on animal studies on exposure to Static Magnetic Fields (SMF) and Static Electric Field (SEF)

A total of 6 articles were selected regarding the *in vivo* biological effects of exposure to the SMF or SEF fields. Four papers examined the effects on rodents, two on *Caenorhabditis elegans* (*C. elegans*) and zebrafish respectively. In rodent studies, exposure to static magnetic fields (SMF) showed protective effects in specific pathological conditions. In particular, SMF treatment reduced liver damage induced by APAP overdose, mitigating oxidative stress, necrosis, and apoptosis, especially when combined with N-acetylcysteine (NAC) (Chen et al.). Additionally, in obese rodents exposed to SMF, a reduction in the Lee index and adipocyte size was observed, suggesting a potential role in energy metabolism (Oktaviani et al.). Conversely, static electric field (SEF) exposure affected immune parameters in mice, leading to a transient reduction in white blood cells and lymphocyte proliferation, accompanied by an increase in superoxide dismutase (SOD) activity, with full recovery at the end of exposure (Dong et al. and Wu et al.). In other animal models, exposure to ultra-high SMFs had significant effects on embryonic development in *Caenorhabditis elegans* (Cheng et al.), increasing germ cell apoptosis and reducing the hatching rate of embryos at intensities ≥ 10 T. However, no transgenerational effects were observed. In zebrafish, exposure to SMF gradients reduced the hatching rate without affecting overall development, while homogeneous 22 T SMFs had no significant impact (Tian et al.).

Overall, these findings highlight that the biological effects of SMF and SEF (in some cases higher than ICNIRP exposure limits) depend on the typology of field exposure, its duration, and the organism considered. Some studies suggest potential therapeutic applications, such as liver damage treatment and adipose metabolism regulation, while others raise concerns about long-term effects, particularly on embryonic development. Further research is needed to understand the molecular mechanisms underlying these responses and to assess the clinical and environmental implications of exposure to such fields.

About the other outcomes and assessed endpoints, results are summarized in Table 1.3 where all significant results are reported.

Table 1.3: Summary of the *in vivo* studies investigating biological effects of SMF and SEF exposure

Outcome	Reference	Population	Exposure	Effect of ELF exposure
Rodent Studies				

Effects on tissues	Chen et al.	Male C57BL/J6 adult mice	0.1 - 0.2 T EXP1. four repeated high dose of APAP (one each 72 h) and immediate exposure to SMF and four repeated high dose of APAP (one each 72 h) and exposure to SMF 3 hours after the injection EXP2. SMF pretreatment for 30 days and then a single sublethal dose of APAP. EXP3. SMF pretreatment exposure alone or in combination with NAC administered 6h and 24h post a sublethal single dose of APAP.	EXP1. ↓ lethality 100 % survival in the downward SMF group ↓ liver necrosis in the downward SMFs group. EXP2. ↓ liver necrosis and apoptosis for both the upward and downward exposures to SMFs. ↓ multiple oxidative stress markers in both SMF exposure groups ↑ GSH levels in both SMF exposure groups EXP3 NAC lost its efficacy when administered after 24 hours, but not when combined with the SMFs exposure.
Oxidative Stress	Dong et al.	Male ICR mice	56.3 ± 1.4 kV/m 28 days	↓ IL-10 and IFN-γ levels, proliferation levels of lymphocytes and the content of intracellular ROS on the 28th day of SEF exposure, with a total recovery on the 7th day after the end of the exposure period. ↑ activity of SOD in SEF exposed group.
Other Outcomes	Oktavian i et al.	Male C57BL/6J mice (model of obese mice with diet)	2 mT 1 h/d for 2, 7, 14 and 21 days	↓ Lee index was significantly reduced in SMF/2days, SMF/7days and SMF/14days ↓ inguinal adipose cell size in SMF/2days. ↑ Tbx15 expression in SMF/2days and SMF/7days.
	Wu et al.	Male ICR mice	56.3 ± 1.4 kV/m. 24 h/d for 7, 14 and 21 days	↓ WBC count and lymphocyte count only after SEF exposure of 7d and 14d. ↑ HPA axis hormone levels in SEF exposure of 7d and 14d. Total recovery after 21d of exposure.
No-mammalian				
Reproduction and development	Cheng et al.	Caenorhabditis elegans (<i>C. elegans</i>)	4 T, 10 T, 14 T and 27 T Single exposure of three hours	↑ germ cell apoptosis of parental worms, but they had no significant effect on germ cell cycle for SMF ≥ 14 T Abnormalities in early embryonic development and hatching for SMFs ≥ 10 T ↓ developmental rate of early embryos for SMFs ≥ 10 T ↓ in the hatching rate of embryos for SMF = 27T. ↓ lifespan of worms for SMF ≥ 10 T during the embryonic stage SMFs had no multigenerational effects on the development rate of <i>C. elegans</i> . ↑ proportion of multi-polar spindle formation in early embryonic cells for SMF ≥ 14 T.
	Tian et al.	Zebrafish embryos	16.8 T (gradient) 22.0 T homogeneous Single exposure of two hours	↓ hatching rate in the gradient SMF exposure and not in the homogeneous one. Zebrafish locomotor behaviors were differentially affected by SMF exposure.

Abbreviations: ↑=increase(d); ↓=decrease(d); APAP: N-acetyl-p-aminophenol, paracetamol, NAC: N-acetylcysteine; GSH: antioxidant glutathione; SOD: superoxide dismutase activity; WBC: white blood cells.

1.4 Cell Studies

Last year, no papers were included in the report and this year, only one study was selected.

The study of Turuntaš et al. [11], assessed the effects of SMF of varying intensities (1 mT and 56 mT) and polarities (upward and downward orientations) on cytokine production in human lymphocyte cultures. Peripheral blood mononuclear cells (PBMCs) were isolated from healthy donors, and CD4+ T cells were activated using monocyte-derived immature or mature dendritic cells (DCs). Experimental groups were exposed to SMF for 6 days, and cytokine levels were measured using ELISA and flow cytometry. Cell viability and proliferation were also assessed. Upward-oriented 56 mT SMF increased IFN- γ and TNF- β in T cells stimulated by immature DCs (n=3), while upward 1 mT SMF elevated IL-17 production (n=3). Downward-oriented 56 mT SMF increased TNF- α in T cells stimulated by mature DCs (n=3). Other cytokines (IL-4, IL-1 β , IL-6, IL-8, and IL-10) showed no significant changes across conditions. No significant differences in cell proliferation were observed across SMF conditions. A slight, statistically significant increase in apoptosis was noted under downward-oriented SMF conditions (n=3), but overall, SMF did not cause substantial cytotoxicity.

This study demonstrated that SMF orientation and intensity distinctly influence cytokine production by T cells activated by DCs.

1.4.1 Conclusions on static field cell studies

The only *in vitro* study presented indicated that SMF of different intensities and orientations can distinctly influence cytokine production in T cells activated by dendritic cells, a finding that requires validation through robust complementary experiments.

Table 1.4: Cell studies on exposure to Static Magnetic Fields (SMF)

Outcome	Reference	Cell type	Exposure condition	Effect
Cytokine production Viability	Turuntaš et al, 2024	Peripheral blood mononuclear cells (PBMCs) n=3	SMF orientation and intensity distinctly influence cytokine production by T cells	SMF orientation and intensity distinctly influence cytokine production by T cells

2. Extremely low frequency (ELF) fields

2.1 Epidemiological studies

In the last report, several studies were published that did not provide clear evidence of presence or absence of risks from exposure to ELF-MF: An Australian case-control study on occupational ELF-MF exposure analysed follicular lymphoma, an Italian case-control study overhead power lines and childhood leukaemia. In line, 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. Also, and 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.

2.1.1 Childhood cancer

Crespi et al. [12] investigated the association between childhood leukaemia and residential proximity to electrical transformer stations situated in residential buildings in Finland, Israel, Hungary, The Netherlands, and Switzerland. All cases and controls lived in buildings housing a transformer station and exposure was determined based on the location of their apartment relative to this transformer. Residing directly above or next door to a station was classified as high exposure, living on the same floor as the exposed apartment or sharing a corner or edge with it was classified as intermediate exposure and all other dwellings in the building were classified as unexposed. Leukaemia cases diagnosed <15 years of age were identified from national leukaemia registers. For each case a control of the same age was selected, preferentially among children living in the same building as the case, but in countries where this was not possible controls were selected among children living in any building with an inbuilt transformer station within the same neighbourhood. The study population included 76 cases, 3 of which were high-exposed and 20491 controls, of which 858 were high-exposed. Control measurements for a subset of the population found that exposure levels for the three exposure categories differed between countries. Mean exposure levels for high-exposed ranged from 0.34 μT in Israel to 0.59 μT in Switzerland. Exposure levels in apartments grouped as “unexposed” levels were generally $\leq 0.1 \mu\text{T}$, but some Finnish apartments in this group had measured levels up to 0.70 μT . Risk estimates (Odds Ratios, ORs) for leukaemia from a random effect logistic regression were 1.39 (95% CI: 0.77– 2.52) and 1.32 (95% CI: 0.39– 4.42) for intermediate and high exposure respectively. The authors concluded that “this study did not find consistent evidence of an elevated risk, but due to small numbers and wide confidence intervals, a risk of the magnitude observed in power lines studies cannot be excluded.”

The primary limitation is the very low number of exposed cases and resulting uncertainty of risk estimates. Also, only age was included as a potential confounder, gender and calendar period were excluded based on a sensitivity analysis of Finnish data, other factors such as socioeconomic position (SEP) were not considered. This might be problematic particularly since several countries had to deviate from the original protocol requirement that cases and controls should live in the same building, although matching was performed on neighbourhood level and thus includes an implicit match on neighbourhood SEP. Finally, there was some overlap between measured exposure levels for the three categories based on the relative location of the transformer station. Altogether these factors may have reduced the power of the study to detect any association.

Norzaee et al. [13] reported results of a case-control study performed in Teheran, Iran, between 2017-2021. Children aged 1-15 years and diagnosed with acute myeloid leukaemia (AML), acute lymphoblastic leukaemia (ALL), non-Hodgkin Lymphoma and Hodgkin lymphoma were included into the study. Controls were randomly selected from healthy children undergoing regular check-ups in the hospitals, or who were visiting the paediatric clinic for treatments related to injuries, infections or other non-blood related disorders. Addresses were geocoded, and several exposures based on land use were assigned to cases and controls. Distance of the home addresses to the nearest power line within 50 or 100m was calculated using a geographic information system. 428 cases of leukaemia, 428 cases of lymphoma, and 428 controls were included. Logistic regression analyses were adjusted for age group, sex, parental smoking and family history of cancer, and additionally for other environmental exposures. Adjusted OR for leukaemia for living within 50m of a power line (based on 12 cases) was 2.90 (95% CI 0.92–9.14), and for living within 100m was 0.96 (95% CI 0.48–1.90). Corresponding risk estimates for lymphoma were 1.56 (95% CI 0.25–9.39) and 0.67 (95% CI 0.38–1.16), respectively.

Strength of this case-control study was the inclusion of a reasonably large group of children, the assessment of incident cases in hospitals, and the inclusion of controls based on the same geographic distribution and presumably from a similar sociodemographic background. Exposure assignment was based on objective spatial data. Limitations include that response rate and number of excluded participants was not reported, and the exposure assessment was based on distance category only and not on magnetic field assessments. Results are in line with previous assessments that indicate that there could be a small excess risk of childhood leukaemia in children living close to overhead power lines.

Duarte-Rodriguez et al. [14] investigated the clustering of childhood Acute Lymphoblastic Leukaemia (ALL). Cases and controls were identified from public hospitals in Greater Mexico City. Controls were frequency matched on sex, age, and health institution and selected to be free of cancer, congenital malformations, haematological diseases, allergies, and infections. After geolocating addresses at the time of diagnosis or interview for cases and controls, the authors used spatial

scan statistics, controlling for population density, to identify clusters. In total, they identified 1,209 cases, 1,054 of which (95.5%) were included in the final analysis, and they identified 8 clusters covering 38.7% of cases. The clusters ranged in radius from 2.39 km to 41.26 km and included between 11 and 132 cases. Plotting these clusters together with high-voltage power lines, electric installations, and petrochemical facilities they noted that 6 clusters were close to high-voltage electricity lines or power lines, and the remaining two were close to petrochemical industrial facilities. The authors conclude: “The identification of SC [clusters] in certain regions of Greater Mexico City suggest the possible role of environmental factors in the aetiology of childhood ALL.”

Limitations of the study include a lack of testing whether the visually observed association deviated from what might occur at random, and additionally, no information was provided to ascertain the completeness of information on ELF-MF and petrochemical facilities. In conclusion, the study does not allow conclusions regarding the association of the clusters with potential risk factors.

Onyije et al. (a) [15] performed a systematic review and meta-analysis of risk factors for Wilms tumour (a disease of the kidney). They included case-control and cohort studies of tumours diagnosed before age 20. In total, they identified 58 studies on a range of risk factors, two of which addressed paternal ELF-EMF occupational exposure. For these two, the pooled effect size of exposures $>0.2\mu\text{T}$ was 0.92 (95% CI: 0.65– 1.30), not supporting an association with this factor. Meta-analyses are, by definition, restricted by the number, size, and quality of included studies. For the present study especially the low number of studies must be considered a limitation. No Risk of Bias analysis was performed in this systematic review, however, with only two studies on paternal ELF-MF exposures such an analysis would not have been very informative for this outcome.

Onyije et al. (b) [16] conducted a systematic review and meta-analysis of studies on risk factors for childhood brain tumours published between 1976 and 2022. They evaluated 181 studies on exposures around conception, during pregnancy, and postnatally, and calculated pooled risk estimates and summary effect sizes (ES) for case-control and cohort studies combined. Regarding sources of ELF-MF, they evaluated electrically heated waterbeds and observed no association for exposure during pregnancy (4 studies, ES: 0.91, 95% CI: 0.54– 1.53) or childhood exposures (2 studies, ES: 1.37, 95% CI: 0.25– 7.43). For the use of electrical blankets, they observed no association with childhood use (4 studies, ES: 0.72, 95% CI: 0.38– 1.35). For use during pregnancy, they identified 7 case-control studies with a summary ES: 1.33 (95% CI: 1.03– 1.70). The authors argue that although electrical blankets are a source of intrauterine exposure, the observed association could be affected by bias, as all included studies were case-control studies and thus prone to recall bias, and no association was observed for other sources of ELF-MF exposure. For studies on residential exposure to power lines during childhood, the pooled estimates did not indicate an association, whether exposure was assessed from power line configuration or from magnetic field strength. For exposures $>0.4\mu\text{T}$, the ES estimate was 2.61 (95% CI: 0.83– 8.20),

and after exclusion of one study with an OR of 10.91 (95% CI: 1.04– 113.08), the ES decreased to 1.95 (95% CI: 0.57– 6.72). The study found the most consistent associations with birth weight <2500g or >4000g. For other exposures where associations were found, the authors note that their results should be interpreted with caution, as results for most risk factors differed by study design, and a causal interpretation for most is not established.

As a meta-analysis, the study is restricted by the number, size, and quality of included studies. Particular limitations were a large proportion of case-control studies, increasing the risk of recall bias, and that the available studies did not allow analysis by subgroups of childhood brain tumours.

2.1.2 Adult cancer

In their study, Juutilainen et al. [17] provided another analysis based on a cohort of Finnish persons who have lived in a residential building with an in-built transformer. Participants had to live in the building for at least 6 months in between the time period of 1971 and 2016. They were classified as exposed if they lived directly adjacent or above the transformer room. Cancer diagnoses were obtained via linkage to the Finnish cancer registry. Overall, 8840 exposed participants were included into the study, who were compared to 179 285 persons living on floors higher up in the same building. Among exposed persons, 572 cases (developing any cancer) were observed, and 30 were exposed in the age group below 15 years. Standardised Incidence Rates (SIR) for any cancer was 1.01 (95% CI 0.93– 1.09). Of 25 analysed cancer sites, the highest SIR was observed for gallbladder cancer (3.92, 95% CI 1.44– 8.69), no other significant associations were observed.

This is an interesting study that has been published previously with a different outcome (Khan et al. 2020 [18]). The main strength of the study design is that it is built entirely based on registry data, which means that there is only negligible risk of participation bias. Given the universal healthcare system in Finland, no major bias due to differential health care seeking is to be expected. The matching on building level should reduce potential for strong confounding by socio-economic position, although some confounding could have been introduced by air pollutants or noise exposure that tend to be somewhat higher at ground floor levels. Interestingly, the study did not support findings of earlier studies suggesting possible effects of ELF-MF exposure in childhood on increased risks of hematolymphopoietic malignancies, melanoma or ALL in adults. The finding on increased risk on gallbladder cancer has not been previously reported and may represent a chance finding.

2.1.3 Symptoms

Nguyen et al. [19] conducted a cross-sectional study of 36 office workers and 43 technicians (from an initial 216) employed at a high voltage transmission system operator or one of two electricity suppliers in Belgium. Office workers were assumed only exposed to 50 Hz magnetic fields at background levels comparable

to the general public, while technicians were exposed to other sources of magnetic fields. Technician's jobs involved all stages of the electricity transmission and distribution processes: operation of the 380/220k high voltage grid, maintenance in the high voltage stations of the protection equipment, testing of new installations, switching on high voltage installations, and other related tasks, and had been exposed to magnetic fields for at least 1 year. Participants completed a survey, kept a logbook during measurement days, and magnetic flux density was recorded by an Emdex II measurement device, which included broadband (40-800 Hz) and 50 Hz harmonics (ELF-MF) measurements. Measurements were performed for at least three consecutive days. Whole blood samples were collected and genetic damage evaluated using the comet and the cytokinesis-block micronucleus (CBMN) assays using slightly modified standard protocols. Residential exposure was similar for office workers and technicians (mean 0.02 μ T (range 0.00-0.08)), and although occupational exposures of technicians were quite low as well, they were higher (mean 0.25 μ T (0.02-1.31)) than those of office workers (mean 0.02 μ T (range 0.00-0.08)). No statistically significant associations between comet or CBMN results and job titles or MF exposures were observed.

2.1.4 Authoritative reports

The EU scientific advisory body SCHEER (the Scientific Committee on Health, Environmental and Emerging Risks) published an addendum to the SCENHIR evaluation from 2015. The update focused on low and intermediate frequencies from 1-100 kHz. The authors restricted themselves to using systematic reviews and meta-analyses and the opinion concludes in summary: No systematic reviews or meta-analyses on ELF-EMF exposure and self-reported symptoms have been identified since 2015. Systematic reviews on ELF-EMF and leukemia, primarily from case-control studies, indicate consistent but moderate risk estimates, with insufficient evidence for a dose-response curve. Epidemiological studies provide weak to moderate evidence for childhood leukemia, but animal models and interaction mechanisms offer weak support, resulting in an overall weak weight of evidence. There is moderate evidence linking occupational ELF-MF exposure to amyotrophic lateral sclerosis (ALS), weak evidence for Alzheimer's disease and dementia, and uncertain to weak evidence for residential exposure to these diseases. No significant association is found with Parkinson's disease or multiple sclerosis. No systematic reviews on ELF-MF and neurophysiological outcomes were identified, preventing definitive conclusions. Available reviews do not support a link between ELF-MF and reproductive or pregnancy outcomes. For IF-EMF, contradictory evidence prevented clear conclusions on health effects. Regarding LF-EMF, exposure conditions may differ for humans, plants, and animals, with species-specific biological effects possible due to unique receptors and structures.

2.1.5 Conclusions on ELF epidemiological studies

Three studies were published in 2024 that addressed exposure to ELF-MF fields and childhood leukaemia or lymphoma. Of these, one study assessed distance to

overhead power lines, one study evaluated exposure from in-built transformer stations and the third study did not directly assess ELF-MF exposure, but rather performed a cluster analysis. All three studies produced results that are in line with previous assessments that there could be a slightly increased risk of childhood leukaemia with higher exposures to magnetic fields. However, none of the studies contribute to the understanding of why such an association could occur. None of the studies produced statistically significant results.

Adults cancers were evaluated in an interesting study from Finland, analysing possible risks of persons who had ever lived close to an in-built transformer station. The study only observed increased risks of gallbladder cancer, which may represent a chance finding.

A study in an occupational setting did not identify reduced DNA integrity in ELF-MF exposed workers.

Several reviews were published that analysed a large list of possible risk factors or associations of ELF-MF exposure and health outcomes. No very strong or clear risks were reported for people exposed to ELF-MF, although some associations were noted, especially for childhood leukaemia, neurodegenerative disease, as was the absence of associations for example for Parkinson’s disease and reproductive outcomes.

Table 2.1: Epidemiological studies investigating ELF-MF fields

Endpoints	Reference	Exposure assessment	Study design, Population	Results
Childhood leukaemia	Crespi 2024	Proximity of apartment to in-built transformer station.	Per country slightly adapted design, most case-control design.	Very low number of exposed cases, risk estimates above unity but not statistically significant.
Childhood leukaemia, lymphoma	Norzaee 2024	Proximity of home to power line (0-50, 50-100m).	Case control study	Elevated but not statistically significant risks observed in children living within 50m of a power line.
Childhood leukaemia (ALL)	Duarte-Rodriguez 2024	Presence of overhead power lines close to clusters of cases.	Cluster analysis (spatial scan) in Greater Mexico City, Mexico.	Presence of clusters indicate that there could be environmental factors at play. No association with ELF-MF fields analysed.

Adult cancer	Juutilainen 2024	Living in proximity to in-built transformers.	Cohort of the Finnish population living in a building with an in-built transformer.	No increased risk for any cancer. Increased risks for gallbladder risk, which may represent a chance finding.
Cytogenetic biomonitoring	Nguyen 2024	Occupational exposure to ELF-MF	Cross sectional, comparing exposed vs unexposed workers in Belgium.	No association of ELF-MF occupational exposure with genetic damage.
Risks from exposure to ELF-MF and IF-MF	SCHEER 2024	Any reported ELF-MF or IF-MF exposure.	Umbrella review, as an update to 2015 review.	Overview of the evidence, highlighting childhood leukaemia, neurodegenerative outcomes and reproductive outcomes.
Wilms tumor	Onyjie 2024 (a)	Paternal ELF-MF exposure to levels >0.2 microT compared to background	Systematic review, evaluating a range of possible risk factors	No association with paternal exposure.
Childhood brain tumors	Onyjie 2024 (b)	A range of exposures around conception, pregnancy and postnatally were examined.	Systematic review.	Several risk estimates above unity observed, but only statistically significant for maternal electric blanket use during pregnancy. This might be due to recall bias.

2.2 Human studies

While a study on the effects of low-frequency fields on working memory and two systematic reviews that also analysed experimental studies in humans were published in 2023, no further studies were published in 2024. As no new publications are available, no new conclusions can be drawn.

2.3 Animal studies

Last year the results of nine papers investigating the health effects of in vivo exposure to magnetic fields (MF) or electric fields (EF) at extremely low frequencies (ELF) were presented. The report concluded that the significant variations in animal models, which describe differing effects following ELF-MF exposure up to the 7 mT range, once again demonstrate the lack of knowledge regarding the biologically relevant mechanisms of ELF-MF, except for oxidative stress and behavioral effects.

2.3.1 Rodents

Abkhezr et al. [20] studied the effects of ELF-MF exposure (50 Hz, 100 μ T, 4 hours/day, for 42 days) combined with prenatal stress (PS) on cognitive and psychological functions in offspring. They evaluated spatial memory (Morris Water Maze (MWM) task), serum corticosterone levels, brain-derived neurotrophic factor (BDNF) concentrations, and hippocampal BDNF levels in adult male offspring. BDNF is a member of the neurotrophin family, whose reduction can impair hippocampal function development in offspring. Twenty-four female Wistar rats were divided into four groups ($n = 6$ per group): the sham group, the PS group, the ELF-MF exposure group, and the PS-ELF-MF exposure group. Animals experienced ELF-MF exposure and/or PS for 21 days before mating and an additional 21 days during pregnancy. At the end of the lactation period, male offspring ($n = 8$ for each group) were separated from their mothers and evaluated at 90 days of age for hippocampal BDNF levels, as well as serum BDNF and corticosterone concentrations. Results indicated that PS or ELF-MF exposure alone did not significantly affect spatial memory in adult male offspring. However, simultaneous exposure to PS and ELF-MF significantly impaired the acquisition of spatial memory but did not affect the recall phase. Moreover, PS significantly increased serum corticosterone levels in offspring compared to both the control and ELF-MF groups. ELF-MF exposure and PS together led to a non-significant decrease in serum corticosterone levels compared to the PS group. ELF-MF exposure did not significantly affect serum or hippocampal BDNF levels compared to the sham group, but BDNF levels were significantly higher in the ELF-MF exposure group than in the stress group.

In the study by Klimek et al. [21], the effect of ELF-MF exposure (50 Hz, 1 mT and 7 mT, 1 hour/day for 7 days) on the locus coeruleus–noradrenergic (LC-NA) system was investigated. The LC-NA system enables adaptation to stressful conditions and can be assessed through the concentration of adrenaline, noradrenaline, and its metabolite 3-Methoxy-4-hydroxyphenylglycol (MHPG), as well as β 2-adrenergic receptor expression. The Plus Maze Test (PMT) was also conducted on some groups: A total of 180 adult male Wistar rats were divided into six groups: ELF/1mT, ELF/PMT/1mT (ELF exposure followed by PMT), ELF/7mT, ELF/PMT/7mT, sham, and sham/PMT. The procedure was repeated three times to examine the organism's adaptive capabilities. Initially, 30 animals per group started the treatment. After 7 days of exposure, the first groups of animals ($n = 10$ per group) were either sacrificed or subjected to PMT. After three weeks, the last 20 animals per group underwent another round of exposure. This cycle was repeated twice more, totaling nine weeks to complete the experiment. Results showed that ELF-MF exposure at 1 mT induced adaptive changes in the LC-NA system by activating compensatory mechanisms. However, ELF exposure at 7 mT led to increased activity in the stress system, as evidenced by a significant decrease in β 2-AR levels, which would strongly inhibit neuroplastic processes in the hippocampus. Moreover, rats exposed to ELF/7mT exhibited moderately increased anxiety-related behavior, spending significantly more time in the closed arms position compared to the sham group.

In the study by Teranishi et al. [22], the effect of ELF-MF magnetic field exposure (a single 4 ms pulse at 10 μ T intensity, repeatedly modulated from 1 to 8 Hz for 8 s, for six weeks) on mitochondrial Electron Transport Chain (ETC) activity and depressive behavior in mice was examined. A chronic social defeat stress (CSDS) protocol was used for 10 consecutive days on male C57BL/6N mice, inducing behavioral defects mimicking depression. Mice were divided into four groups: ELF exposure, ELF/CSDS, sham, and sham/CSDS ($n = 13$ – 22 per group). Results showed that immobility times in ELF/CSDS mice were significantly reduced compared to the CSDS group in both behavioral tests (tail suspension and forced swim tests performed after two weeks of exposure). Plasma corticosterone levels six weeks after CSDS were not significantly different between the groups. However, ELF/CSDS mice exhibited a significant increase in specific mitochondrial ETC protein levels compared to the other groups. CSDS alone had no effect on mitochondrial oxygen consumption rates in the prefrontal cortex, but six weeks of ELF treatment enhanced it. Other oxidative stress analyses suggested that, under these experimental conditions, ELF magnetic field exposure exerted beneficial effects on mitochondrial energy production, antioxidation, and dynamics in a mouse model of depression.

In the study by Gokce et al. [23], the effect of ELF-MF pulsed magnetic fields at varying intensities on apoptosis-related protein expression levels and liver morphology in rats was analyzed. A total of forty Wistar albino rats (gender not specified) were divided into four groups ($n = 10$ per group): control, sham group, 1 mT, and 5 mT groups. The ELF-MF pulsed magnetic fields consisted of 96 trains of pulses (each lasting 2 minutes, with a 30-second gap between pulses) at a frequency of 50 Hz. The amplitudes were set at 1 mT and 5 mT. Exposure was applied for 4 hours/day, 5 days per week, for 8 weeks. At the end of the exposure period, the animals were sacrificed, and their liver tissues were examined morphologically. Additionally, the expression levels of proteins related to apoptosis and inflammation in these tissues were analyzed. No significant effects were observed for any of the evaluated endpoints.

Kalantar et al. [24] investigated the combined effect of curcumin (CUR) and ELF magnetic field exposure (50 Hz, 1.5 mT) during pregnancy on the liver, hippocampus, and kidneys of the offspring. Fifteen pregnant Wistar rats were divided into six groups: control, sham, ELF-MF exposure (30 min/day during pregnancy), CUR (50 mg/kg daily CUR administered intraperitoneally during pregnancy), ELF+CUR, and a DMSO (dimethyl sulfoxide) group, which received the CUR solvent (DMSO) intraperitoneally under similar conditions during pregnancy. The offspring were divided according to the maternal group ($n = 6$ per group) and sacrificed at 4 weeks of age. Histopathological analysis of the liver, hippocampus, and kidneys showed that ELF exposure led to significant increases in necrotic areas in hippocampal tissue, hyperemia and necrotic cells in the kidneys, and degeneration in liver tissue compared to the EMF+CUR and sham groups.

The aim of the study by Morabito et al. [25] was to investigate the possible effects of ELF exposure (50 Hz, 0.1 and 1 mT, 1 hour/day, 5 days/week, for 1 or 5 weeks) on skeletal muscle. A total of 72 male C57BL/6 adult mice were divided into 12 groups ($n = 6$ per group): four sham groups fed a standard diet with or without N-acetylcysteine (NAC) and/or exposed for 1 or 2 weeks, four ELF/0.1 mT groups, and four ELF/1 mT groups, with the same treatment as the sham-exposed groups. NAC, an antioxidant supplement administered through drinking water, was used to investigate whether antioxidant supplementation could modulate oxidative status and the changes induced by ELF exposure. At the end of the exposure period, the animals were sacrificed, and skeletal muscle samples were collected. Several biological endpoints were evaluated, and the results showed that ELF exposure modulated the myogenic process, influencing the redox status of skeletal muscle without evidence of a dose-dependent effect. Specifically, there was a transient increase in muscle strength, potentially linked to muscle fiber recruitment and activation, as indicated by higher expression levels of PAX7 (a transcription factor involved in myogenesis) and myosin heavy chain (MyH). Moreover, ELF exposure induced transient increases in the expression levels of superoxide dismutase 1 (SOD1) and catalase enzymes, total antioxidant capacity, and protein carbonyl levels—markers of oxidative damage. The presence of NAC had various effects: some tested parameters mimicked the ELF-induced effect, while others counteracted it.

Yang et al. [26] evaluated the toxic effects of prolonged exposure to ELF magnetic fields (rotating magnetic field at 4 Hz, 0.2 T, 2 hours/day for 10 months). This signal is used for therapeutic purposes; therefore, it was necessary to assess the safety of long-term exposure to this type of signal. Twenty-four female C57BL/6 mice were divided into two groups: sham-exposed and ELF-exposed ($n = 12$ per group). The safety of the exposure was assessed through the evaluation of multiple biological endpoints. During the exposure period, a behavioral test (open field test) was performed once a month. At the end of the exposure period, a comprehensive assessment of overall murine health was conducted, including blood parameter analysis, histo-morphological examination of major organs, and skeletal assessments using X-ray and micro-CT imaging. Additionally, immune system function and lipid metabolism were evaluated through immune-chip analysis and metabolomics. No significant effects were found.

2.3.2 Fish

The study by Krylov et al. [27] aimed to investigate the combined effects of mercury and ELF magnetic fields on the digestive enzyme activity of common carp (*Cyprinus carpio*). Mercury, like other heavy metals that accumulate in organisms and cause harmful effects, is a major source of anthropogenic pollution in aquatic ecosystems. Seventy-eight fish were used in the experiment: six were analyzed to measure the initial mercury content in the intestines, liver, and muscles before the experiments. The remaining 72 fish were divided into two groups and fed for six months with diets containing either a low mercury concentration (0.02 mg/kg, named LHg) or a high mercury concentration (0.27

mg/kg, named HHg) before magnetic field exposure. The exposure system allowed for the quasi-nullification of the geomagnetic field (GMF), and the experiment involved three different types of magnetic field exposures: one with resonance parameters for potassium ions (7.63 Hz, 35 μ T, 19.4 μ T residual GMF, named K-MF), one with resonance parameters for calcium ions (18.5 Hz, 44.5 μ T, 24.2 μ T residual GMF, named Ca-MF), and quasi-zero GMF exposure. Additionally, a control group was included. At the end of the study, each experimental group consisted of eight fish exposed for one hour. The amylolytic activity (total activity of enzymes hydrolyzing starch: α -amylase, glucoamylase, and maltase) and proteolytic activity (total activity of serine proteinases) in the fish intestine were assessed. Results showed that LHg fish exhibited a significant decrease in amylolytic activity following both K-MF and Ca-MF exposure compared to the sham group, whereas HHg fish showed significantly increased activity under quasi-zero GMF and K-MF conditions. Proteolytic activity followed a similar pattern, with opposite effects observed between the two dietary groups. These results suggest that mercury accumulation in fish can alter enzymatic responses to magnetic field exposure. However, the authors specify that "the mechanisms of ELFMF influence on organisms remain uncertain and warrant further investigation."

2.3.3 Conclusions

A total of 15 articles were selected investigating the *in vivo* biological effects of exposure to the ELF fields. After a full-text analysis, only 8 articles were used for the drafting of this report. All the articles, except for one that examines the effects of ELF exposure on a species of carp, discuss the effects of exposure on rodents. Five articles focused on the analysis of biological effects related to the exposures related to the energy transmission (50 Hz, from 10 μ T to 7 mT), while the other three examined the effects of more specific signals that could be intended for therapeutic or other purposes, aiming to assess their potential toxicity. Thus, the studies reviewed provide insights into the effects of ELF magnetic field exposure on various biological systems across different species. In rodents, ELF exposure combined with prenatal stress was found to impair spatial memory acquisition, alter stress hormone levels, and influence neurotrophic factors (Abkhezr et al.). Furthermore, ELF exposure modulated the locus coeruleus–noradrenergic system, with higher field intensities (7 mT) inducing stress-like responses and anxiety-related behaviors (Klimek et al.). In contrast, ELF exposure appeared to have beneficial effects on mitochondrial function and oxidative stress markers in a mouse model of depression, suggesting potential therapeutic applications (Theranishi et al.). Histopathological studies revealed that ELF exposure influenced tissue morphology and oxidative status. While no significant effects were observed on liver morphology and apoptosis-related proteins in one study (Gokce et al.), other research showed ELF exposure contributing to tissue damage in the liver, hippocampus, and kidneys of offspring (Kandar et al.). It is important to note that in the two papers the ELF signals examined are very different from each other: in Gokce et al. a pulse magnetic signal was used, while in Kalantar et al. a 50 Hz, and amplitude of 1.5 mT was adopted. Additionally, ELF exposure influenced skeletal muscle function by modulating redox balance and myogenic

processes, with antioxidant supplementation playing a complex role in these responses (Morabito et al.). Importantly, long-term ELF exposure at a signal used for therapeutic purposes did not produce significant toxic effects in mice (Yang et al.). Beyond mammals, the effects of ELF exposure in fish were found to be influenced by environmental pollutants, such as mercury (Krylov et al.). The study on common carp demonstrated that dietary mercury accumulation altered enzymatic responses to ELF magnetic fields, highlighting the potential interactions between ELF exposure and chemical contaminants in aquatic ecosystems.

Overall, these findings underscore the diverse and context-dependent biological effects of ELF magnetic field exposure. While some studies suggest potential risks, particularly at higher intensities or in combination with other stressors, others indicate possible beneficial effects on cellular function and adaptation. Further research is needed to elucidate the underlying mechanisms and long-term consequences of ELF exposure in both environmental and therapeutic contexts.

About the other outcomes and assessed endpoints, results are summarized in Table 1 where all the statistically significant results are reported. In Table 2 the list of excluded papers and motivation of exclusion is shown.

Table 2.3: Summary of the animal studies investigating biological effects of ELF exposure

Outcome	Reference	Population	Exposure	Effect of ELF exposure
Rodent Studies				
Behavior	Abkhezzar et al.	Wistar rats Male offspring observed	50 Hz 100 μ T 4 h/d for 42 days (exposure started during pregnancy and for 21 days after birth)	No effect of PS or ELF exposure alone on spatial memory in the offspring. PS and ELF exposure significantly affected the acquisition of spatial memory but not the spatial memory recall phase. \uparrow corticosterone levels in PS group No effect of ELF exposure on the hippocampal BDNF levels compared to sham group, but \uparrow compared to the PS group.
	Klimek et al.	Male Wistar rats	50 Hz 1 mT 7 mT 1h/d for 7 days of exposure interspersed with three weeks of break (one group 1 week of exposure, one group two weeks of exposure, 1 group 3 weeks of exposure)	Adaptive changes in the LC-NA system for ELF/1mT exposure. \uparrow activity of the stress system for ELF/7mT exposure revealed by \downarrow β 2-AR level \downarrow anxiety-related behavior for ELF/7mT group.
	Theranishi et al.	Male C57BL/6N mice treated with CSDS (mouse model depression)	4 ms pulses at a 10 μ T intensity repeatedly modulated from 1 to 8 Hz	\downarrow immobility times in the ELF/CSDS mice respect to the CSDS group in both behavioral tests \uparrow levels of some proteins of mitochondrial ETC in ELF/CSDS

			Single train of pulses for 8 s for two or six weeks	group with respect to the other groups. ELF magnetic field exposure has beneficial effects on mitochondrial energy production, mitochondrial antioxidation, and mitochondrial dynamics in a mouse model of depression.
Effects on tissue and Oxidative Stress	Gokce et al.	Winstar albino rats (gender not specified)	96 trains of pulses (duration 2 min for each pulse and a 30 s gap between pulses) with a pulse frequency of 50 Hz. 1 mT and 5 mT. 4 h/d, 5 d/w for 8 weeks	No effects on morphology of liver tissue, in the expression levels of proteins related to apoptosis and inflammation liver.
	Kalantar et al.	Winstar rats Offspring observed (gender not specified)	50 Hz 1.5 mT 30 min/d during pregnancy CUR treatment (50 mg/kg/daily intraperitoneal during pregnancy)	↑ necrotic areas in hippocampal tissue, the amount of hyperemia and necrotic cells in kidneys, degeneration in liver tissue in ELF exposed group compared with EMF+CUR and sham groups.
	Morabito et al.	Male C57BL/6 adult mice	50 Hz, 0.1 mT 1 mT 1 h/d, 5 d/w, for 1 or 5 weeks	ELF exposure modulated the myogenic process, influencing the redox status of skeletal muscle (no dose-dependent effect) ELF exposure induced transient increases in the expression levels of SOD1 and catalase enzymes, in total antioxidant capacity, and in protein carbonyl levels, markers of oxidative damage.
	Yang et al.	Female C57BL/6 mice	4 Hz 0.2 T 2 h/d for 10 months	No effects on blood parameters, on histology of major organs, on skeletal analysis (X-ray and micro-CT imaging), on immune system and lipid metabolism.
Fish				
	Krylov et al.	Cyprinus carpio	Resonance parameters for potassium ions: 7.63 Hz, 35 μT, 19.4 μT residual GMF Resonance parameters for calcium ions: 18.5 Hz, 44.5 μT, 24.2 μT residual GMF Quasi zero GMF exposure. 1 hour 0.02 mg/kg of Hg (low mercury content, LHg) 0.27 mg/kg of Hg (high mercury content, HHg)	↓ amylolytic activity in the LHg group at both frequencies ↑ amylolytic activity in the HHg group after the quasi zero exposure and the 7.63 Hz exposure. Similar patterns for proteolytic activity with opposite effects observed between the two dietary groups.

Abbreviations: ↑=increase(d); ↓=decrease(d); PS: prenatal stress; BDNF: brain-derived neurotrophic factor; LC-NA: locus coeruleus–noradrenergic; CSDS: Chronic Social Defeat Stress; CUR: Curcumin; SOD1: superoxide dismutase 1.

2.4 Cell studies

Last year's report revealed that ELF-EMF exposure can have varying effects on cellular processes, highlighting the complexity and diversity of cellular responses to this stimulus.

In 2024, 6 papers examined the biological effects of ELF on cellular and molecular mechanisms. Two studies investigated their influence on tumorigenicity, cell proliferation and associated biomarkers. One study explored ELF field interactions with epigenetic regulation, including DNA methylation, histone modifications, and microRNA biogenesis. Neuronal activity and calcium oscillations were the focus of one study, which analyzed exposure thresholds and network responses. Two additional studies examined ELF field interactions with cell viability, while one study assessed DNA integrity in lymphoma cells under specific exposure conditions.

2.4.1 Tumorigenic processes

The study by Colciago et al. [28] explored the effects of magnetic field (MF) exposure (50 Hz, 0.1 T for 10 minutes) on primary Schwann cell (SC) cultures derived from neonatal rat sciatic nerves. The research aimed to evaluate cellular, epigenetic, and functional changes induced by 50 Hz MF exposure, which could contribute to tumorigenic processes.

Compared to the sham group, 50 Hz MF exposure increased SC proliferation and colony formation in soft agar, indicating enhanced anchorage-independent growth, a hallmark of cellular transformation and tumorigenicity (based on three independent experiments with four samples each). Cell cycle analysis revealed an accumulation of cells in the G2 phase, consistent with a stress-induced cell cycle checkpoint response. While global DNA methylation was reduced following exposure, no significant changes were observed in the methylation status of CpG (Cytosine-phosphate-Guanine) islands within the promoter of the *Nf2* (neurofibromin type 2) gene. Additionally, exposure downregulated DNA methyltransferases (DNMT3a/3b, enzymes responsible for adding methyl groups to DNA) and histone deacetylases (HDAC1/2, enzymes that remove acetyl groups from histones, leading to chromatin compaction and transcriptional repression), suggesting potential chromatin structure relaxation. The exposed cells demonstrated upregulation of genes associated with oxidative stress and hypoxia, such as *HMOX1* (heme oxygenase 1), which catalyzes the rate-limiting step in heme degradation, releasing iron and carbon monoxide. However, most gene expression changes were transient. Furthermore, exposure transiently disrupted mitochondrial membrane potential (an indicator of mitochondrial health and function) without affecting mitochondrial mass, indicating oxidative stress.

The authors suggest that 50 Hz MF exposure may contribute to oncogenic processes in Schwann cells by promoting a less differentiated and more proliferative phenotype, potentially relevant to conditions like schwannomas (tumors of Schwann cells in the peripheral nervous system).

Impacts of 50 Hz MF (5 mT, 1 h) on NIH/3T3 mouse fibroblasts at 15th–20th passages (referred to as “aged fibroblasts”) and the effects of metformin (Met), a known NF- κ B (nuclear factor-kappa B) inhibitor with anti-cancer properties, were evaluated in the study by Soydas et al. (Soydas et al., 2024). The 50 Hz MF promoted cell proliferation, elevated pro-metastatic markers (matrix metalloproteinases MMP2/9), and reduced epithelial marker (E-cadherin CDH1) expression through NF- κ B activation. Metformin administered 24 h before 50 Hz exposure counteracted MF-induced carcinogenic effects in a dose-dependent manner, with the strongest effect observed at 10 mM (n=5), by suppressing NF- κ B activity, downregulating MMP2/9, and restoring CDH1 expression. These results suggest that Met may help mitigate the effects of MF exposure by counteracting its influence on NF- κ B activation, MMP2/9 expression, and CDH1 regulation. However, the absence of a control group treated with Met alone limits the conclusions regarding its specific role in these processes.

2.4.2 Epigenetic

Wydorski et al. [29] investigate how short-term exposure to ELF-MF impacts epigenetic regulation mechanisms in the endometrium of pigs during the peri-implantation period. Endometrial slices from pigs were exposed to a 50 Hz ELF-MF for 2 hours at 8 mT (n=5). DNA methylation levels, histone modifications, and proteins involved in microRNA biogenesis were analyzed using quantitative PCR and Western blot techniques. Global DNA methylation and histone deacetylase (HDAC) activity were also assessed. 50 Hz exposure increased global DNA methylation and HDAC activity. Expressions of several epigenetic regulators (e.g., DNA Cytosine-5-Methyltransferase 1 (DNMT1), Enhancer of Zeste 2 (EZH2)) decreased, while DNA (Cytosine-5)-Methyltransferase 3a (DNMT3a) expression increased. MicroRNA biogenesis-related proteins (Dicer 1, Ribonuclease III (DICER1), DiGeorge Syndrome Critical Region 8 (DGCR8)) were altered, suggesting changes in post-transcriptional regulation. These findings highlight 50 Hz potential to impact epigenetic regulation in the endometrium slices.

2.4.3 Calcium oscillation

The study by Saito et al. [30] aimed to evaluate the effects of ELF-EF exposure on intracellular calcium oscillations $[Ca^{2+}]_i$, a marker of neuronal network activity, in human cortical spheroids (hCS). Additionally, the study sought to establish the threshold of stimulus effects and to model the induced electric field (iEF) distribution in hCS using numerical dosimetry. hCS were developed, containing excitatory and inhibitory neurons mimicking human cortical networks and long-term culturing (up to 60 days) was used to stabilize synchronized bursting activity. A 50 Hz sinusoidal ELF-EF was applied using a parallel-plate electrode setup. Voltage levels ranged from 1–5 V_{pp} (Voltage peak to peak), and exposure durations were varied (1, 3, and 5 seconds). Neuronal activity was assessed using extracellular multi-electrode array (MEA) recordings and calcium imaging with Fluo-8 fluorescent indicators. Synchronized bursting activity was observed after

5–6 weeks of culture and stabilized after 7–9 weeks, indicating functional neuronal networks. ELF-EF exposure increased the frequency of $[Ca^{2+}]_i$ bursts in hCS, particularly at 3 Vpp, with significant modulation occurring at exposure durations of 3–5 seconds. The minimum threshold for observable effects on burst frequency was 2 Vpp under 5 second exposure. The study demonstrated that ELF-EF exposure modulates $[Ca^{2+}]_i$ oscillations in hCS, with effects dependent on exposure intensity and duration.

2.4.4 Cell viability

Wydorski et al. [31] explore the impact of ELF-MF exposure on apoptosis and oxidative stress in endometrial slices of pigs. Samples were treated or not (control) with ELF-MF (50 Hz, 8 mT) for 2 hours as described previously above (n=5). Apoptosis-related (caspase 3 (CASP3), Cell Death-Inducing DFFA-Like Effector B (CIDEB), Cell Death-Inducing DFFA-Like Effector B (GADD45G) and oxidative stress-related (Nitric Oxide Synthase 3 (NOS3), Tumor Protein p53 Inducible Protein 3 (TP53I3) gene expressions were analyzed using real-time PCR, Western blot, and ELISA. CASP3/7 activity and nitric oxide synthase (NOS) activity were also measured. CASP7 expression and protein levels decreased, while CIDEB, GADD45G, and NOS3 levels increased, suggesting enhanced oxidative stress and apoptosis potential. NOS activity was unchanged, though NOS3 protein levels were elevated. Authors concluded that short-term ELF-MF exposure influences apoptosis- and oxidative stress-related pathways in the endometrium.

2.4.5 Genotoxicity

Worel et al. [32] experiments aimed to assess whether ELF-MF (50 Hz, 50, 200, and 1000 μ T, 24 h) induce DNA damage or influence chemically induced DNA damage in human Jurkat lymphoma cells. The cells were simultaneously or sequentially exposed to ELF-MF and mutagens relevant to occupational exposures, including 4NQO (4-Nitroquinoline 1-oxide), BPDE (Benzo[a]pyrene diol epoxide), CrO₃ (Chromium trioxide), and NiCl₂ (Nickel dichloride). No significant DNA damage was observed across all flux densities with ELF-MF alone in Jurkat cells (three cultures, each two slides, 50 cells analyzed). 50 Hz exposure did not significantly enhance or reduce DNA damage caused by any of the tested mutagens. The extent of DNA damage in treated cells remained similar to controls without ELF-MF exposure. These findings suggest that 50 Hz exposure at occupational and environmental levels is unlikely to pose a significant genotoxic risk. The paper also examined the effects of RF-EMF at 1950 MHz; see the RF-EMF section for details.

2.4.6 Conclusions on ELF field cell studies

The body of evidence from the 2024 studies indicates that ELF-MF exposure can modulate cellular and molecular processes, particularly concerning proliferation, oxidative stress, epigenetic regulation, and neuronal activity. However, the effects are often transient, vary across cell types, and depend on exposure parameters.

The inconsistencies in findings suggest that ELF-MF may influence certain biological pathways, but possible associated risks remain unclear.

Table 2.4: Cell studies on exposure to Extremely low frequency (ELF-MF or ELF-EF) fields

Outcome	Reference	Population	Exposure	Effect
Epigenetic, cell cycle, oxidative stress	Colciago et al, 2024	Primary Schwann cell (3 independent experiments, 4 samples each)	50 Hz, 0.1 T, 10 min	Promotion of proliferation, stress responses, epigenetic changes, and tumorigenicity
Calcium oscillations	Saito et al., 2024	Human cortical spheroids (hCS) n=4	50 Hz, ELF-EF, 1–5 Vpp, 1, 3, and 5 sec	Calcium oscillations with effects dependent on exposure intensity and duration
Viability, proliferation, metastatic markers	Soydas et al., 2024	NIH/3T3 mouse fibroblasts n=5	50 Hz, 5 mT, 1 h	ELF-MF promotes proliferation and metastasis
DNA damages	Worel et al., 2024	Human Jurkat lymphoma cells n=3	50 Hz, 50, 200, and 1000 μ T, 24 h \pm chemicals	No significant DNA damage
Epigenetic	Wydorski et al., 2024	Pig endometrium slices (n=5)	50 Hz, 2 h, 8 mT	Expressions of several epigenetic regulators were altered
Apoptosis and oxidative stress	Wydorski et al., 2024	Pig endometrium slices (n=5)	50 Hz, 2 h, 8 mT	Apoptosis and oxidative stress-related pathways were influenced

3. Intermediate frequency (IF) fields

3.1 Epidemiological studies

In last years' report, a single study from Japan was summarised that investigated whether exposure of pregnant women to induction cooking could affect birth outcomes. The authors observed increased risks of premature birth but concluded that the association was unlikely causal. Only few epidemiological studies on this exposure exist.

In 2024, no epidemiological studies on IF-MF exposure were found.

3.2 Human studies

As in 2023, no new publications were found.

3.3 Animal studies

Last year the results of two papers investigating the health effects of *in vivo* exposure to intermediate frequency (IF) fields (SMF) showed no relevant biological effects.

In 2024, only one paper addressing *in vivo* IF field exposure was published. In Zhao et al. [33], the effects of IF magnetic field exposure (90 kHz, 0.6 ± 0.4 mT, 2 hours/day for 2, 4, and 8 weeks) on cognitive functions and neuronal excitation in exposed mice were investigated. The frequency of 90 kHz is commonly used in the development of wireless power transfer systems for the automotive industry. In this experiment, 24 male Kunming mice were divided into four groups: a sham group, IF/2 weeks, IF/4 weeks, and IF/8 weeks. At the end of the exposure period, the Novel Object Recognition (NOR) test was performed to assess the animals' learning and memory capabilities. Additionally, whole-cell patch-clamp (a technique to measure ionic currents that flow through single membran channels) experiments were conducted on brain slices containing the complete hippocampus to record action potentials (AP) and potassium (K⁺) currents. The results of this study indicated that IF magnetic field exposure had no significant impact on the cognitive function of mice. However, patch-clamp assays revealed that IF exposure significantly reduced K⁺ outflow in granular neurons of the hippocampal dentate gyrus, decreasing the intracellular-extracellular K⁺ concentration difference. This reduction lowered the threshold for action potential triggering and enhanced neuronal excitability in the hippocampal region. These effects were independent of the duration of exposure.

Table 3.3: Summary of the animal studies investigating biological effects of IF exposure.

Outcome	Reference	Population	Exposure	Effect IF exposure
Behaviour and patch clamp	Zhao et al.	Male Kunming mice	90 kHz, 0.6 ± 0.4 mT, 2 hours/day for 2, 4, and 8 weeks	No effects on the cognitive function of mice. ↓K ⁺ outflow in granular neurons

3.4 Cell studies

No cell studies have been published in the period of interest.

4. Radiofrequency (RF) fields

4.1 Epidemiological studies

Last year several studies were published on adult cancer risk from use of mobile phones. A prospective cohort study of women found no increased risk of brain tumours and two incidence trend studies demonstrated that brain tumor risk increases exceeding 20% after 15 years of use can be excluded. Different aspects of mobile phone use were associated with semen quality parameters in two studies and reduced blood pressure in women in one study. Chance could however not be ruled out as a likely cause in these studies.

4.1.1 Pregnancy outcomes

Buyukeren [34] reported an analysis of specific absorption rate (SAR) values of mobile phones, daily maternal phone use and neonatal outcomes in children born in Konya Hospital, Turkey. Of overall 2286 women who gave birth between September 2020 and February 2021 at the hospital, 1495 were included into the study, after excluding refugees, women who gave birth to multiples, who had known diseases or too little information on health status or phone use. Although a range of neonatal outcomes were collected (gestational age, birth weight and length, head circumference, APGAR 5-min score, health status), only statistics based on small for gestational age (SGA) was presented, stratified by duration of phone use of the mother and Specific Absorption Rate (SAR) of the used phone was reported. The authors report the same amount of phone use (190min daily) of mothers of SGA as for non-SGA babies, but the SAR values of the phones were higher in the SGA group.

SAR level of a phone by itself and as declared by the manufacturer is not predictive for the exposure of RF-EMF, but the way the phone is used (e.g. for calling, texting or surfing) in addition to connection quality would be relevant for exposure. Unfortunately, although use information like calling or texting was collected, this information was not presented. Overall, the study is not informative regarding an association of RF-EMF exposure of mothers during pregnancy and birth outcomes in their children.

Molasaraie et al. [35] performed a case-control study on the use of mobile phones and the internet in relation to miscarriage. In 2019, women with a previous miscarriage referred to urban health centres in the Iranian city of Zanjan were selected as cases. Mothers with a successful pregnancy were selected from the same health centres as controls. Women whose last pregnancy was a provoked abortion were excluded. Information was collected from health centre records and by questionnaire. The questionnaire included questions on hours of mobile phone use and whether the mobile phone was turned off at night (yes/no), as well as hours of internet use and whether the modem was turned off at night. Presumably, all questions related to the time of the latest pregnancy, but this is not stated. In total, 211 cases and 394 controls participated; it is not reported how many were

invited (response rate unclear). Controls were younger, better educated, and less likely to have had previous pregnancy complications or miscarriages. Neither cases nor controls reported any smoking or alcohol consumption. Initially, all factors were compared between cases and controls using Chi-square tests, and factors with $p < 0.2$ were included in a logistic regression model. Hours of internet use (OR 1.07, 95% CI: 0.99– 1.15), mobile phone use (OR: 1.12, 95% CI: 0.86– 1.45), and turning off mobile phones at night (OR 0.97, 95% CI: 0.58– 1.76) were the RF-related exposures included in this model. The authors concluded: “Although the effect was small and a borderline statistical significance was seen, it appears reasonable to take preventive measures to reduce exposure to low-frequency electromagnetic waves by pregnant women.”

The study did not identify any immediate associations indicative of a link with RF-EMF exposure. The borderline significant association observed with internet use may be inconsequential or may be related to aspects of this activity, or it may be driven by an association with an unidentified risk factor. Other limitations include potential participation bias, a limited number of confounders (e.g., socioeconomic status was only covered by education), and there was no information about factors such as obesity. Additionally, there might be concerns about social desirability bias regarding the no smoking and drinking observation.

4.1.2 Adult cancer

Feychting et al. [36] presented the findings of the international prospective COSMOS (Cohort Study on Mobile Phones and Health) study in relation to glioma, meningioma, and acoustic neuroma risk. They recruited 24,574 participants (64% women) aged 18+ from Denmark, Finland, the Netherlands, Sweden and the UK between 2007 and 2012, who accrued 1,836,479 person-years of follow-up. Participants were recruited through mobile network subscriber lists from Denmark, Finland and Sweden, and additionally in the UK from the electoral register (35%), while in the Netherlands participants were recruited from three existing cohorts. Median follow-up duration was 7.12 years. Participants completed a baseline questionnaire on mobile phone use 3 months prior to recruitment, and for a subgroup of volunteers. Additionally mobile phone use data were obtained from their operators for the same 3-month period. The latter was used for calibration of self-reported call time. Information about baseline and past hands-free device use was subtracted from total call-time. Use of mobile phones for other purposes, such as texting, was not included in the exposure estimate, as corresponding RF-EMF exposure to the head is negligible. Cancer occurrence was obtained through linkage of the cohort to national cancer registries, and over the study period 149 glioma, 89 meningioma, and 29 cases of acoustic neuroma occurred. Models were adjusted for country, sex, educational level, and marital status, and employed attained age as the underlying time-scale for Cox regression models. 1.2% of participants had at least one missing datapoint, which was imputed.

Adjusted HR per 100 regression-calibrated cumulative hours of mobile phone call-time was 1.00 (95 % CI 0.98–1.02) for glioma, 1.01 (95 % CI 0.96–1.06) for

meningioma, and 1.02 (95 % CI 0.99–1.06) for acoustic neuroma. To evaluate impact on the highest user group specifically, additional analyses for glioma risk using the 90th percentile cut-point ($\geq 1,908$ regression-calibrated cumulative hours) was conducted, but did not indicate any excess risk with a HR of glioma of 1.07 (95 % CI 0.62–1.86). More than 15 years of mobile phone use was also not associated with an increased glioma risk (HR 0.97 (95% CI 0.62–1.52)) or meningioma risk (HR 1.24 (95% CI 0.60– 2.59)). There was little difference between the calibrated and uncalibrated results. The researchers interpret these findings as indicating that the cumulative amount of mobile phone use was not associated with the risk of developing glioma, meningioma, or acoustic neuroma.

This is a large and well conducted study. Its main limitations are weaknesses in the exposure assessment, and in particular that measured RF-EMF exposure is not available while also mobile phone use information was not collected after baseline. Nonetheless, the results convincingly indicate an absence between mobile phone and brain cancer risk in the general population.

Karipidis et al. (2025) [37] conducted a systematic review in the series of reviews commissioned by WHO. Where feasible, the authors included a meta-analysis of the associations between RF-EMF exposure and risk of leukaemia, non-Hodgkin's lymphoma, and thyroid cancer related to mobile phone use and cancers of the lymphohematopoietic system and oral cavity/pharynx cancer in occupational populations. The OHAT Risk-of-Bias tool was used to assess study quality. This was one of the series of systematic reviews commissioned by WHO, and it was conducted according to a pre-specified protocol. Exposure from mobile phone use was classified as 'ever use', 'time since start of first use', cumulative hours of use, and cumulative number of calls. With respect to environmental exposures, studies based on measurements, modelling, or geocoded distance to broadcast transmitters were included, but those based on self-estimated distance were excluded. Studies of occupational populations were included if the exposure assessment was based on measurements or estimates derived from job-exposure matrices or source-exposure matrices, or those based on job title or task if this was well characterized in terms of source and type. Studies based on self-reported exposure were excluded, as were those with main exposures between 0Hz and 10 MHz. 3,867 records were identified, of which 26 were included in the review. Articles were published between 1988 and 2019 and included 143 different exposure-outcome pairs, including 65 types of neoplasms. Of these, only 19 pairs satisfied the criteria for inclusion in quantitative synthesis. The researchers concluded that RF-EMF exposure was not associated with increased risk of leukemia, thyroid cancer, or non-Hodgkin's lymphoma either defined as ever/never exposed or as long-term (10+ years) of mobile phone use. Occupational exposure was also not associated with increased risk of lymphohematopoietic system tumours or oral cavity/pharynx cancer. However, there were insufficient studies to conduct more detailed analyses. The researchers further conclude that the quality of the evidence was low.

This was a well conducted systematic review and meta-analysis of the highest quality evidence based on a pre-specified protocol. Despite this, the quality of the included studies was low, and although the evidence is indicative of an absence of an association between RF-EMF exposure and these cancers, it precludes strong conclusions on causality.

(Please note that while this systematic review was actually published outside of the time frame of this report, it was published very early in 2025. Given the many WHO commissioned reviews included in this year's report, also the paper by Karipidis et al. (2025) was included here.)

Bouaoun et al. [38] investigated the potential impact of recall and selection bias in case-control studies on mobile phone usage and risk of glioma. Specifically, they examined the Interphone study, which indicated that heavy mobile phone use could be associated with an increased risk of glioma. In that study, individuals reporting to use a phone <1/week constituted the reference group, and mobile phone users were categorized into groups based on deciles of usage. Usage in the highest decile was associated with an elevated risk, whereas lower usage categories were associated with a decreased risk. The decreased part of this J-shaped relationship has been attributed to bias, whereas it has been the subject of debate to what extent the elevated risk among the highest exposure represented a true risk. Apart from data from the Interphone questionnaire, information for the present study was collected from a short Interphone non-responder questionnaire and two validation studies, which also included comparisons of self-reported mobile phone use and mobile phone operator data. Based on the potential errors observed in these data, the authors simulated two types of error: random error, reflecting lack of precision in recalling mobile use, and systematic error, where there was underreporting among light users and overreporting among heavy users. They then used Monte Carlo simulation analysis to evaluate 5,000 datasets, each containing 1,000 cases and 2,000 controls, with data on true exposure (derived from operator data) and error-prone exposure simulated according to one of four scenarios.

Scenario 1: Greater random and systematic error among cases.

Scenario 2: Only random error, but greater among cases.

Scenario 3: Non-differential random error, but greater systematic error in cases.

Scenario 4: Only non-differential random error.

The scenarios were evaluated under the condition that there was no true correlation between mobile phone use and the risk of glioma. Scenario 1, which most closely reflected the biases observed in validation studies, produced exactly a J-shaped curve as observed in the original Interphone study, with a positive association for the highest decile of exposure. Scenarios 2 and 3 also produced elevated risk estimates at high exposure but showed decreased risk among very low exposure, while Scenario 4 did not lead to deviations from the null. The authors therefore argue that even in a situation where no true association exists, the results of Interphone could arise due to biases and errors. They conclude,

“Some uncertainty remains, but the evidence from the present simulation study shifts the overall assessment to making it less likely that heavy mobile phone use is causally related to an increased glioma risk.”

Limitations of the study include the fact that the size of the biases included in simulations may not be completely representative of the true biases as they were only derived from smaller samples of the complete Interphone eligible population. Other biases and potential confounding factors than those included in the present study could also still have been present in the Interphone results.

Moon et al. [39] published a meta-analysis of RF-EMF and brain tumours. Case control studies and cohort studies were analysed separately with focus on the case control studies. The authors rated the studies regarding potential selection and recall bias. They evaluated regular users, users of less or more than 10 years, and ipsi-and contralateral users compared to non-regular users. The analysis covered glioma, meningioma, acoustic neuroma, pituitary tumours, and overall CNS tumours. They also conducted an analysis restricted to individuals with more than 896 hours of cumulative phone use. This threshold appears to have been applied by extracting the highest exposure category from each study, provided it exceeded 896 hours. In that analysis they used the ipsilateral risk estimates when available. After screening they included 19 case-control and 5 cohort studies.

When comparing regular and non-regular users, for all CNS tumours and for the subgroups, ORs were close to the null. When restricting analyses to phone use for more than 10 years or ipsilateral use, the ORs increased. E.g. for glioma, when compared to non-regular use, the ORs were 1.08 (95% CI: 0.86– 1.35, 6 studies) for regular-use, 1.32 (95% CI: 1.01– 1.71, 4 studies) for use >10 years and 1.45 (95% CI: 1.15– 1.82, 8 studies) for ipsilateral use. In the analysis of those with highest hours of cumulative use >896 hours and prioritizing ipsilateral estimates the resulting combined ORs were 1.66 (95% CI: 1.32– 2.44) for glioma, 1.29 (95% CI: 1.08– 1.54) for meningioma 1.84 (95% CI: 0.78– 4.37) for acoustic neuroma and 1.59 (95% CI: 1.25– 2.02) for all CNS tumours.

Results from cohort studies were not integrated with the above analyses and risk estimates were close to one for glioma, meningioma and all CNS tumours. The highest estimate was 1.61 (95% CI: 0.91– 2.85) for acoustic neuroma among users of >10 years.

The authors conclude: “In this meta-analysis, as the exposure subcategory used became more concrete, the pooled ORs demonstrated higher values with statistical significance.”

Limitations: the ORs for regular use and use longer than 10 years in the present study are in line with the estimates in the meta-analysis by Karapidis et al. especially when considering that the cohorts were not part of the risk estimates in Moon et al. The subsequent analyses are however all likely to have increased the likelihood of biased estimates. Laterality estimates in case-control studies may be particularly prone to recall bias and multiple biases can affect study results, so

elevated ipsilateral estimates may not correspond to decreased contralateral estimates, as other biases might obscure this relationship. The focus on the highest usage category may also have biased the results. As demonstrated by Bouanoun et al. (summarized in this year's report) the highest exposure category is particularly susceptible to elevated risk estimates due to likely biases. Furthermore, the 896 h cut-off seems arbitrary and in the author's response to the peer review they state "Therefore, the authors needed to set a rather higher standpoint (>896 hours) to produce an increased pooled OR with statistical significance. If the authors used cumulative hours of use under, for example, 600 hours, the pooled OR might have been statistically equivocal." Another limitation is that even though Moon and colleagues assessed risk of bias, they did not use it in sensitivity analyses, nor did they address that some risk estimates from case control studies are unlikely to be compatible with observed incidence trends.

The study does also suffer from some inconsistencies. E.g. for cohort studies, the recent COSMOS publication summarized in the present SSM report is listed among the included cohorts but is not included in the meta-analysis of cohorts. This analysis does however contain two publications from the Million Women Study, leading to some women being included twice. The study by Christensen (2005) is listed as excluded but is included in the meta-analyses. Yoon is not included in the analysis of glioma by length of usage but is included in the analysis restricted to those with >896 hours of use. And a final example the CEFALO study by Aydin et al. is included but no other studies on childhood tumours are included.

Turuban et al. [40] investigated the potential association between occupational exposure to intermediate and radiofrequency electromagnetic fields (100 kHz-300 GHz) and the risk of meningioma and glioma. Cases and controls were adults from the INTEROCC population, a subset from Australia, Canada, France, Germany, Israel, New Zealand, and the United Kingdom of the original INTERPHONE study (2000-2004). Controls were identified from various types of population registers. Participation rates were 69% for glioma cases, 79% for meningioma cases, and 50% for controls. The final population numbered 1,819 glioma cases, 1,758 meningioma cases, and 5,227 controls. Participants answered an extensive questionnaire including detailed job histories. A JEM was used to provide separate intensity, and prevalence estimates for electric and magnetic RF-fields. The authors formed three exposure estimates with decreasing risk of overestimating exposure: 1) RF intensity scores estimated over all jobs, 2) RF intensity scores calculated only for jobs with an exposure prevalence above the median, and 3) RF intensity only calculated over jobs for which the participant had reported specific RF-EMF sources in the questionnaire. Exposures were categorized based on the 50th, 75th, and 90th percentiles among controls. Conditional logistic regression assessed associations with RF exposure over various time windows. Most analyses showed no positive associations, but in several cases, a significantly reduced risk was observed. For exposure method 1, electric field exposure above the 90th percentile, 1-4 years before diagnosis was significantly associated (OR 1.36; 95% CI 1.08–1.72) with elevated risk of

glioma, and though not significant, a similar tendency was apparent for the magnetic field. There was an indication of dose response across lower exposures, but it was not statistically significant, and the association was not apparent in the more restrictive exposure models. For meningioma, electric field exposure above the 90th percentile 5-9 years prior to diagnosis was associated with elevated risk of meningioma in exposure model 3 (OR 2.30; 95% CI 1.11–4.7) with a similar though not significant tendency for the magnetic field. There was no indication of this association in the two less restrictive exposure models.

The authors argue that the observed associations might be chance findings, particularly for glioma, where the association was only apparent in exposure model 1 which the authors considered most prone to exposure misclassification. It should also be noted that alternatively, the results could relate to control participation bias, where controls might be more likely to be mobile phone users and of better socioeconomic status since the INTERPHONE study was designed to address mobile phone-related exposure.

The authors conclude: “a few positive associations between exposure to IF-RF/RF in cumulative and time weighted average exposure analyses were found with glioma in Method 1 in the highest exposure category in the 1- to 4-year time window of exposure, and with meningioma in Method 3 in the 5- to 9-year window prior to diagnosis/reference date. However, these statistically significant results, not consistent across analysis methods, could be due to chance, and will require verification in other independent studies.”

Limitations include potential recall and participation bias. Also, few participants held exposed jobs, and even in these jobs, exposure prevalence was generally low. E.g., for medical doctors, the prevalence was 0.7%. While the authors tried to address this, they are unlikely to have completely resolved it, and the number of participants with high exposure may be even lower than observed. A JEM is also only as good as the data that was available to generate it, and is inherently prone to Berkson errors reducing statistical power to detect associations. All these factors may have impaired the ability to detect associations. A final note, that given the available data, the separation of E- and H- field may not be complete and the results for the two were similar and their correlation was high ≥ 0.84 . This means that likely, the study was not able to completely disentangle effects from electric vs from magnetic fields exposures.

As part of the WHO series of reviews Karipidis et al. [37] systematically reviewed and meta-analysed studies on RF-EMF and the risk of glioma, meningioma, acoustic neuroma, pituitary, and salivary gland tumours as well as paediatric brain tumours and leukaemia's. Exposure was evaluated by source: near-field exposure from mobile and cordless phone use, far-field exposure from fixed-site transmitters, and occupational exposures. The review report on 63 articles published from 1994 to 2022, covering 119 distinct exposure–outcome pairs. An adapted version of the OHAT risk-of-bias tool was used to assess study quality,

classifying each study into one of three tiers (low, moderate, and high potential for bias).

For RF-EMF exposure from mobile phone use, the overall meta-relative risk (mRR) for glioma was 1.01 (95% CI: 0.89–1.13), and for use for 10+ years the mRR was 1.22 (0.94–1.58). The later estimate was reduced to 0.97 (0.87–1.08) when leaving out one study by Hardel and Carlberg. Analysis only of studies with lowest risk of bias, or excluding studies with ORs demonstrated to be incompatible with incidence trends, did also produce risk estimates close to the null. For use of mobile phones there was no association with risk of meningioma (ever use vs never use mRR: 0.92, 0.82–1.02, 10 studies, 2990 exposed cases), pituitary tumours (mRR: 0.81, 0.61–1.06, 5 studies, 466 exposed cases), salivary gland tumours (mRR: 0.91, 95% CI: 0.79–1.06, 10 studies, 611 exposed cases) acoustic neuroma (mRR: 1.03 0.85–1.24, 11 studies, 1614 exposed cases) or paediatric brain tumours (mRR = 1.06, 95 % CI: 0.74–1.51, 3 studies, 733 exposed cases). Association among long term users was evaluated for meningioma and acoustic neuroma. For meningioma it was also close to the null. For acoustic neuroma, an elevated risk in the intermediary 5-9 years of use was suggested to relate to detection bias. Few studies addressed cordless phones. The meta-analysis found mRRs close to one for meningioma and acoustic neuroma. For glioma, the mRR was 1.23 (95% CI: 0.87–1.74, 4 studies). The few studies on fixed site transmitters and childhood cancers or on occupational exposure and glioma risk did not produce mRR indicative of elevated risk. The authors note that the individual studies reporting positive associations were generally in tier two i.e. had higher potential of risk of biases. Though theoretically a very strong design the authors do not evaluate laterality studies as the reporting of preferred side of head by cases and controls has high risk of recall bias and misclassification.

The authors concluded that near field RF-EMF exposure to the head from mobile phone use likely did not increase the risk of glioma, meningioma, acoustic neuroma, pituitary tumours, and salivary gland tumours in adults, or of paediatric brain tumours. This conclusion was based on evidence that was rated to be of moderate certainty. They also concluded that near field RF-EMF exposure to the head from cordless phone use did not increase the risk of glioma, meningioma or acoustic neuroma (low certainty evidence). For whole-body far-field RF-EMF exposure from fixed-site transmitters (broadcasting antennas or base stations), the authors concluded that it likely did not increase childhood leukaemia risk (moderate certainty), and paediatric brain tumours (low certainty evidence). Regarding occupational RF-EMF exposure, the conclusion was that it did not increase the risk of brain cancer/glioma (low certainty evidence).

Particularly for fixed-site transmitters and paediatric tumours and occupational exposure brain tumours the small number of studies and differences in exposure sources and metrics call for caution when interpreting results. The *a priori* formulated and published protocol and meticulous attention to assess risk of bias and avoid double counting of participants are strengths of the review. Being a

meta-analysis the study is limited by the number and quality of available studies most of which were case control studies and therefore susceptible to recall and participation bias.

4.1.3 Reproduction

Johnson et al. [41] conducted a systematic review evaluating the evidence for associations between RF-EMF exposure and adverse female reproductive outcomes. This study is one of a series of systematic reviews commissioned by the WHO, and follows a protocol published in the peer-reviewed literature prior to start of data extraction. The OHAT GRADE tool was used to assess the quality of each study. The authors initially identified 20,329 records and finally reviewed 8 studies performed in the general and 10 studies of occupational populations. Studies had to have an estimate of SAR at the reproductive organs or, if not available, use a surrogate RF-EMF exposure measure from modelling or measurements. Studies based on self-reported phone use were included, but those based on self-reported distance to base stations or other sources were excluded. Occupational studies included those based on measured exposure, observations, expert assessment and/or a job-exposure matrix, but not those based on job title alone. The researchers concluded that there was little evidence of an association between RF-EMF from mobile phones and congenital anomalies, preterm birth, or low birth weight. The research notes a weakly increased risk for small for gestational (SGA) age in the general population (RR 1.13; 95% CI 1.02–1.24). However, they also concluded that because of the low quality of most studies, the evidence for SGA was very uncertain.

This is a well conducted systematic review and meta-analysis using a detailed protocol. However, although the review did not indicate an association between RF-EMF and female reproductive outcomes from environmental or occupational exposures, because of the low quality of the included studies the synthesis of the evidence does not permit a strong conclusion either way.

Kenny et al. [42] published one of the WHO commissioned systematic reviews on RF-EMF exposure and male fertility, here on observational studies only. The authors identified nine publications of longitudinal studies, of which two were performed in occupational settings. OHAT Risk of Bias and Grade tools were applied. Regarding the exposure, a focus was put on mobile phone use (duration of use or call time), and the paper also reports results based on phone position during non-use. A range of different outcomes were summarized, including sperm concentration, motility and morphology. Most of the studies only assessed mobile phone use as a source of RF-EMF exposure. The authors report that the included studies did not suggest that RF-EMF exposure from mobile phone usage or from carrying mobile phones in a pocket would lead to a reduction of sperm parameters relevant for male fertility. The authors also concluded that the evidence was very weak, which was partly due to insufficient quality of the exposure assessment.

This is a well-performed systematic review highlighting that although overall there was a suggestion of absence of effects, the underlying evidence for this

rating was very weak. A particular shortcoming is the inaccurate exposure assessment.

Motchidlover et al. [43] performed a systematic review on RF-EMF and light exposure and sperm parameters. They summarized 6 studies performed in humans and 6 in animals. Level of evidence and risk of bias criteria are mentioned but not further applied or explained in the publication. The authors conclude that most of the discussed studies reported effects and conclude that thermal effects appear to be more deleterious than non-thermal effects.

Although the authors discuss established exposure guidelines, designed to protect humans from thermal effects, this is not further taken into account in the discussion of what the study results mean. The authors identified three observational studies that they included in their systematic review. Kenny et al. 2024 (see this report) in their systematic review identified nine observational studies, which seems to indicate that the search was not complete.

4.1.4 Self-reported electromagnetic hypersensitivity (EHS) and symptoms

Ajmal et al. [44] investigated the potential relationship between indoor RF-EMF sources and mobile phone usage patterns with behavioral problems in Japanese children aged 8–17 years. The cohort study, conducted as part of the Hokkaido Study on Environment and Children’s Health, enrolled 2465 children (5221 invited) and followed them from late 2020 to early 2022. Behavioral outcomes were assessed using the Strength and Difficulties Questionnaire (SDQ), with “total difficulties” dichotomized at scores ≥ 13 and “problematic prosocial behavior” at scores ≤ 5 . Parents and children provided information on household Wi-Fi, cordless phones, and mobile phones, including details on call durations, audio and video streaming, and online gaming. In a cross-sectional analysis of information collected at baseline—after adjustment for age, sex, self-reported health, developmental support, sleep, maternal education, household income, and internet addiction—no elevated ORs were observed. Cordless phone calls >4 min/week, mobile phone calls (via Wi-Fi) of 10–40 min/week, and audio streaming for 60–120 min/week, were associated with reduced odds of behavioral problems. In the longitudinal analysis, among children who were free of total difficulties at baseline, those with mobile phone internet call durations >40 min/week had an increased risk (OR 2.01, 95% CI 1.14–3.57) of developing behavioral difficulties, with no clear trend seen in the lower exposure groups. Additionally, improvement in total difficulty scores was associated with having a cordless phone and mobile phone network calls of <5 min/week. No associations were found for changes in problematic prosocial behavior.

The authors conclude that the inconsistent patterns suggest that the cross-sectional associations may result from residual confounding or be chance findings due to the number of comparisons made. They conclude “The inconsistent findings in our longitudinal analysis indicate the absence of causality rather than the reverse causality in our cross-sectional results.”

A key limitation of the study is the crude categorization of age (8-11 and 12-17 years) and small number of children in the highly exposed categories, which may have impaired the ability to detect associations. Additionally, the author reported phone usage by technology but employed different cut-offs which complicates direct comparisons.

On commission by the WHO Rösli et al. [45] conducted a systematic review and meta-analysis on RF-EMF and tinnitus, migraine and non-specific symptoms according to a protocol published in advance and the deviations from the protocol are explained in the paper. The OHAT risk of bias tool was used to evaluate studies. They looked at case-control studies and cohort studies assessing exposure periods of at least a week and included 13 papers addressing tinnitus (3 papers), migraine (1), headache (6), sleep disturbance (5) or used a composite symptoms score (5). Most studies were of cohort design and only one addresses occupational exposure. The meta-analysis found none of these endpoints to be associated with RF-EMF: for tinnitus, exposure to the brain was associated with a combined RR of 1.43 (95% CI: 0.94–2.18) per 100 min phone (wireless or mobile) use /week. For headache the standardized mean difference SMD was -0.6 (-2.38–1.10) per 100 min phone use /week for brain exposure and 0.17 (-0.30–0.03) per V/m for whole body exposure. For sleep disturbance the corresponding SMDs were 2.01 (-2.95–6.97) and 1.51 (-2.00–2.18) and for symptom-scores they were 0.01 (-0.04–0.08) and 1.13 (-0.94–3.23). The authors concluded “Overall, mostly absence of associations between various outcomes and RF-EMF exposure proxies were found with substantial heterogeneity between studies suggesting that RF-EMF exposure below guideline values does not cause tinnitus, migraine or any non-specific symptoms. Since the review topic includes various inherent challenges related to confounding control and exposure assessment, the evidence was judged to be very uncertain.”

As stressed by the authors low number of studies per endpoint, risk of bias and imprecisions in exposure and outcome assessment render the quality of evidence uncertain. Particularly they point out that these end points are vulnerable to bias as they can only be ascertained via self-report, direct or indirect through a medical practitioner. Additionally, even if associations are observed it is difficult to ascertain that they are due to RF-EMF and not through other factors or behaviours associated with for instance use of mobile phones.

He et al. [46] performed a Mendelian randomization study on the association between digital device use and risk of migraine. Genome-wide association studies (GWAS) data and self-reported information about mobile phone use, television watching, computer use, and playing computer games were obtained from UK Biobank and GWAS data and information about migraine was obtained from the Finnish FinnGenn project and the European “International Headache Genetics Consortium” serving as discovery and replication datasets, respectively, and ultimately combined to increase the study population. The authors employed both univariable MR (UVMR) and multivariable MR (MVMR) analyses to account for

potential confounding factors: stroke, physical activity, hypertension, insomnia, major depression, alcohol use, smoking and BMI. Risk of migraine was associated with mobile phone use (OR: 1.58, 95% CI: 1.24–2.02) and television watching (OR:1.63, 95% CI:1.43–1.86) but not with computer use or playing computer games. When dividing migraines into those with and without aura, associations were only present for migraine without aura. The authors suggest blue light or electromagnetic radiation as possible mechanistic causes. The authors conclude: “our study provides evidence of the possible causal relationship between frequent mobile phone use, television watching, and migraine risk, particularly migraine without aura.”

As mentioned in the paper, even though they did adjust for some confounders, unmeasured confounders may have influenced the results. This concern is particularly relevant given the complexity of traits like mobile phone use and television watching, which are unlikely to be associated with specific genetic variants. Such complexity may lead to confounding due to pleiotropy beyond the detection capabilities of the tests employed in the study. Furthermore, the reliance on self-reported device usage, rather than direct measurement, introduces the potential for recall bias. Finally, it should be noted that associations between electronic devices and migraine have been reported previously but the present study does not provide additional evidence regarding the mechanism.

Köteles et al. [47] analysed data of the Västerbotten Environmental Health Study, a repeat survey on environment and health performed in adults aged 18-79 in Sweden between 2010 and 2013. 3406 participants filled in the baseline questionnaire, and at the three-year follow up, 2326 (73%) persons participated again. In the questionnaire the authors asked, among other things, “are you getting symptoms from certain switched-on electrical devices that you believe most other people are not getting symptoms from?”. The authors called this “symptoms associated with environmental factors”, or SAEF(-EMF). In addition, an Environmental Symptom-Attribution Scale (ESAS) was used to quantify the degree to which symptoms and/or annoyance were attributed to specific environmental exposures and sources. The ESAS asked “rate to what extent the following environments/sources bother you”; 10 items pertained to EMF sources. A Patient Health Questionnaire Somatic Symptom Scale (PHQ-15) assessed the extent to which participants were bothered by 15 frequently reported symptoms. Data were analysed cross-sectionally and longitudinally using logistic regression adjusted for socio-demographic variables (age sex, educational level). About 5% of participants reported EMF-related symptoms. Longitudinally and pertaining to EMF, only attribution (i.e. the ESAS scale) predicted the development of reporting symptoms attributed specifically to EMF (SAEF-EMF). Reporting symptoms (i.e. the PHQ-15) scale did not predict SAEF-EMF.

The longitudinal design is a strength of this study. Given the similarities in the questions of SAEF-EMF and attribution, it is somewhat unclear in how far the development over time really changed. However, it is of interest that symptoms as

such did not predict attribution of symptoms to EMF, in contrast to what has been reported from a few other studies into the same topic.

4.1.5 Other outcomes

Traini et al. (2024) [48] conducted a prospective cohort study to investigate the association between mobile phone and occurrence of headaches and migraine in the general population. The study made use of the Dutch and UK cohorts of the COSMOS (Cohort Study of Mobile Phone Use and Health) study, and after exclusions included 78,437 people recruited between 2009 and 2012 from an initial 88,466 (NL COSMOS) and 99,424 (UK COSMOS). Participants completed a baseline questionnaire upon recruitment and a follow-up questionnaire between 2015 and 2018. Mobile phone use information was self-reported at baseline for the 3-months prior to baseline and included weekly-call-time, proportion of use with hands-free devices, frequency of text messages, use of multiple mobile phones and whether other people use the participant's phone. Participants also reported call-time on cordless phones. Outgoing and incoming voice call duration for the same 3-month period was obtained from network operators but was only obtained for 3% of Dutch and 58% of UK participants and did include information from 2G and 3G networks. The operator data was used for country-specific regression calibration of self-reported information. RF-EMF exposure was estimated from this information using an organ-specific integrated algorithm. Outcome data were collected at baseline and follow-up, with the primary outcome being self-reported weekly headache at follow-up. Secondary outcomes were severe weekly headache, daily headache, and migraine diagnosis at follow-up. Severity was obtained from the Headache Impact Test (HIT-6). Complete-case data was available for 58,229 participants with missing data for the others imputed. 14.8% of participants reported weekly headache, 5.6% severe weekly headache, 14.5% daily headaches, and 11.4% migraine at baseline. Of those headache-free at baseline, 8.2% reported weekly headaches at follow-up. Results from 2-exposure models (mutually adjusting for both call-time and texting at baseline) did not indicate an increased risk of weekly headache (OR 1.04; 95% CI 0.94–1.15) in the highest category and no evidence of a trend ($p=0.29$). An increased risk of weekly headache was observed with texting in the highest exposed group (OR 1.40; 95% CI 1.25–1.56), and a trend with increased texting was also observed. For secondary outcomes, increased risk in the highest call-time group was observed for severe weekly headache (OR 1.25; 95% CI 1.04–1.51; p -trend 0.04), but not for daily headaches or migraine. All OR for the different outcomes were significantly increased in the highest texting group with statistically significant trends observed. Results from sensitivity analyses were compatible with the main findings.

The researchers interpret these findings as providing evidence that effects on headaches are related to mobile phone use, but not to RF-EMF exposure; the latter being much lower for texting compared to calling. The study had a number of limitations, which were primarily related to limitations in the exposure assessment, including that measured RF-EMF exposure was not available and that

transient symptoms such as headaches may be plausible associated to acute peak exposure rather than the average exposure metric used in the study.

Malvandi et al. [49] performed a cross-sectional study on base stations and sleep quality in Sabzevar city, Iran. 41 antennas were identified and spot measurements of electric field strength (V/m) were performed with a broadband device (TES 593 electrosmog meter (TES Electronics Co, Taiwan). Measurements were taken at 1m above ground, directed towards the antenna and repeated three times each. Measurements were taken across different distances from antennas and at different time intervals during the day. Measurement durations were not described. Participants were randomly selected based on distance categories around base stations, having lived at least 5 years at the current residence, and were aged 18-30 years. Exclusion criteria included regular sleeping pill use, shiftwork, smoking and some chronic diseases. Participants filled in the Pittsburgh Sleep Quality Index (PSQI) and associations between electric field values and sleep was analysed. The authors reported worse sleep quality in persons living within 100m from a mobile phone base station, as compared to living further than 300m away.

This is a weak study in the sense that personal exposure to RF-EMF was not assessed, only area-level exposure. It is unclear in how far this would translate to personal exposure. Potential confounders were not taken into account. Overall, the study is not informative regarding a possible association between RF-EMF exposure from mobile phone base stations and sleep quality in residents.

Girela-Serrano et al. [50] systematically reviewed papers assessing the relationship between duration or frequency of mobile phone or wireless device use and children and adolescents' mental health. Exposure was defined as use of mobile devices that use radiofrequency electromagnetic fields for connection, such as mobile phones, tablets and smartphones. 25 observational studies published between 2011 and 2019 were included, of which 10 were cohort studies and 15 were cross-sectional studies, Risk of Bias analysis was performed. The authors concluded that they found suggestive but limited evidence that greater mobile phone/device use may be associated with poorer mental health in children and adolescents. Risk of Bias was low only in four studies. Only few studies tried to disentangle RF-EMF exposure from usage of the devices as such. Regarding RF-EMF exposure, the authors report that they found no evidence supporting a direct impact of RF-EMF on mental health.

This is a thoroughly performed systematic review. However, by far the majority of studies assessed usage characteristics of mobile devices and not RF-EMF exposures. Disentangling these types of exposures remains an ongoing challenge.

Zhang et al. [51] analysed the UK Biobank study on mobile phone use and cardiovascular outcomes. The UK biobank is a study that was set up between 2006-2010. Participants answered if they used a mobile phone at least weekly (defined as regular use), and if so, how much time they talked on it (in categories

of <5, 5-29, 30-59, 1-3h, 4-6h >6h per week; and for how many years (≤ 1 , 2-4, 5-8, 9+ years). The primary outcome was incident cardiovascular disease (CVD), a composite of incident stroke, coronary heart disease, atrial fibrillation and heart failure. The secondary outcomes included incident stroke, coronary heart disease, atrial fibrillation and heart failure separately. Information regarding a range of potential confounders such as age, sex, income, lifestyle (physical activity, smoking, alcohol consumption), use of medication (antihypertensive, hypoglycaemic), BMI, blood pressure, history of diabetes, in addition to blood measurements (e.g. cholesterol, blood glucose) was available. Participants were followed up health using data linkage with registries until the end of 2021, median follow up time was 12.3 years. Cox proportional hazard analysis was performed, adjusted for a range of *a priori* selected confounders and performed a range of sensitivity analyses to assess robustness of findings. The authors also analysed self-reported sleep quality, stress and neuroticism as possible moderators. 444,027 participants were included in the current analysis, of which 378,161 individuals reported being regular mobile phone users. The study population had a mean age of 56 years and 44% were men. There was a statistically significant trend of an increased risk of cardiovascular disease across increasing duration of mobile phone use per week, with the highest risk estimate in the group reporting to be calling for over 6 hours per week with a HR of 1.21 (95% CI 1.14–1.28). Using handsfree devices or speakerphones was not associated with cardiovascular disease. Mediation analysis indicated that poor sleep, stress and neuroticism significantly mediated associations between mobile phone use and cardiovascular disease. The authors highlighted that it was the frequency of mobile phone use rather than the total duration that were driving effects of mobile phone use on cardiovascular disease risk. Further, the authors conclude that since incident cardiovascular disease was partly mediated by poor sleep and stress, decreasing time spent on mobile phones could be a helpful preventive measure.

This is one of several published studies that analysed the UK biobank data regarding mobile phone use and health outcomes. Of interest here is on the one side the statistically significant trend across mobile phone use categories, but also the finding that use of speakerphones or handsfree devices was not associated with the outcome. This is of interest as the use of such devices or functions is known to considerably decrease the exposure to the head. As discussed in the previous report (Zhang et al. 2023), despite the impressive list 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. A possible explanation for the apparent exposure-response could therefore be that the year of first mobile phone use was associated with lifestyle factors not sufficiently accounted for in the analysis. As also highlighted by the authors, the results appear to be more informative regarding mobile phone use as compared to RF-EMF exposure as such.

Song et al. [52] conducted a Mendelian randomization study to investigate the association between mobile phone use and glaucoma. Genetic data and self-

reported mobile phone usage information were obtained from the UK Biobank, while data on glaucoma and genetic variants were obtained from the Finnish FinnGen project. The researchers identified 29 SNPs associated with the duration of mobile phone use and not directly associated with glaucoma. They found an association between mobile phone usage and an increased risk of glaucoma, with odds ratios ranging from 1.36 (95% CI: 1.05–1.75) to 1.88 (95% CI: 0.53–6.68). The authors concluded that their findings provide robust evidence supporting a causal relationship between prolonged mobile phone use and an increased risk of glaucoma.

In Mendelian randomization (MR) studies, genetic variants are used as proxies for exposures to explore possible causal relationships with health outcomes. A key limitation is pleiotropy, where a genetic variant affects multiple traits. If these additional traits are related to the outcome, they can introduce residual confounding.

For complex behaviors like mobile phone use, it is unlikely that specific genetic variants directly determine usage time. Instead, associations may reflect broader traits—such as personality or lifestyle factors—that influence both phone use and disease risk. Therefore, while the analysis shows an association between mobile phone use and glaucoma, it does not establish that phone use itself causes glaucoma.

Rangesh et al. [53] published a study comparing the metabolic profiles of two groups with different levels of RF-EMF exposure. Using a handheld EMF meter, they identified a location with high exposure levels (126.8 mW/m^2) and one with low levels ($45.17 \text{ } \mu\text{W/m}^2$) and then recruited 30 healthy men from each area. They analysed urine samples from these men for metabolites and found significant differences between the groups for 29 metabolites. The authors conclude, "Preliminary findings suggest a connection between oxidative stress and gut microbiota imbalance. However, further research is needed to validate these biomarkers and understand the effects of RF-EM radiation on human health." Limitations: The two locations compared may have different exposure levels but will also differ in many other aspects, particularly since one is situated in a very rural area while the other is in a more urban location (according to Google Maps). Even if differences in metabolic profiles exist between the groups, the study does not allow any conclusions about the cause of these differences.

Watten et al. [54] investigated associations of self-reported electrohypersensitivity (EHS), connectedness to nature (CN), sensory processing sensitivity (SPS, the ability to perceive, process, and react to environmental stimuli), and gender. The study population, 400 men and 225 women, were volunteers from students participating in a mandatory course and volunteers from the public. 225 men were randomly sampled to ensure a final population of equal men and women. Participants filled in an online questionnaire on items of interest. EHS was assessed with questions on sensitivity to electromagnetic fields from 1)

computers, 2) electric appliances, 3) fluorescent lighting, 4) microwave ovens, 5) mobile phones, 6) power lines, 7) radio/television transmitters, 8) telecommunication masts, and 9) television. All questions were answered on Likert scales. For EHS, most answered “not at all” to the questions, and each item was therefore dichotomized into those answering no and the rest. A combined score (EHS index) then counted the number of items to which a person reported sensitivity.

SPS was assessed with the 27-item Highly Sensitive Person Scale aggregated to one score. Example questions include “Are you easily overwhelmed by strong sensory input?” and “Are you made uncomfortable by loud noises?”. CN was assessed with the 14-item Connectedness to Nature Scale. Example questions include “I often feel a sense of oneness with the natural world around me” and “I often feel a kinship with animals and plants.” For CN and EHS, scores were calculated as the mean over all items. MANOVA and structural equation models were used to analyse data. Most women (86.7%) and men (94.7%) reported no EHS. Women had higher mean values on perceived sensitivity for 5 out of 9 categories of electromagnetic equipment (computers, electrical appliances, fluorescent lighting, mobile phones, and television) and they had higher overall EHS, SPS and CN scores. The gender differences disappeared when adjusting for SPS. The authors conclude that “the present study provides the first empirical evidence that highly sensitive individuals are capable of perceiving electromagnetic radiation.”

A major limitation of the study is that all factors are self-reported without physical validation; it is therefore only possible to make conclusions about perceived EHS, and the observed association between SPS and EHS could be due to a common underlying risk factor or characteristic, e.g., related to personality. Additionally, the volunteer nature of participants means that observed associations may not be directly applicable to the general public.

Kadhim et al. 2024 investigated oxidative stress, antioxidant levels, and thyroid function in 40 males working with electrical substations and 40 working with cellular communication towers. The study is summarized under ELF. Hasbek et al. [55] investigated the relationship between mobile phone usage and the levels of two micro-RNAs, miRNA-574-5p and miRNA-30C-5p, in patients diagnosed with differentiated thyroid cancer (DTC). The study included 50 patients with DTC undergoing screening at a hospital clinic and 50 healthy volunteers. The participation rate is not provided, and it is not described how the controls were recruited. During a clinic visit the participants provided blood samples and questionnaire data on family history of thyroid cancer, high-dose radiation exposure to the neck, and smartphone usage. Specific factors assessed included years of mobile phone usage, daily usage time, whether participants kept their phones turned on and near them at night, and if they had a Wi-Fi device in the bedroom. The study found that none of these factors were significantly associated with micro-RNA expression levels. Patients were less likely to have

Wi-Fi in their bedrooms and to keep their phones by them at night compared to healthy volunteers.

The authors concluded that there was no significant relationship between mobile phone usage and miRNA expression levels. Limitations of the study include a lack of information about the recruitment procedure and participation rate, which increases the risk that the cases and controls were not representative of the same source population. Additionally, the small study size, the simple yes/no assessment of many evaluated exposures, and the absence of consideration for potential socioeconomic factors are limitations. Finally, the study is retrospective, and mobile phone habits were assessed after diagnosis, which may not accurately reflect conditions prior to diagnosis.

Çeleğen et al. [56] investigated maternal risk factors for congenital anomalies of the kidney and urinary tract (CAKUT) in offspring. The study included 57 cases, patients < 2 years of age diagnosed at a Turkish nephrology clinic, and 57 controls selected from children undergoing routine abdominal imaging at the same clinic. Mothers of both cases and controls completed a questionnaire that covered various factors, including maternal and paternal demographics, obstetric characteristics, medical histories, body mass index (BMI) and folic acid use.

Additionally, the questionnaire assessed the use of electronic devices, including computers, microwave ovens, television, and wireless internet at home apparently in yes/no-questions. For mobile phone usage, data were collected on the number of calls made, daily call duration, app usage, and the use of hands-free equipment. Effective specific absorption rate (SAR) exposure was calculated by multiplying the phone-specific average SAR values by call time and expressed as Wh/Kg.

Variables associated with CAKUT in univariate analysis ($p < 0.1$) were included in a multivariate logistic regression using backward selection to identify the most predictive model: Excessive weight gain during pregnancy (odds ratio [OR] 4.4, 95% CI 1.4–14.2), preconception use of folic acid (OR 0.29, 95% CI 0.11–0.79), and effective SAR value (OR 1.7, 95% CI 1.1–2.9) were significantly associated with the risk of CAKUT.

The authors suggest that electromagnetic fields (EMF) can generate biological stress and free radicals, concluding that "mobile phone-related EMF exposure during pregnancy may be associated with an increased risk of CAKUT in offspring." Limitations of the study include the small sample size, pooling of endpoints that may differ in aetiology, and a relatively crude categorization of covariates. Additionally, the participation rate among cases and controls is not reported. Regarding mobile phone usage, the limited adjustment for lifestyle factors and the simplistic categorization of weight (excessive weight gain for BMI yes/no) and occupation (working yes/no) likely leave room for residual confounding from factors associated with mobile phone use.

Elyasi et al. [57] undertook an allegedly systematic review on any adverse health effects of mobile phones. They searched international databases with a standardized search string ending up with only 20 studies published between 2007 and 2022 i.e. not nearly all relevant studies. Furthermore, the included studies were a mixture of animal, human and epidemiological studies and many relevant studies were not identified and there is no meaningful analysis or discussion of results. The study is not informative.

Benke et al. [58] published one of the systematic reviews commissioned by the WHO. They assessed longitudinal observational studies (cohort or case-control studies) and summarized effects of mobile phone use (calling, as a proxy for RF-EMF exposure) on cognition (global cognitive function, as well as domain specific: complex attention, executive function, learning and memory, language, perceptual-motor ability and social cognition). Two studies could be meta-analysed as they had used similar exposure and outcome assessment. Overall, the paper included 5 studies that reported data from four cohorts in the review. Risk of Bias was assessed, in line with the other WHO-commissioned systematic reviews. Overall, results of 4639 participants were reported, of which 2808 were adults and 1831 were children or adolescents. Studies were performed in Australia, Singapore and Switzerland. The authors did not report suggestions that RF-EMF exposure from the use of mobile phones would have long-term effects on cognition, here assessed as complex attention, executive function and learning and memory among children. They also mentioned that the evidence had low to very low certainty. In addition, they reported that language, perceptual motor ability and social cognition were not assessed in any of the included studies and that therefore, there was no available evidence.

This is one of the recent systematic reviews that have been performed thoroughly, with a Risk of Bias assessment, and an a priori defined protocol. Similar as to most of the other systematic reviews in this series, there is little to no suggestion of effects, but also certainty of the evidence was very low. The authors highlight further research needs improving exposure assessment and address also different types of population subgroups and cognitive outcomes.

4.1.6 Conclusions on epidemiological studies

The prospective COSMOS cohort found no association between cumulative amount of mobile phone use and the risk of developing glioma, meningioma, or acoustic neuroma. In the same cohort, an association with headaches was reported, likely related to phone use rather than RF-EMF per se. Similarly, a systematic review suggested that greater mobile phone use may be linked to poorer mental health in children and adolescents and a UK-biobank study found associations with cardiovascular disease. In both cases the authors considered mechanisms other than a direct effect of RF-EMF as likely explanations. These results highlight the challenge of disentangling RF-EMF effects from other effects of mobile phone use when exposure is measured in terms of mobile phone use rather than actual RF-EMF exposure. Two Mendelian randomization studies reported associations between mobile phone use and migraine or glaucoma.

However, because genetic influences on mobile phone use likely act through complex traits such as lifestyle or personality, this method cannot reliably isolate the effect of mobile phone use from other risk factors associated with these traits. This year, WHO-commissioned reviews were published on leukemia, non-Hodgkin lymphoma, thyroid cancer, glioma, meningioma, acoustic neuroma, pituitary and salivary gland tumors, as well as pediatric brain tumors and leukemias, cognition, symptoms, and male and female reproduction. For cancer endpoints, the evidence suggested no associations. The quality of evidence was rated as moderate for mobile phone use and tumors of the brain or salivary glands, and for far-field exposure and childhood leukemia risk. For all other cancer outcomes, the quality of evidence was rated as low. A positive association was reported for small-for-gestational-age; however, the authors emphasized that the supporting evidence was of low quality. For all other evaluated endpoints, the conclusion was that current data do not suggest associations at exposure levels below existing guidelines, the quality of evidence was consistently rated as low.

Table 4.1: Epidemiological studies investigating RF-EMF fields

Endpoints	Reference	Exposure assessment	Study design, Population	Results
Birth outcomes (small for gestational age, SGA).	Büyükeren 2024	Phone use of mother during pregnancy, SAR value of phone.	Cross-sectional[FD1] . 1495 mothers who gave birth in a hospital in Konya, Turkey.	Phone use was similar, but SAR values of phones differed in mothers who had given birth to children who were SGA. Not informative regarding RF-EMF.
Miscarriage	Molasaraie 2024	Phone, internet use, self-reported	Case-control. Women with previous miscarriage referred to urban health centre in Zanjan (n=211) compared to mothers with successful pregnancy from same centres (n=394).	Hours of internet, phone use had small excess risks, mobile phone at night didn't. None of these were statistically significant. Relevant potential for bias in results.
Glioma, meningioma, acoustic neuroma	Feychting 2024	Baseline questionnaire on current (3 months) and past mobile phone use. For subgroup also mobile phone use data from operators for same 3-month period	Cohort (COSMOS). 24,574 participants from Denmark, Finland, the Netherlands, Sweden and the UK between 2007 and 2012	No excess risk for any of the outcomes. Cumulative amount of mobile phone use not associated with risk of developing glioma, meningioma, acoustic neuroma.

Potential impact of recall, selection bias in case-control studies on mobile phone usage and risk of glioma	Bouanoun 2024	Self-reported mobile phone use	Interphone case-control study	Evidence from simulations shifts overall assessment to making it less likely that heavy mobile phone use is causally related to an increased glioma risk.
Glioma, meningioma, acoustic neuroma, pituitary, salivary gland tumours. Paediatric brain tumours and leukaemia's	Karipidis 2024	Near-field exposure from mobile and cordless phone use, far-field exposure from fixed-site transmitters, and occupational exposures.	63 articles published from 1994 to 2022, covering 119 distinct exposure–outcome pairs.	RF-EMF likely did not increase the risk of glioma, meningioma, acoustic neuroma, pituitary tumours, and salivary gland tumours in adults, or of paediatric brain tumours. RF-EMF from broadcasting antennas, or base stations: likely did not increase childhood leukaemia risk (moderate certainty), paediatric brain tumours (low certainty evidence). Regarding occupational RF-EMF exposure, the conclusion was that it did not increase the risk of brain cancer/glioma (low certainty evidence).
Leukaemia, non-Hodgkin's lymphoma, thyroid cancer related to mobile phone use. Lymphohematopoietic system and oral cavity/ pharynx cancers in occupational populations	Karipidis 2025	Mobile phone use as 'ever use', 'time since start of first use', cumulative hours of use, cumulative number of calls. Occupational studies with measurements, job-exposure matrices, source-exposure matrices, job title or task.	Systematic review and meta-analyses, 143 different exposure-outcome pairs	RF-EMF exposure was not associated with increased risk of leukemia, thyroid cancer, or non-Hodgkin's lymphoma. Occupational RF exposure was not associated with lymphohematopoietic system tumours or oral cavity/pharynx cancer. The quality of the evidence was low.
Glioma, meningioma, acoustic neuroma, pituitary tumours, and CNS tumours	Moon 2024	Regular/ non-regular users	Meta-analysis of 19 case-control and 5 cohort studies.	Authors report increased glioma risk, all outcomes, for longest use and ipsilateral use. Significant weaknesses in design and conduct of the study speak against causal interpretation.

Meningioma, glioma	Turuban 2024	Job-exposure matrix linked to self-reported occupational history.	Case-control study. 1,8189 glioma cases and 1,758 meningioma cases (5,227 controls)	With the exception of a few excess risks for glioma and meningioma for specific exposure-lagging time combinations, no excess risks were observed for the majority of analyses. Authors argue that likely positive findings are due to chance.
Congenital anomalies, preterm birth, low birth weight, small for gestational (SGA)	Johnson 2024	Estimate of SAR at reproductive organs or other surrogate RF-EMF exposure measure. Occupational studies also observations, expert assessment or job-exposure matrix	Systematic review, 8 general population, 10 occupational studies	Little evidence of an association with any outcome, with the exception of small excess risk for SGA. The SGA association was of a low quality.
Male fertility	Kenny 2024	RF-EMF from mobile phone use during calling or when the phone is in the pocket.	Systematic review of observational studies	Overall there was a suggestion of absence of effects, but the underlying evidence for this rating was very weak.
Sperm parameters (male fertility)	Motchidlover 2024	RF-EMF	Systematic review	Included studies reported effects, but likely this review was incomplete.
Behavioural problems	Ajmal 2024	Self-reported use of WiFi, cordless phones, mobile phones	Cohort study of 2,465 children	Inconsistent risk patterns suggest cross-sectional associations may result from residual confounding or chance.
Tinnitus, migraine, non-specific symptoms	Rööslä 2024	Duration of mobile phone use	Systematic review and meta-analysis, 13 case-control and cohort studies	None of the endpoints was associated with RF-EMF exposure. Low number of studies and study weaknesses render evidence uncertain

Migraine	He 2924	Self-reported mobile phone use, television watching, computer use, playing computer games	GWAS study in BioBank UK based on Mendelian randomization.	Migraine was associated with mobile phone use and television watching, but not computer use or playing computer games. Authors indicate this may be due to blue light exposure rather than RF-EMF. Study weaknesses prevent a strong causal explanation.
Symptoms attributed to EMF exposure	Köteles 2024	Self reports of attribution and of symptoms.	Cross-sectional and longitudinal analysis in 3226 Swedish persons in 2010 and 2013.	Having symptoms did not predict attribution of symptoms to EMF exposure over time.
Headaches and migraine	Traini 2024	Self-reported baseline and follow-up (2015-2018) survey on mobile phone use. Voice call duration also from provider..	Prospective cohort study including Dutch and UK cohorts of the COSMOS study (n=78,437 people recruited 2009-2012).	Effects on headaches related to mobile phone use, but not to RF-EMF exposure.
Cognition	Benke 2024	RF-EMF from mobile phone use	Systematic review of observational studies.	The authors did not observe long-term effects of RF-EMF exposure on cognition (here: complex attention, executive function, learning, and memory among children). The evidence was rated to have low to very low certainty.
Sleep quality	Malvandi 2024	Area-level RF-EMF from base stations, distance to base stations.	Cross sectional study performed in 436 residents living in Sabzevar, Iran.	This study is not informative.
Mental health of children and adolescents	Girela-Serrano 2024	Duration of use of mobile devices including phones	Systematic review	The authors reported no impact from RF-EMF on mental health, however, only few studies attempted to disentangle effects from RF-EMF exposure from those of mobile phone usage as such.

Cardiovascular disease (CVD; composite of incident stroke, coronary heart disease, atrial fibrillation, heart failure)	Zhang 2024	Mobile phone use at baseline (2006-2010)	Analysis of UK Biobank data. Longitudinal analysis with nearly 450,000 participants with a median follow-up of over 12 years	Associations of phone use with cardiovascular risk. Sensitivity analyses indicated result may be due to usage of a mobile phone as such, rather than due to RF-EMF exposure.
Glaucoma	Song 2024	Self-reported mobile phone usage	Mendelian randomization study of UK Biobank	Authors reported an increased risk of glaucoma with mobile phone use. Residual confounding from undetected pleiotropy may be an explanation.
Metabolite levels in urine samples	Rangesh 2024	Measured high and low RF-EMF locations	Cross-sectional study of 30 men	Reported differences for 29 metabolites linked to oxidative stress and gut microbiota. Differences in locations not accounted for (amongst other factors) prohibit conclusions on link between RF and outcomes.
Self-reported electrohypersensitivity (EHS), connectedness to nature (CN), sensory processing sensitivity	Watten 2024	Online survey on EMF sources and outcomes	Cross-sectional study of 400 men and 225 women	Authors conclude that study shows that sensitive individuals are capable of perceiving electromagnetic radiation. However, major methodological weaknesses prohibit this conclusion.
Levels of two micro-RNAs, miRNA-574-5p and miRNA-30C-5p in patients with differentiated thyroid cancer	Hasbek 2024	Questionnaire including on smartphone use	50 thyroid cancer patients and 50 healthy controls.	No significant relationship between mobile phone usage and miRNA expression levels
Congenital anomalies of kidney and urinary tract in offspring	Çeleğin 2024	Self-reports of electronic device use. SAR value of phone.	Hospital based, 57 cases, patients < 2 years of age diagnosed at nephrology clinic, 57 controls children undergoing routine imaging	Excess risk observed in association with SAR estimates. Result not informative regarding RF-EMF effects.

Any adverse health effect	Elyasi 2024		Systematic review based on 20 studies between 2007 and 2022.	
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4.2 Human studies

In 2023, three studies were published on the effects of RF-EMF on the waking electroencephalogram (EEG), which, like previous studies, produced inconsistent results.

Already in 2023, Jamal et al. [59] published results from a randomized, triple-blind, crossover study on the influence of exposure to 3.5 GHz antenna signals on the autonomic nervous system, measured by EEG. The results showed no significant changes in the waking EEG power spectra in healthy young adults. In 2024, Jamal et al. [60] published additional data on skin temperature and electrodermal activity (EDA), which had already been collected in the 2023 study but not published at that time. For the present publication, the sample was expanded by 10 more individuals. Twenty-four healthy young men and 20 women (mean age \pm SD: 26.5 \pm 4.8 years) underwent two separate sessions, scheduled at the same time of day for each participant, no more than one week apart. The experiments were conducted in an electrically shielded room, and exposure was realised using a far-field antenna (electrical field intensity: 1 to 2 V/m), placed 1.2 m and 45 degrees to the right of the participant. EEG was recorded during a 17 min pre- and post- exposure condition, as well as during the 26 min exposure/sham condition in a total of seven runs (2 baseline, 3 real exposure, 2 sham exposure). EDA was stimulated by 10 repeated beeps (60dB) of 0.3s length each and 15s intervals to evoke event-related skin conductance responses (SCRs) and was measured at the beginning of each run for 2.5 minutes. Skin temperature was recorded on the left hand, head and neck. Temperature increased statistically significantly during and after exposure in the neck region, but only after exposure in the head region. Statistically significant minimal differences compared to sham exposure were observed in three of eight EDA endpoints and global mean skin conductance in the post-exposure phase. The magnitude of changes did not exceed normal physiological fluctuations. The study was well conducted and the observed partial changes in skin temperature were within the normal physiological range.

In 2024, Prins et al. (2025; online 2024) [61] conducted a systematic review and meta-analysis on the effects of mobile phone electromagnetic fields on EEG and event-related potentials (ERPs). They analysed 31 (61%) studies investigating resting state wake EEG and 20 (39%) studies focusing on ERP. The authors concluded that none of the studies was free from Risk of Bias (ROB). EEG was not affected by RF-EMF when recorded during the task performance in the ERP

studies, but did show evidence of an increase in alpha frequency band of the resting-eye-opening EEG under 2G exposure. No significant evidence of an effect of 2G- exposure with eyes closed or 3G-exposure with eyes open was observed. Due to the inconsistencies in study designs, the authors recommend adherence to methodological standards and prior publication of study protocols to overcome the heterogeneity in this field of research.

Two systematic reviews with meta-analyses on different endpoints in experimental human studies, published in 2024, were commissioned by the WHO. Bosch-Capblanch et al. [62]) conducted a systematic review of the evidence from experimental studies on RF-EMF exposure and self-reported symptoms, as one of the reviews commissioned by WHO. Studies were included that applied electric, magnetic or electromagnetic fields in the frequency range of 100 kHz to 300 GHz, including both near-field and far-field exposures. Studies had to be parallel or crossover trials conducted either in laboratories or elsewhere, and needed to have at least one active exposure and one control condition. Participants or researchers needed to have been blinded and an exposure estimate needed to be available, to be included. Studies on impacts on implants were excluded. Studies had to report on symptoms and/or EMF perception to be included. Risk of bias assessment was conducted for all included studies based on an adapted version of the OHAT tool. Of an initial 8,908 citations, 41 were included in the final review which included studies from various countries conducted between 1998 and 2022 including 2,874 participants in total. Thirty included studies presented SAR data and described near field exposures from 0.01 to 6.0 W/kg (median/mean 1.4/1.6 W/kg). Thirty studies reported symptoms and 23 perceptions (of which 12 reported both). The research team concluded that, overall, the evidence suggested no or small non-significant effects of exposure only. The evidence further suggested that study participants could not perceive EMF exposure better than chance and that electrohypersensitive individuals were also not better than the general population in perceiving exposure. The researchers further conclude that acute RF-EMF exposure below regulatory limits does not cause symptoms and corresponding claims in everyday life are related to perceived and not to real EMF exposure status.

This is a methodologically very strong synthesis of the available evidence, particularly in its approach to exclude methodologically weak studies. The pre-study protocol that was published is a further methodologically strong characteristic of this study, which prevents biased evaluations through “cherry-picking” of the evidence. No firm conclusions can be drawn regarding the potential effects on elderly or chronically ill individuals, who may be less susceptible.

The second systematic review commissioned by the WHO was conducted by Pophof et al. [63] on the effects of short-term exposure to RF-EMF on cognitive performance in experimental studies. The authors published a protocol prior to their review (Pophof et al. 2021), applied the same analytical approaches like Bosch-Capblanch et al. (2024) using the ROB and GRADE tools in a total of 76

studies with 3,846 participants, 50 of which were included into meta-analyses. There was no statistically significant effect of RF-EMF on any of the analysed speed- and accuracy- related outcome parameters of six domains of cognitive performance. In summary, the results indicate, with high to low certainty of evidence, that short-term RF-EMF exposure does not reduce cognitive performance in experimental human studies.

Bijlsma et al. [64] investigated the effects of 2.45 GHz radiofrequency exposure of a baby monitor during sleep at home on subjective and objective sleep quality and heart rate variability (HRV) in 12 healthy adults. In a four-week randomized, double-blind, crossover pilot study, nine women (mean age \pm SD: 41 ± 9 years) and three men (mean age \pm SD: 47 ± 3 years) were randomly exposed to either an active or an inactive (sham) baby monitor for seven nights. The commercially available baby monitor consisted of a digital wireless monitor, placed within half a metre of the bedside table, and a digital wireless camera installed at the other end of the room. The transmitting power was 15 dBm, and operated at a frequency of 2.45 GHz. Ambient EMFs were measured before baseline and at the end of the study in the participant's bedroom. There was a one-week acclimation period before the intervention week, and a one-week washout period. At the end of each week, self-rated sleep quality was retrospectively assessed using the Pittsburgh Insomnia Rating Scale (PIRS-20). Objective sleep measurements included actigraphy and a portable-single channel polysomnography (PSG) recording. HRV was measured using an ambulatory electrocardiogram (ECG). The data analyses included data sets from 8 to 11 participants. Sleep quality on the PIRS-20 was statistically significantly worse during RF-EMF exposure compared to sham exposure. Three participants scored above the normal cut-off value under exposure, while all others were within the normal range. None of the measures of objective sleep quality derived from PSG and actigraphy were altered. EEG power density in the higher frequency bands (gamma, beta, and theta bands) was statistically significantly higher during Non-REM sleep, no data was presented for REM sleep. The observed changes occurred within normal physiological fluctuations. HRV measurements did not differ significantly between conditions. Forty-four percent of individuals correctly identified verum exposure. No information was provided on the number of participants to whom this percentage applied and whether the correct identification was related to sleep quality. The authors concluded that exposure to a 2.45 GHz radiofrequency baby monitor under real-world conditions may disrupt some people's sleep. However, they noted that the study lacked sufficient power, group sizes were unequal across conditions, and specific exposure dosimetry would be required to confirm these findings. A major shortcoming of the study is that it was clearly underpowered.

4.1.1 Conclusions on RF-EMF studies

While objective measures of sleep quality remained unaffected in a pilot study, small changes were observed in some of the power spectra in some frequency bands during sleep. Another experimental study reported slight changes in some skin resistance parameters that were within the normal fluctuations.

If physiological changes are observed, they appear to be small, do not affect all analysed parameters and are within a normal physiologic range. A systematic review and meta-analysis on the effects of mobile phone RF-EMF on resting EEG and ERPs exclusively observed changes during 2G exposure in the resting state wake EEG with eyes open, but not under other 2G or 3G exposure conditions and not during task performance measured by event-related potentials. The authors recommend standardizing and pre-publishing study protocols to address the reported inconsistencies in EEG studies. Two systematic reviews and meta-analyses, commissioned by the World Health Organization (WHO) showed no effects of RF-EMF on non-specific symptoms and RF-EMF perception in healthy adults and individuals with IEL-EMF (Bosch-Capblanch et al. 2024) and high to low evidence of no effects on cognitive performance (Pophof et al. 2024).

Table 4.2: Experimental human studies on exposure to RF-EMF

Outcome	Reference	Population	Exposure condition	Effects
<p>Pittsburgh Insomnia Rating Scale (PIRS-20)</p> <p>Actigraphy (sleep onset latency, sleep efficiency, total sleep time, wake after sleep onset)</p> <p>Single channel polysomnography (Wake, Light sleep [N1 & N2 stages], deep sleep [N3 stage], rapid eye movement sleep [REM] and power spectra in REM and Non-REM sleep in alpha, beta, delta, theta and gamma frequency bands)</p> <p>Portable electrocardiography (ECG; heart rate variability)</p>	Bijlsma et al. (2024)	9 women (mean age \pm SD: 41 \pm 9 years), 3 men (mean age \pm SD: 47 \pm 3 years); data was analysed from 8 -11 participants	<p>Double-blind, randomised, placebo-controlled, crossover</p> <p>Baby monitor (2.45 GHz RF) active for 7 nights at home</p>	<p>PIRS-20 score statistically significantly worse during real exposure as compared to placebo (n=11)</p> <p>Statistically significant increase in theta, beta and gamma bands in NREM sleep only (n=10)</p> <p>All other outcome parameter did not differ between exposure conditions</p>
<p>Autonomous nervous system activity measured by:</p> <p>Skin temperature (head, neck, hand)</p> <p>Electrodermal activity (EDA, auditory event-related skin conductance responses, SCR)</p>	Jamal et al. (2024)	<p>44 healthy volunteers (24 males, 20 females)</p> <p>Mean age \pm SD: 26.5 \pm 4.8 years</p>	<p>2 exposure conditions:</p> <p>Real exposure: 3.5G pulse-modulated; EMF far-field antenna-emitted; in electrically shielded room</p> <p>Sham exposure</p> <p>Exposure duration approx. 26min each,</p>	<p>Head and neck temperature increased statistically significantly after verum exposure; neck temperature already during exposure.</p> <p>Subtle changes in global mean skin conductance and in three EDA parameters (CDA, Tonic activity as well as CDA and TTP Latency) following exposure, indicating a potentially</p>

			pre- and post-exposure condition of 17min randomised; triple-blinded; counterbalanced; sham-controlled	faster response to auditory stimuli, but still within normal physiological range. [CDA: continuous decomposition analysis; TTP: trough-to-peak]
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4.3 Animal studies

In the last year's report, most studies reported effects of RF-EMF exposure, but because of the heterogeneity of the studies, the limited sample sizes and inconsistencies in the results, it was difficult to draw general conclusions.

4.3.1 Rodents

Yavas et al. [65] evaluated the effects of RF-EMF on rat brain and testicular tissue. Male Sprague Dawley rats aged 4-5 months were split into exposure (n=7) and sham group (n=7). Rats were exposed to 2100 MHz GSM-like modulated signals for 5 hours a day for 2 weeks. The SAR was calculated to be 292 mW/kg for brain tissue and 163 mW/kg for testicular tissue. Blinded histopathological evaluation revealed vascular changes and oedema in brain tissue and spermatogenic cell degeneration in testicular tissue, which was more severe in the exposed group than the sham group. The exposed group showed statistically significant reduction of *bax* gene expression (pro-apoptotic protein) in brain tissue and testicular tissue by Real-Time quantitative PCR and statistically significant more DNA damage in brain tissue in the neutral comet assay.

Yardim et al. [66] exposed 12-16-week-old male Wistar Albino rats (n=6 per group) to 2600 MHz fields (modulation not indicated) for 30 min per day, 5 days per week during 30 days. The whole-body SAR_{10g} was 0.297 W/kg and testicular tissue was analysed. Exposure resulted in increased oxidative stress, witnessed by an increase of lipid peroxidation and nitric oxide levels and a decrease of glutathione levels and antioxidant levels. Histological evaluation revealed a decrease in cell population and connective tissue elements under RF-EMF exposure, accompanied by marked oedema in the testicular tissues. Injection with 10 mg/kg melatonin daily for one month reduced these effects.

Effects of 2100 Hz RF-EMF (modulation frequency 217 Hz, pulse width 0.577 ms, power range of the generator 0–2 W) exposure on endoplasmic reticulum (ER) stress in rat testis were reported by Kirimlioglu et al. [67]. Three-months-old male albino Wistar rats (n=10 per group) were exposed 2 h per day for one or ten weeks. The average whole-body SAR value was 0.16 W/kg and the average testis SAR value was 0.0347 W/kg. Levels of C/EBP homologous protein (Chop) and caspase 12 increased after one week of exposure. After ten weeks of exposure, levels of Glucose-regulated protein 78 (Grp78), phosphorylated protein kinase RNA-like endoplasmic reticulum kinase (p-Perk) and Chop were increased.

According to the authors, those results indicate ER stress and ER stress-mediated induction of apoptosis in the testis of exposed rats.

In the study by Pang et al. [68], 8-week-old male Wistar rats (n=3-5 per group) were exposed 30 min to pulsed 2856 MHz fields (pulse width of 400 ns and peak power density of 100 W/cm²) with a whole-body average SAR of 10.17 W/kg and a testicular tissue SAR of 34.2 W/kg. RF-EMF exposure led to reduced sperm motility, reduced hormone levels and induced structural damage, oxidative stress and apoptosis in testicular tissue. Those effects were ameliorated by blueberry anthocyanins (100 mg/kg, 200 mg/kg, or 400 mg/kg) that were administered daily to rats by gavage, starting 14 days before microwave radiation and continuing until 7 days after.

Katirci et al. [69] exposed eight-week-old male Wistar rats (n=10) to 2100 MHz RF-EMF (modulation frequency 217 Hz, pulse width 0.577 ms, power range of the generator 0–2 W) for 2 h per day at a whole-body SAR level of 0.16 W/kg and a mean SAR value for the testis of 0.0347 W/kg. After one or ten weeks of exposure, testicular morphology, expression levels of TAM receptors (Tyro3, Axl and Mer), their ligands (Gas6 and Pros1) and of cleaved caspase-3 (apoptosis marker) were investigated by immunohistochemistry in the testes. Abnormal processes of spermatogenesis and seminiferous tubule morphology were observed in the RF EMF exposed groups. No statistically significant differences were observed in the expression of TAM receptors, their ligands or of cleaved caspase-3 between exposed and sham-exposed groups.

Bontempi et al. [70] investigated changes in neuronal activity in several distinct brain regions of male Sprague Dawley rats (age not given). After habituation, only the heads of restrained animals were exposed to 900 MHz fields (GSM-modulation, 1/8 duty factor, pulsed at 217 Hz). In experiment 1, animals (n=9 per group) were exposed to brain average SAR levels of 0, 0.5, 1, 2, 4, and 6 W/kg for 2 h. Immediately after the end of exposure, brains were processed for immunohistochemistry (c-fos). In experiment 2, animals (n=12 per group) were exposed to brain average SAR levels of 1 or 3.5 W/kg for 45 min for 10 or 14 days, respectively. Immediately after exposure, animals were submitted daily to either a spatial working memory task or a spatial reference memory task. After 10 or 14 days, respectively, 6 animals per group were randomly selected for brain immunohistochemistry (c-fos). C-fos, an indirect marker of neuronal activity, was analyzed in 23 brain regions. Acute exposure (experiment 1) induced a statistically significantly increased c-fos expression in five brain regions at only 1 W/kg, while a statistically significantly reduced c-fos expression was observed in one brain region (temporal cortex) at all SAR levels. In experiment 2, six brain regions displayed a statistically significant decrease in c-fos labeling, four of those had shown an increase in experiment 1. However, because behavioral performance evolved similarly in all groups, the authors concluded that RF EMF-induced changes in brain activity patterns are insufficient to induce detectable deficits in behavioral paradigms used in the study.

Baliga et al. [71] exposed 6-week-old Swiss albino (ICR) male mice to 915 MHz fields (continuous wave), 24 h per day for 0 (baseline group), 3, 6 or 9 days (n=5 per group). The whole-body SAR was 1.17 W/kg. After exposure, brain, liver and kidney were harvested. The exposed groups showed statistically significantly higher mean body temperatures at days 3, 6 and 9 compared to the sham-exposed groups. Number of apoptotic cells was counted in one organ sample per treatment group. A significantly higher number of apoptotic cells was found in the exposed groups compared to the sham-exposed groups in all organs, with the highest number of apoptotic cells in brain tissue. Using scanning electron microscopy, the surface morphology of brain samples (n=4 per treatment group) was analysed. RF EMF exposure induced various types of structural deformations at days 3-9 compared to baseline (results for sham group not presented). Gene expression of p53 and HSP-70 was analysed in brain, liver and lung (n=3 per treatment group) using quantitative PCR (qPCR). The p53 expression was statistically significantly increased after 9 days of exposure, and that of HSP-70 after 6 and 9 days of exposure, compared to the baseline group. Expression of p53 and HSP-70 in the exposed group was also significantly different to the sham group (unclear at which time points).

The WHO commissioned a systematic review and meta-analysis on the effects of RF-EMF exposure (range 100 kHz to 300 GHz) on male fertility in nonhuman mammals and human sperm *in vitro* which was conducted by Cordelli et al. [72]. The methods used to conduct the review were described in a detailed study protocol [73]. As indicators of reproductive system impairment, decrease of fertility, effects on semen quality, toxicity in reproductive organs and hormonal effects were considered. A total of 117 papers on animal studies and 10 papers on human sperm exposed *in vitro* were included. Risk of bias (RoB) of individual studies was evaluated using the RoB Rating Tool developed by OHAT, with minor modifications informed by RoB expertise developed within SYRCLE. Most of the studies were rated as “some concern” or “high concern”, with the main reasons being lack of blinding and poor exposure characterization. The meta-analysis of animal studies provided evidence of adverse effects for all considered endpoints but the rate of infertile males and the size of the sired litters. In the certainty assessment according to GRADE methodology, a moderate certainty of evidence was assigned to the reduction of pregnancy rate and to the evidence of non-effect on litter size. A low certainty of evidence was assigned to the reduction of sperm count, while all other meta-analysis results had a very low certainty of evidence. No dose-response relationship or a minimum effective exposure level could be determined. According to the authors, it is not known the extent to which the conclusion of the meta-analysis can be applied to human exposure levels because most studies tested exposure levels above 0.4 W/kg.

Xue et al. [74] exposed 8-week-old male C57BL/6J mice (n=10 per group) to 2650 MHz RF-EMF for 2 h, followed by 800 MHz RF-EMF exposure for an additional 2 h (modulation not indicated). Mice were exposed daily for 21 days excluding days 7, 14 and 21 for behavioural testing (open field test, elevated plus maze test). SAR was 4 W/kg. Rectal temperature measurements of 3 mice per

group revealed temperature increases of less than 1°C. The exposed group showed anxiety-like behaviour at all 3 days. Serum corticosterone and corticotropin levels were statistically significantly increased, while the gene expression of cannabinoid receptor 1 Type (CB1R, encoded by *Cnr1*) and the levels of CB1R protein and its ligand 2-arachidonoylglycerol in the cerebral cortex statistically significantly decreased. Additionally, the cannabinoid receptor agonist Win55-212-2 significantly improved the anxiety-like behaviour, while the cannabinoid receptor antagonist AM251 effectively countered the anti-anxiety effects of Win55-221-2.

Kim et al. [75] investigated the impacts of LTE signal exposure on thyroid hormones and thyroid hormone-regulating factors during childhood and adolescence. Four-week-old male C57BL/6 mice (n=7-10 per group) were exposed to a 1760 MHz LTE signal (QPSK modulation signal, whole-body average SAR 4 W/kg) or a positive control (lead, 300 ppm in drinking water) for 8 h daily for 4 weeks. Lead was selected owing to its established influence on thyroid hormones. Subsequently, the mice underwent behavioural tests including open field, marble burying, and nest building. Blood pituitary (BDNF, ACTH) and thyroid hormone (TSH, T3, T4) levels, and thyroid hormone-regulating genes within the hypothalamus–pituitary–thyroid axis (*Trh*, *Dio2*, *Dio3*, *Oatp1c1*, *Trhr*, *Tshβ*) were analysed. Lead exposure demonstrated a significant dysregulation of the hypothalamus–pituitary–thyroid axis and associated behavioural changes. In contrast, the LTE exposed group showed no behavioural changes or gene expression alterations in the thyroid and pituitary glands, but Type 2 and Type 3 Deiodinases (*Dio2*, *Dio3*) expressions were significantly reduced in the hypothalamus compared to the sham-exposed group.

Deng et al. [76] investigated the effect of carrier frequency (2.4 GHz and 935 MHz), pulse modulation frequency (10, 100 and 1000 Hz), pulse shape (square or sinusoidal) and duty cycle (1/8 or continuous) on wakefulness in 6-10-week-old male C57BL/6 mice (n=12-19 per group). The time-averaged output power was 8 W, resulting in a peak output power of 64 W for the 1/8 duty cycle exposure settings. Maximum local SAR was 3.6 W/kg. Two weeks before the experiment, four cranial electroencephalogram (EEG) electrodes were implanted and electrodes for electromyography (EMG) were inserted under the trapezius muscle. Mice were exposed 24 h per day for 9 days. A statistically significant increase of wakefulness and a statistically significant decrease in rapid eye movement (REM) and nonrapid eye movement (NREM) sleep was demonstrated at 100 and 1000 Hz modulation and 2.4 GHz but not at 10 Hz or for 935 MHz. Replacement of 100 Hz square-pulsed modulation by sinusoidal-pulsed modulation also led to a statistically significant increase of wakefulness but continuous sinusoidal amplitude modulation had no effect.

In the study by Wang et al. [77] nine-week-old male C57BL/6 mice (n=8 per group) were exposed to 4900 MHz fields (modulation not indicated), 1 h per day for 21 days. Mice were whole-body exposed at an average power density of 50 W/m² (measurement site not indicated). Faecal samples were collected at the end

of exposure to detect gut microorganisms and metabolites by 16S rRNA gene sequencing and High Performance Liquid Chromatography-Mass Spectrometry, respectively. The RF-EMF exposed group showed a reduced microbial diversity and a changed microbial community distribution compared to the sham-exposed group. Metabolomics profiling identified 258 significantly differentially abundant metabolites in the exposed group, 57 could be assigned to specific metabolic pathways that are documented in the Kyoto Encyclopaedia of Genes and Genomes (KEGG).

In another study by the same group [78], 6-8-week old male C57BL/6 mice were exposed to 4900 MHz fields (pulse wave) for 35 days, 1 h per day, at an average power density of 50 W/m² (measurement site not indicated). After exposure, untargeted metabolomics was performed on brain tissue and serum samples (n=6 per group), while Tandem Mass Tags (TMT) quantitative proteomics was performed on brain tissue samples (n=3 per group). In the exposed group, there were 104 and 153 up- and down-regulated differentially expressed metabolites (DEMs) in brain and serum, respectively, and the DEMs were significantly enriched in glycerophospholipid metabolism. Moreover, 10 up-regulated and 51 down-regulated differentially expressed proteins (DEPs) in brain were discovered in the RF exposed group. Functional correlation analysis showed that most DEMs and DEPs showed a significant correlation.

In 2023, Pinto et al. [79] published a systematic review on RF-EMF and cancer in animal experimental studies. Their results showed low or inadequate evidence for an association between RF-EMF and cancer. However, instead of being directly carcinogenic, RF-EMF could, in principle, also have a co-carcinogenic effect. This means that RF-EMF could intensify the effect of a known carcinogenic agent. Therefore, the same group conducted a second systematic review on co-exposure studies [15]. The methods used to conduct the review were described in a detailed study protocol [80]. A total of 25 studies were included in this systematic review and 18 were included in the meta-analysis. RoB was assessed for all studies following the criteria provided by OHAT and individual studies were assigned into one of three quality categories, i.e. “low quality”, “intermediate quality”, or “high quality”. The overall assessment of the quality of the evidence and of the level of evidence for health effects was done according to GRADE. Studies were of overall good quality, with 10 studies being of high, 10 studies of moderate and only five studies of low quality. The meta-analysis resulted in statistically significant findings ($p < 0.01$) for malignant tumours of the kidney (4 papers, RR = 2.34, 95% CI, 1.34–4.03, $p = 0.0002$) and liver (4 papers, RR = 1.39, 95% CI 1.08–1.80, $p = 0.002$), as well as for benign lung tumours (4 papers, 8 studies, RR = 1.65, 95% CI 1.35–2.02, $p = 4 \times 10^{-9}$). For these tumour types, the quality of the evidence was rated as moderate as well as the level of evidence for health effects. For benign skin tumours, there was evidence of no health effect with a high quality of the evidence. For all other tumour types, the evidence for health effects was rated as inadequate. Although the level of evidence for health effects was moderate for kidney, liver and lung, with a numerically small but statistically significant increase, the authors concluded that

the results cannot be considered definitively conclusive. This was due to the limited number of papers and individual comparisons of treated- and sham-exposed animals within these papers, and the diversity of carcinogenic agents used. The same was concluded for benign skin cancers.

The WHO commissioned another systematic review on the effects of RF-EMF exposure (range 100 kHz to 300 GHz) on biomarkers of oxidative stress in *in vivo* and *in vitro*, which was conducted by Meyer et al. [81]. The methods used to conduct the review were described in a study protocol beforehand [Mevisen et al, 2022 [82]]. Standard chronic cancer bioassays but also studies on tumour-prone animal models, initiation-(co-)promotion studies and studies with implantation of cancer cells were considered in the systematic review. A risk of bias (RoB) assessment was conducted using the Office of Health Assessment and Translation (OHAT) tool. In addition, study sensitivity was assessed separately using methods utilized by the National Toxicology Program (NTP) Report on Carcinogens (RoC). Although the authors noted sensitivity issues and lack of blinding in some studies, all studies except two were judged as having high quality.

Studies were considered unsuitable for meta-analysis due to heterogeneity in study design, species, strain, sex, exposure characteristics, and cancer outcomes. The results of the studies were therefore presented narratively. Studies were grouped according to the organ/organ system. Subsequent analyses focused on those organs where at least one exposure group in one study showed an increase in cancer outcomes compared to sham exposure or if there was a statistically significant dose-response relationship. If this was the case, the authors concluded that there was an effect of the exposure in that organ/organ system, regardless of null outcomes in other studies.

For the gastrointestinal/digestive, urinary, endocrine, musculoskeletal, reproductive, and auditory system, as well as for kidney and mammary gland, the authors concluded that there was “no or minimal evidence for cancer-related effects of RF-EMF exposure-related cancer outcomes”. For lymphoma, adrenal gland, liver and lung, an increase of cancer-related outcomes was observed but the evidence was judged as moderate because of some inconsistencies in findings. For the organs brain and heart, statistically significant increases of glial-cell derived tumors and of malignant heart schwannomas, respectively, were observed in two independent studies each. For both observations, the certainty was judged as high. The authors noted that despite the high level of certainty, extrapolation of risk from animal cancer studies to humans is particularly complex for RF-EMF.

What is striking about the results of this systematic review is that for all organs, for which cancer-related effects were observed, the results depend heavily on one to two chronic bioassays for which the authors saw no significant concerns for risk of bias. These are namely the NTP studies [83, 84] on mice and rats and the study by Falcioni et al. 2018. However, for those studies, limitations have been described elsewhere [SSM 2018 [85] ; FDA [86] , ICNIRP [87]]. In addition, for most of the organs/organ systems, many more studies have been published that

did not report statistically significant effects of RF-EMF exposure as compared to studies showing effects, but those were not adequately taken into account by the approach the authors used to arrive at their conclusions. In essence, an approach to interpret only positive findings and omit null findings contradicts the underlying objective of a systematic review to provide an overview of all existing evidence of a topic. There are additional procedures that the authors followed that remain unclear, e.g. it is unclear which historical controls were used to calculate the trend for oligodendrogliomas in Anderson et al. 2004. It is also unclear why only oligodendrogliomas were considered in the calculation and not all glial-cell derived tumours, as it is the case in the NTP study on rats and in Falcioni et al. 2018. These uncertainties limit the validity of the results of this systematic review. Its results are also in contrast to the results of a recently published systematic review by Pinto et al. in 2023 [88].

Please note that this systematic review was published outside of the time frame of this report. Given the many WHO commissioned reviews included in this year's report, also the paper by Mevissen et al. (2025) was included.

Pardhiya et al. [89] analysed the combined effects of conjugated manganese dioxide nanoparticles and exposure to RF-EMF on haematological parameters, oxidative status and genotoxicity in ten-week-old male Wistar rats (n=6 per group). Rats were exposed to 2002 MHz fields (modulation not indicated) at a whole-body SAR of 1.2 W/kg for 2 h per day, six days per week for eight weeks. RF-EMF exposure had statistically significant effects on several haematological parameters and induced DNA damage in blood cells. Those effects were ameliorated by manganese dioxide nanoparticles that were administered subcutaneously to rats (probably 12.5 mg/kg but not indicated for the group that received both, RF-EMF and nanoparticles).

Sylvester et al. [90] investigated the core body temperature response of free-moving adult male and female C57BL/6 mice (34 to 43 weeks of age, n= 12 per group), during and following a 2 h exposure to 1950 MHz RF-EMF (modulation not indicated) within custom-built reverberation chambers, using temperature capsules implanted within the intraperitoneal cavity and data continuously logged and transmitted via radio telemetry postexposure. Comparing RF-EMF exposures (WBA-SAR of 1.25, 2.5, 3.75, and 5 W/kg) to the sham-exposed condition, they identified a peak in core body temperature within the first 16 min of RF-EMF exposure (+0.15, +0.31, +0.24, +0.37°C at 1.25, 2.5, 3.75, and 5W/kg respectively; statistically significant at whole-body average SAR ≥ 2.5 W/kg only), which largely dissipated for the remainder of the exposure period. Immediately before the end of exposure, only the core body temperature of the 5 W/kg condition was statistically differentiable from sham. Based on the findings, the authors concluded that mice are able to effectively compensate for the increased thermal load at RF-EMF strengths up to 5 W/kg. In addition, the elevated core body temperature at the end of the exposure period in the 5 W/kg condition was statistically significantly reduced compared to the sham condition immediately after RF-EMF exposure ceased. According to the authors, this

indicates that measures of core body temperatures that are done at the end of an RF-EMF exposure period may not reflect the actual change in the core body temperature of mice caused by RF-EMF exposure.

Effects of RF EMF exposure on the development of young Sprague Dawley rats was investigated by Bodin et al. [91]. Pregnant rats (n=8-9 per group) of 10-12 weeks of age were exposed to 900 MHz RF EMF (continuous wave) from gestational day 8 until the weaning of the pups at postnatal day 17. At birth, litters were reduced to 3 males and 3 females and housed with the mother until postnatal day 20. After weaning, rats from the same litter were housed 4 or 3 per cage per gender and experimental group until postnatal day 43. RF EMF exposures were performed in reverberation chambers 8 h per day with a whole-body SAR of 0 (sham), 0.08 W/kg (general public exposure) or 0.4 W/kg (occupational exposure group) for the pregnant rats. The corresponding postnatal whole-body SAR for the pups was approximately 0.024 W/kg (public exposure group) or 0.12 W/kg (occupational exposure group), respectively. It grew with the body weight and reached 0.4 or 0.08 W/kg when the pups were about 14 days of age. Peak whole-body SAR values for the pups reached 0.20 W/kg (public exposure group) and 0.90 W/kg (occupational exposure group), respectively, at postnatal day 27. There were no effects of exposure on litter size, sex ratio, number of siblings, and weight and length of pups at birth. A statistically significant decrease in body mass was observed for male pups of the occupational exposure group from postnatal day 6 until postnatal day 43. Male and female pups showed statistically significantly earlier pinna ear detachment and eye opening in both exposure groups. Only male pups in the public exposure group showed statistically significantly earlier incisor eruption. According to the authors, those data suggest variations in development time of rats when exposed in utero and after birth to whole-body SAR values equal to the limit values for public and occupational exposure of humans. In 2023, in contrast to the present results, the same group reported a delay in incisor eruption in males and females at 3500 MHz and a whole-body SAR of 0.07 W/kg.

Bektas et al. [91] exposed 8-10-weeks-old male Wistar Albino rats to 3500 MHz fields (1/8 duty factor, pulse repetition rate 217 Hz), 2 h per day for 30 days. The whole-body SAR was 0.037 W/kg. Half of the animals was made diabetic by administration of streptozotocin, which is capable of destroying pancreatic islet β -cells. Healthy and diabetic rats were exposed and sham-exposed (4 groups, 7 animals per group). After exposure, blood and adipose tissue samples were collected and processed for measurement of total antioxidant status (TAS), total oxidant status (TOS), H_2O_2 , insulin and of hormones that regulate energy metabolism (nesfatin-1, ghrelin, irisin). Exposure increased blood glucose levels in healthy but not diabetic rats. In blood and adipose tissue of diabetic rats, RF EMF exposure increased levels of ghrelin, irisin, TOS and H_2O_2 , and decreased levels of nesfatin-1, TAS and insulin. The statistical analysis of group comparisons is not always clear; groups of diabetic rats were compared with healthy rats and sometimes only the difference between exposed diabetic rats and exposed or sham-exposed healthy rats was significant.

4.3.2 Other species

Šofranková et al. [92] exposed male and female ticks (*Ixodes Ricinus*) to 900 MHz fields for 10 min, 1, 3 or 24 h and a field intensity of 2 V/m (frequently occurring intensity in urbanized habitats) or 40 V/m. Ticks were divided into three biological replications with 5 ticks per replication, treatment condition and sex. Immediately after exposure, the synganglia of ticks were dissected and total RNA extracted. Using qPCR, expression levels of the neuropeptides *mip* and *sifa* and the neuropeptide receptors *mip-r1* and *sifa-r1* were analysed at all time points. For the statistical analysis, the control groups from all four time points were combined and not regarded separately. Statistically significantly increased levels of *sifa* and *sifa-r1* were observed in males and females at 2 V/m at several time points, while at 40 V/m the expression levels were statistically significantly decreased at most time points compared to the control group.

Parker et al. [93] determined the thresholds for skin burns from superficially penetrating RF-EMF energy in living female pigs (*Sus scrofa*). Exposure conditions for the main study were established in a pilot-study. Pigs (n=8 per frequency) were exposed for 5 seconds at power densities of 4 to 30 W/cm² at 8200 MHz (CW) or to power densities of 2 to 15 W/cm² at 95 GHz (pulsed). Exposure sites were marked on the flanks of each pig and exposed or sham-exposed. In addition, two positive thermal control exposures were conducted per frequency. Biopsies were collected from each burn site (7 (95 GHz) or 8 (8.2 GHz) exposure conditions, 2 sham exposures, 2 positive controls) at 1 h, 24 h, 72 h and 168 h post exposure. Each sample was assessed in a blinded way by a burn pathologist. Burn wounds were classified based on the deepest tissue damaged as superficial, partial-thickness, or full-thickness, which determines the wound management necessary for successful healing. Injury severity increased in a dose-dependent manner. Thresholds were found, below which the severity was consistently low. The transition between superficial burns and more severe partial thickness or full thickness burns occurred quicker for the 8.2 GHz frequency. Specifically, while the severity of burns for 95 GHz exposures gradually increased over the full range of power densities, the 8.2 GHz exposures had a marked change at 10-15 W/cm². This effect was assumed to reflect the deeper penetration of the lower frequency field energy. The authors point out that 8.2 GHz exposures at 10-15 W/cm² power densities are less than 10 times the IEEE limit [23], yet they resulted in partial thickness and full thickness burns. Although porcine skin is considered a surrogate of human skin, differences have been reported regarding the mechanical characteristics of full thickness burned human and porcine skin [94]. It is therefore unclear how generalizable these results are.

4.3.3 Conclusion

This year's report is quite heterogenous in terms of investigated endpoints (see Table 1 for an overview). The organs most often targeted include testis and brain. Effects on brain were also frequently analyzed in previous reports. This year, all included experimental 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 exposure conditions. The exposure parameters, such as frequency, duration and exposure level, again vary considerably between studies. Like in the previous report, it is striking that most of the included studies on rodents only examined male animals. However, it cannot be excluded that females, due to potential differences in susceptibility, show different effects of RF-EMF exposure.

Three comprehensive systematic reviews, commissioned by WHO, were published on oxidative stress, male fertility and cancer. Adverse effects were observed on pregnancy rate and sperm count with moderate or low certainty, but most studies evaluated exposure levels that were higher than the limits set in international guidelines. The certainty of evidence for or against an effect on oxidative stress was very low due to high risk of bias and inconsistencies of results. Therefore, no suggestions to confirm or reconsider current human exposure limits were given by these systematic reviews.

The third systematic review commissioned by WHO concluded on high or moderate evidence for an increased risk of cancer in several organs, but this was based on only two animal studies. This result is also in contrast to a systematic review published in 2023, which concluded on either low or inadequate health evidence for an association between RF exposure and carcinogenesis *in vivo*.

Another systematic review examined effects of co-exposure to RF-EMF and a carcinogenic agent. The results showed moderate health evidence for liver, kidney and benign lung tumours. However, the increase in risk was small and not considered definitively conclusive by the authors.

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). Even some of the included studies had not mentioned the site of power density measurement or had a rather vague description of exposure and/or dosimetry. Another limitation is the low number of animals used in the majority of studies (n<10 per group), a problem that was already addressed in last year's report. A small sample size can lead to false-positive as well as false-negative results.

Overall, due to the above-mentioned limitations and inconsistencies, it is difficult to draw a conclusion other than that under certain circumstances some effects of RF-EMF exposure are observed in experimental animals. Effects on the reproductive system of male rodents are seen especially at exposure levels above the international exposure limits. High quality studies at exposure levels relevant for the general population would be needed to adequately assess the health risk for humans. There is no substantial evidence that RF-EMF exposure induces oxidative stress *in vivo*, but higher quality studies are needed to draw definitive conclusions.

Table 4.3: Summary of animal studies on exposure to RF-EMF

Outcome	Reference	Species	Exposure conditions	Effect
Rodents				
Effects on brain, male reproductive and other organs	Yavas et al.	Male Sprague Dawley rats	5 h/d for 2 weeks 2100 MHz Brain SAR: 292 mW/kg Testicular SAR: 163 mW/kg	Vascular changes and oedema in brain, spermatogenic cell degeneration in testicular tissue ↑ DNA damage in brain □ bax gene expression in brain and testicular tissue
	Yardim et al.	Male Wistar Albino rats	30 min/d, 5d/week for 30 days 2600 MHz Whole-body SAR: 0.279 W/kg	□ Oxidative stress in testis □ Cell population and connective tissue elements and □ oedema in testis; Effects of exposure were ameliorated by melatonin
	Kirimlioglu et al.	Male albino Wistar rats	2 h/d, 1 or 10 weeks 2100 MHz (modulation frequency 217 Hz, pulse width 0.577 ms) Whole-body SAR: 0.16 W/kg Testis SAR: 0.0347 W/kg	Induction of endoplasmic reticulum stress
	Pang et al.	Male Wistar rats	30 min 2857 MHz (pulse width 400 ns, peak power density 100 W/cm ²) Whole-body SAR: 10.17 W/kg Testicular SAR: 34.2 W/kg	□ Sperm motility, hormone levels □ Structural damage, oxidative stress, apoptosis in testicular tissue; Effects of exposure were ameliorated by blueberry anthocyanins
	Katirci et al.	Male Wistar rats	2 h/d, 1 or 10 weeks 2100 MHz (modulation frequency 217 Hz, pulse width 0.577 ms) Whole-body SAR: 0.16 W/kg Testis SAR: 0.0347 W/kg	Abnormal spermatogenesis and seminiferous tubule morphology; No effect on TAM receptors and ligands
	Bontempi et al.	Male Sprague Dawley rats	Exp. 1: 2 h Exp. 2: 45 min for 10 or 14 days 900 MHz (GSM modulation, 1/8 duty factor, pulsed at 217 Hz) Brain SAR: Experiment 1: 0.5, 1, 2, 4, 6 W/kg Experiment 2: 3.5 W/kg	□ c-fos expression in 5 brain regions and □ in one brain region (exp. 1) □ c-fos expression in 6 brain regions (exp. 2)
	Baliga et al.	Male Swiss albino mice	24 h for 0, 3, 6, 9 days 915 MHz (CW)	□ number of apoptotic cells

Outcome	Reference	Species	Exposure conditions	Effect
			Whole-body SAR: 1.17 W/kg	<input type="checkbox"/> expression of p53 and HSP-70 <input type="checkbox"/> structural deformation of brain surface morphology
	Cordelli et al.	Nonhuman mammals and human sperm <i>in vitro</i>	Systematic Review 100 kHz - 300 GHz	Moderate CoE for reduced pregnancy rate and non-effect on litter size Low CoE for reduced sperm count Mostly ≥ 0.4 W/kg exposures, therefore implications for human exposure levels unknown
Behaviour and sleep	Xue et al.	Male C57BL/6J mice	2 h + 2 h daily for 21 days 2650 MHz followed by 800 MHz SAR 4 W/kg	Anxiety-like behavior <input type="checkbox"/> levels of corticosterone and corticotrophin <input type="checkbox"/> gene expression of CB1R and 2-arachidonoylglycerol in cerebral cortex
	Kim et al.	Male C57BL/6 mice	8 h/d, 7 d/week, 4 weeks 1760 MHz (QPSK modulated) Whole-body SAR: 4 W/kg	No effects on behavior <input type="checkbox"/> expression levels of Deiodinase Type 2 and 3 in hypothalamus
	Deng et al.	Male C57BL/6 mice	24/d for 9 days 2400 or 935 MHz; pulse modulation: 10, 100 or 1000 Hz; pulse shape: square or sinusoidal; duty cycle: 1/8 or continuous Max. local SAR: 3.6 W/kg	<input type="checkbox"/> wakefulness <input type="checkbox"/> rapid eye movement and nonrapid eye movement at 2400 MHz and 100 or 1000 Hz square- and sinusoidal-pulsed modulation
Microbiome and metabolism	Wang et al.	Male C57BL/6 mice	1 h/d, 21 days 4900 MHz PD 50 W/m ²	Reduced microbial diversity, changed microbial community and metabolites in feces
	Wang et al.	Male C57BL/6 mice	1 h/d, 35 days 4900 MHz PD 50 W/m ²	Up- and downregulation of metabolites in brain and serum and of proteins in brain
Cancer	Pinto et al.	Rodents	Systematic review 100 kHz - 300 GHz	Moderate evidence for health effects for liver, kidney and benign lung tumours
	Mevissen et al.	Rodents	Systematic review 100 kHz - 300 GHz	Increase of malignant schwannomas of the heart and gliomas with high certainty; Increase of pheochromocytoma, hepatoblastomas, lymphoma and neoplasms of the lung with moderate certainty
Physiology	Pardhiya et al.	Male Wistar rats	2 h/d, 6 d/week for 8 weeks	Changes in haematological parameters

Outcome	Reference	Species	Exposure conditions	Effect
			2002 MHz Whole-body SAR: 1.2 W/kg	Induction of DNA damage in blood cells
	Sylvester et al.	Male and female C57BL/6 mice	2 h 1950 MHz Whole-body SAR: 1.25, 2.5, 3.74, 5 W/kg	<input type="checkbox"/> core body temperature at all SAR levels, only significant at 5 W/kg immediately before end of exposure; after end of exposure significant reduction of core body temperature at 5 W/kg
	Bodin et al.	Pregnant Sprague Dawley rats and male and female pups	8 h/day from GD 8 until weaning at PND 17 900 MHz (CW) Whole-body SAR: 0.08 or 0.4 W/kg	No effects on litter size, sex ratio, number of siblings, length and weight at birth <input type="checkbox"/> male body mass from PND 6 until 43 Earlier pinna ear detachment and eye opening in both sexes
	Bektas et al.	Male Wistar albino rats One group made diabetic	2 h/d for 30 days 3500 MHz (1/8 duty cycle, pulse repetition rate 217 Hz) Whole-body SAR: 0.037 W/kg	<input type="checkbox"/> total oxidant status, H ₂ O ₂ , irisin, ghrelin <input type="checkbox"/> total antioxidant status, insulin, nesfatin-1
	Meyer et al.	<i>In vivo</i> and <i>in vitro</i> models of humans and other mammals	Systematic review 100 kHz - 300 GHz	Very low certainty of evidence overall for the relation between RF-EMF exposure and oxidative stress
Other species				
Neurophysiological effects	Šofranková et al.	Male and female ticks (<i>Ixodes Ricinus</i>)	10 min, 1 h, 3 h, 24 h 900 MHz 2 or 40 V/m	↑ sifa and sifa-r1 at 2 V/m at several timepoints <input type="checkbox"/> sifa and sifa-r1 at 40 V/m at most timepoints
Burns	Parker et al.	Female pigs (<i>Sus scrofa</i>)	5 sec 8200 MHz or 95 GHz PD: 4-30 W/cm ² or 2-15 W/cm ²	Threshold levels identified, below which severity of injuries is consistently low; At 8.2 GHz marked change in severity at 10-15 W/cm ² , while for 95 GHz severity gradually increases

Abbreviations: ↑ increase; ↓ decrease; SAR: Specific absorption rate; TAM: Tyro3, Axl and Mer receptors; GSM: Global System for Mobile communications; CW: Continuous wave; CoE: certainty of evidence; HSP-70: Heat shock protein 70; CB1R: Cannabinoid receptor 1 Type; PD: Power density; GD: Gestational day; PND: Postnatal day.

4.4 Cell studies

4.4.1 Cell proliferation, cell cycle, and DNA damage

Massaro [95] and co-workers investigated the effect of continuous and pulsed exposure at 1600 MHz in cultures of human fibroblasts (HF) by evaluating several parameters related to cytotoxicity and genotoxicity (Massaro et al., 2024). The exposure was two hours long at a Specific Absorption Rate (SAR) of 0.4 W/kg

and the pulsed exposure was obtained by using an amplitude modulated signal with a pulse period of 2 ms and a duty cycle of 27.5%.

In particular, cell cycle, ultrastructure, protein expression, mitotic spindle, micronucleus frequency, chromosome segregation and γ -H2AX/53BP1 foci formation were analyzed. The temperature was monitored by means of a fiber optic thermometer and the maximum increase during the exposure period was 0.35°C for both continuous and pulsed exposure.

No significant effect was observed on cell cycle, chromosome segregation, micronuclei and γ -H2AX/53BP1 foci, indicating lack of cytotoxic and genotoxic effects, although mitotic spindle alterations were sporadically detected. Cell morphology (nuclei/cytoplasm ratio, cellular shape, vacuoles in the cytoplasm) also resulted unaffected by the exposure.

When expression of different heat-shock proteins (i.e., HSP-90, HSP-60, and HSP-25) and phospho-AKT (protein-kinase B, a protein involved in the phosphorylation of several proteins) were examined, a slight but statistically significant increase or decrease ($p \leq 0.05$) was detected based on the signal (CW or pulsed) employed but only after 20 h from the RF exposure. Ultrastructural analysis of cell morphology revealed some modifications for both CW and pulsed RF exposure in terms of cytoskeletal organization and number of lysosomes. In this paper the number of independent experiments is not reported for all the endpoints investigated and in some cases it is just two. In addition, no blind procedures have been followed and positive controls have been provided for MN assay and foci formation only.

Worel et al. [32] investigated the effect of exposure to 1950 MHz, UMTS signal, at SAR value of 0.25, 0.50 and 1.0 W/kg on DNA stability in an astrocytoma cell line (1321N1). Cultures exposed and treated simultaneously or sequentially with mutagens were also included in the study design to evaluate if the exposure is able to affect chemically-induced DNA damage. To this purpose 4-Nitroquinoline 1-oxide (4NQO), Benzo(a)pyrene diol epoxide (BPDE), Chromium trioxide (CrO₃) and Nickel chloride (NiCl₂) were employed. The experiments were carried out blind and controlling temperature; chemical treatments served as positive controls. Simultaneous exposures were 16 hours long, while in experiments with sequential exposure the cells were first exposed for 16 h and then treated with the test chemicals for more 16 h.

DNA damage was measured in single cell gel electrophoresis (comet) assays. A slight but statistically significant decrease in DNA damage was detected in cultures exposed at 0.25 W/kg compared to sham-exposed ones ($p < 0.05$) while no differences were detected for the other exposure conditions and for all the co-exposure protocols tested. [It is not clear how many independent experiments have been carried out].

In the same paper, the authors also investigate the effect of ELF-MF (50 Hz) in human derived lymphoma (Jurkat) cells (see section 2.4).

Sannino et al. [96] also investigated the effect of exposure and co-exposure to chemicals on a human neuroblastoma cell line (SH-SY5Y). In previous studies, they reported that 20 h pre-exposure of SH-SY5Y cells to 1950 MHz, UMTS signal, at SAR of 0.3 and 1.25 W/kg, was able to reduce the oxidative DNA damage induced by a subsequent treatment with menadione in the alkaline comet assay, without inducing genotoxicity per se (Falone et al, 2018; Sannino et al, 2022). In this study, the authors used the same cell model and the same electromagnetic conditions to test different exposure durations and timing along the 72 h culture period. The results obtained in at least three independent experiments for each condition, carried out blinded, indicate that shorter exposure durations than 20 h, that is, 10, 3, and 1 h per day for 3 days, were still capable to exert the protective effect while not inducing DNA damage per se.

In addition, to provide some hints into the mechanisms underpinning the observed phenomenon, thioredoxin-1, heat shock transcription factor 1, heat shock protein 70, and poly [ADP-ribose] polymerase 1, were tested following 3 h of radiofrequency exposure in western blot and qRT-PCR experiments. They were selected as key molecular players involved in the cellular stress response. No effect resulted from molecular analysis under the experimental conditions adopted.

In a study conducted by Goh et al, [97] the authors improved the exposure system employed in earlier investigations [Choi et al., 2020; Kim et al., 2021] by stabilizing the power control and eliminating the thermal effect and measured several parameters in various human cell types that resulted altered in their previous investigations [Goh et al, 2024].

Cell cultures were exposed to 1700 MHz, LTE signal, and the temperature was maintained at $37 \pm 0.5^\circ\text{C}$ by circulating water within the exposure chamber. The experiments were carried out on four cell lines with different growth rate: human adenocarcinoma HeLa cells, human hepatocellular carcinoma Huh7 cells, human adipose-derived stem ASCs cells and B103 rat neuroblastoma. In particular, to assess cell proliferation, measured by applying the MTT (3-(4, 5-dimethylthiazolyl-2)-2, 5-diphenyltetrazolium bromide) test, Huh7 and ASCs cells were exposed at 0.4 and 4 W/kg for 24 h followed by 48 h incubation. In a second set of experiments Huh7, HeLa and B103 cells were exposed at 0.4, 1, 4 and 8W/kg for 72h and ASCs cells were exposed at 8 W/kg for 72 h. Proliferation of all cell types, which displayed different growth rates, did not change significantly compared to sham controls.

In addition, apoptosis, cell cycle progression (flow cytometric techniques), DNA damage (foci-formation) and the activation of extracellular signal-regulated kinases (ERK) pathway (Western blot) were also evaluated and resulted unaffected in HeLa, Huh7 and B103 cells exposed for 72 h at 8 W/kg SAR. The

latter is usually triggered in response to various stresses. UV radiation was used as positive control and worked properly.

However, when the thermal control system was turned off and the subsequent temperature increase induced by the RF-EMF was not controlled during 72 h continuous exposure to SAR of 8 W/Kg, cell proliferation increased by 35.2% at the maximum in all the cell lines investigated. For all the experimental conditions tested at least three independent experiments were performed.

Therefore, the authors stated that the effects detected in their previous investigations were due to the induced thermal changes rather than the RF-EMF exposure itself.

The authors refer to control cultures but from the text it seems they assessed sham exposed controls.

4.4.2 Other cellular endpoints

To evaluate the effects of exposure to 1800 MHz, continuous wave (CW) and GSM modulated, on signal transduction and protein and cytokine expression, Bellier and co-workers exposed differentiated human-derived monocytic THP-1 cells for 0.5, 4, or 24 h at a SAR of 0 (sham) or 2.0W/kg (Bellier et al. [98]). Positive controls were provided and worked properly. The exposure was carried out blind. No effects were detected in the expression levels of cytokines (GM-CSF, IFN- γ , IL-1 β , IL-6, IL-10, TNF- α) and total ST proteins (CREB, JNK, NF- κ B, p38, ERK1/2, Akt, p70S6k, STAT3, STAT5) for all the experimental conditions examined, except for IL-6 after exposure to GSM modulation, where a slight difference compared to sham exposed samples was detected ($P = 0.042$), but no difference between exposed and sham exposed samples for any exposure condition remained following adjustment for multiple comparisons.

Tuysuz et al. [99] investigated exposure to 2100 MHz, 1.12 ± 0.18 W/kg SAR, on viability, apoptosis, and gene expressions in human glioblastoma cells (U118-MG) following different exposure durations.

The exposure system was designed and manufactured to expose cell cultures in a controlled environmental and electromagnetic conditions. It was placed inside a CO₂ incubator to maintain optimal cell culture conditions in terms of temperature, CO₂ and humidity.

Cell viability was assessed by applying a colorimetric assay. Apoptosis was measured by flow cytometry (Annexin V/Propidium Iodide assay). Early apoptotic cells were identified as Annexin V positive and PI negative (AnnexinV⁺/PI⁻), whereas late apoptotic cells exhibit Annexin V/PI double positive (Annexin V⁺/PI⁺). Gene expression was examined by Quantitative Real-Time Polymerase Chain Reaction (qRT-PCR) by evaluating the mRNA expression levels of Caspase 3 (CASP3), Caspase 8 (CASP8), Caspase 9

(CASP9), BCL2, BAX, CYCLIN D1 (CYCD1), cMYC, cFOS, and glyceraldehyde 3 phosphate dehydrogenase (GAPDH).

For each endpoint, three independent experiments were carried out blinded and for each experiment four cultures were set up to test sham condition and three RF exposure durations: 1, 24 and 48 h. No effect was detected for all the endpoints investigated when RF was given for 1 or 24 h.

On the contrary, 48 h RF exposure induced a statistically significant decrease of cell viability compared to sham exposed controls ($p < 0.01$). Apoptotic activity also resulted increased ($p < 0.01$) for both early and late apoptosis.

The expression of the selected proliferative and apoptotic genes did not change after 1 h exposure, but a significantly upregulation was detected after 24 h exposure, with more than a two-fold increase in CASP3, CASP8, CASP9, and BAX levels compared to the sham controls and the most notable effects were observed after 48 h exposure ($p < 0.001$).

Cantu et al. [100] investigated whether a transcriptional response occurs in neurons following exposure to RF, under both thermal and nonthermal conditions (Cantu et al, 2024). To this purpose, rat primary hippocampal neurons (PHNs) were subjected to a single (one-time) or a multiple (3-times, once a day) 1 h exposure to 3 GHz, continuous wave, at 0.57 or 5.91 W/kg SAR, which induced a temperature increase of about 0.3 °C or 3.6 °C, respectively.

By performing high throughput RNA sequencing, the authors analyzed the expression level of 14,348 genes at three specific time points (0, 4, and 24 h) post-exposure (three independent experiments). Only a small number of genes with more than a twofold change in gene expression were significantly different from the sham samples ($p \leq 0.05$) when the higher exposure conditions were tested, inducing a significant temperature increase, reaching up to 3.6 ± 0.6 °C. However, since the expression of these genes was not significant at 24 h post exposure, and reverted to baseline at 24 h post exposure, these results suggest lack of nonthermal effects on gene expression.

In a study carried out by Uzun et al. [101] the effect of RF exposure on amniocytes of 33 pregnant women was investigated by examining the changes in the expression of genes related to signal transduction and neurogenesis.

For each experiment, 4 cell cultures were assessed to test the following conditions: unexposed control, sham-exposure, exposure at 1800 MHz, 0.89 W/kg SAR and exposure at 2100 MHz, 2.73 W/kg at SAR. RF was given 2 h per day for seven days.

Wingless-related integration site (Wnts) are secreted factors associated to neurogenesis that regulate cell growth, motility, and differentiation during embryonic development. Several genes with significant roles in various stages of

the Wnt signaling pathway were examined (HES1, Neurod1, Neurod2, Neurog1, and Neurog2) by employing real-time PCR. The results showed that a significant increase was detected for all of them following exposure to 2100 MHz ($p < 0.001$), without affecting cell morphology and cell number.

RF-EMF and Sham exposure were not concurrent; in addition, it is not clear if for each experimental condition the results are reported for all the 33 donors.

Martin et al. [102] evaluated the effect of exposure to 60 GHz on two primary cultures of keratinocytes (HEK and NHEK) and one keratinocyte derivate cell line (HaCaT). The exposure was 3 h long at incident power density of 20 mW/cm². Since the exposure induced a temperature increase of about 3 °C, for each experiment cultures experiencing the same increase were also included (heath shock control). The expression of selected genes was evaluated using the Bulk RNA Barcoding and sequencing (BRB-seq) technology. The effect of exposure was quite similar and very modest: by comparing cultures sham exposed, exposed and heath shock controls the gene expression varies marginally depending on the cell model, with respectively 0, 4, and 14 modified genes for NHEK, HEK and HaCaT cells, respectively. All modified genes were linked to the thermal effect. A second set of experiments was carried out on HaCat cells exposed for 3 h at incident power density of 5, 10 and 20 mW/cm². 34 genes were found to be significantly differentially expressed, and a functional analysis revealed a significant association with response to heat, demonstrating that the main observed effect is the heat effect.

In a third set of experiments HaCaT cells were exposed for 14 h to 10 mW/cm². Also in this case, no effect was detected.

Altogether, these results show a lack of athermal effect on keratinocytes exposed up to 20 mW/cm².

Romeo et al. [103] conducted a systematic review with a narrative synthesis on the genotoxicity of RF EMF on mammalian cells *in vitro*, according to a protocol published in advance. The deviations from the protocol are reported in the paper. The guidelines provided by the National Toxicology Program-Office of Health Assessment and Translation (NTP-OHAT) were followed, adapted to the evaluation of *in vitro* studies. The authors identified 159 articles eligible for inclusion and from the extracted data 1111 experiments were identified (defined as independent specific combinations of diverse biological and electromagnetic parameters). A range of different outcomes were summarized, including DNA strand breaks, micronuclei, 8-hydroxy-2-deoisguanosine adducts, chromosomal aberrations, sister chromatid exchange, aneuploidy, spindle disturbances, mutations and chromatin condensation. Limitations of the evidence included the frequent reporting of findings in graphical display only, and the large heterogeneity of experimental data, which precluded a *meta*-analysis. The authors reached an overall assessment of “low” confidence in the evidence that RF EMF induces genotoxic effects in mammalian cells. However, 80% of experiments reviewed showed no effect of RF exposure, independently of the exposure features, level, and duration (moderate evidence of no effect). Therefore, they

concluded that the analysis of the included papers, although only qualitative, suggests that RF exposure does not increase the occurrence of genotoxic effects *in vitro*.

4.4.3 Conclusions on RF cell studies

Two comprehensive systematic reviews, commissioned by WHO, were published on oxidative stress and male fertility, including animal and *in vitro* studies (see section 4.3). Concerning male fertility, 10 papers on human sperm exposed *in vitro* were included. They indicated a small detrimental effect of RF-EMF exposure on vitality and no-effect on DNA/chromatin alterations. A very low certainty was attributed to these results (Cordelli et al., 2024).

The systematic review on oxidative stress (Meyer et al, 2024) considered 11 *in vitro* studies in which cells were exposed to a frequency range between 800 and 2450 MHz. The results reported an inconsistent increase in biomarkers for oxidized DNA bases. A third systematic review showed no effects on genotoxicity (Romeo et al., 2024).

As in previous years, there is a large variety of endpoints, cell types and exposure parameters investigated with results difficult to compare. The additional fourteen 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

Outcome	Reference	Cell type	Exposure conditions	Effect
Cytotoxicity and genotoxicity.	Massaro et al. (2024)	Human dermal fibroblasts (HDF) n = 2-3 or not reported	1600 MHz, CW and PW 0.4 W/kg ; 2 h	No effect on cell cycle, cell morphology and genotoxicity. Slight ↑ or ↓ in the expression of some HSPs and phospho-AKT. Some modifications of cytoskeletal organization and number of lysosomes for both CW and PW exposure.

DNA stability (comet assay)	Worel et al. (2024)	Astrocytoma cell line n = not clear	1950 MHz, UMTS 0.25, 0.50, 1 W/kg 16 h Co-exposure to 4NQO, BPDE, CrO ₃ and NiCl ₂ (simultaneous and sequential)	↓ in DNA damage after exposure at 0.25 W/kg. No effects for all the other exposure conditions and co-exposure protocols.
DNA damage (comet assay); protein expression	Sannino et al. (2024)	Human neuroblastoma cell line (SH-SY5Y) n = 3-4	1950 MHz, UMTS 0.3 and 1.25 W/kg 3, 10, 20 h, 1h/day for 3 days Co-exposure to MD (after RF)	No effect of RF alone. ↓ of MD-induced DNA damage for all the conditions tested; No effect on protein expression at 1.25 W/kg for 3 h
Proliferation, cell cycle, apoptosis, DNA damage, ERK signal pathway	Goh et al. (2024)	Human adenocarcinoma (HeLa) cells, Human hepatocellular carcinoma (Huh7) cells, Human adipose-derived stem (ASCs) cells, B103 rat neuroblastoma n = 3	1700 MHz LTE 0.4 - 8 W/kg 24 or 72 h	No effects. Increased cell proliferation at 8W/kg due to thermal effects
Signal transduction and protein and cytokine expression	Bellier et al. (2024)	Differentiated human-derived monocytic (THP-1) cells n = 3-6	1800 MHz CW and GSM 2 W/kg 0.5, 4 and 24 h	No effects.
Viability, apoptosis	Tuysuz et al. (2024)	Human glioblastoma (U118-MG) cells n = 3	2100 MHz 1 W/kg 1, 24 and 48 h	No effect following 1 and 24 h exposure; ↓ in viability and ↑ in apoptosis after 48 h exposure.

Gene transcription	Cantu et al. (2024)	Rat primary hippocampal neurons n = 3	3 GHz 0.57 and 5.91 W/kg 1 h and 1 h three times/day	Slight change in gene expression due to T° increase, reverted after 24 h
Gene expression	Uzun et al. (2024)	Amniocytes of 33 pregnant women	1800 MHz 0.89 W/kg 2100 MHz 2.73 W/kg 2h/d for 7 days	↑ in genes related to Wnt signaling pathway in cells exposed to 2100 MHz
Gene expression	Martin et al. (2024)	Human keratinocytes (HEK, NHEK and HaCaT cells) n = 3-6	60.4 GHz 5, 10, 20 mW/cm ² 3 h or 14 h	No athermal effect

Abbreviations: ↓: decrease; ↑: increase; BPDE: Benzo(a)pyrene diol epoxide; CrO₃: Chromium trioxide; CW: Continuous wave; ERK: extracellular signal-regulated kinases; HSP: heat shock proteins; LTE: Long-Term Evolution; MD: menadione; MN: micronuclei; NiCl₂: Nickel chloride; 4NQO: Nitroquinoline 1-oxide; phospho-AKT: protein-kinase B. PW: pulsed wave; Wnt: Wingless-related integration site

Studies excluded from analysis

Harmonised inclusion/exclusion criteria for report

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. 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.

Excluded epidemiological studies

Alharbi et al. [104]	2A
Ben Ishai et al. [105]	1H
Besset et al. [106]	1G
Bevington et al. [107]	1E
Brosnan et al. [108]	1A
Cao et al. [109]	2A
Costa et al. [110]	1D
D'Adamo et al. [111]	2A
Dart et al. [112]	1B
Dieper et al. [113]	1D
Eicher et al. [114]	1G

Gharib et al. [115]	2B
Gulati et al. [116]	2B
Hardell et al. [117]	1E
He et al. [118]	2D
Jayaraju et al. [119]	1G
Jha et al. [120]	2B
Karamazi et al. [121]	2A
Kavoussi et al. [122]	1H
Khabarova et al. [123]	1A
Kojimahara et al. [124]	1G
Koohestanidehaghi et al. [125]	1H
Malavolti et al. [126]	1G
Malvandi et al. [49]	2E
Markovska et al. [127]	1J
Molua et al. [128]	1H
Prins et al. [61]	2A
Saroch et al. [129]	1G
Sharma et al. [130]	2B
Shen et al. [131]	1H
Simson et al. [132]	1H
Söylemez et al. [133]	2B
Taton et al. [134]	1G
Thoradit et al. [135]	1E
Vemula et al. [136]	1G
Wdowiak et al. [137]	1H
Yamaguchi-Sekino et al. [138]	1G
Yuasa et al. [139]	2A
Zhang et al. [140]	2A
Zhou et al. [141]	2B

Excluded Human studies

ELF

Rathebe et al. [142]	Non-systematic review; conference proceeding
Weerasinghe et al. [143]	Non-experimental; major flaws in study design (e.g., selection of study population; control condition; dosimetry)

RF

Calvente and Nunez [144]	Non-systematic review
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Dale et al. [145]	Study design: not randomized, unbalanced
Eskandani and Zibaii [146]	Non-systematic review
Omid et al. 2024 [147]	Non-systematic review
Rok et al. [148]	Missing information on blinding; lack of sham control
Sousouri et al. [149]	Preprint server, not yet peer reviewed

Excluded Animal studies

ELF

Reference	Reason for Exclusion
Degtyarevskaya et al. [150]	Lack of information on exposure conditions
Krzystolik et al. [151]	Not controlled exposure conditions
Krzystolik et al. [152]	Not controlled exposure conditions
Li et al. [153]	Theranostic
Nicolazo et al. [154]	Uncontrolled exposure conditions, no sham exposure
Sissons et al. [155]	Low number animal for each group
Styazhkina et al. [156]	Irrelevant Exposure (1.7 MHz)

RF

Reference	Reason for exclusion
Zhou et al. [157]	1.j
Toribio D, Thielens A. [158]	1.b
Cho et al. [159]	4.c
Zahmatkesh et al. [160]	4.c
Xin et al. [161]	1.j
Vilić et al. [162]	4.c
Tripathi et al. [163]	1.f
Torres-Ruiz et al. [164]	1.j
Tombarkiewicz et al. [165]	4.c
Tahir et al. [166]	1.j, 4.c
Shang et al. [167]	1.j, 4.c
Seify et al. [168]	1.j
Samoylova et al. [169]	1.j

Ramalingam et al. [170]	1.j
Qin et al. [171]	1.j
Popovicova et al. [172]	1.j
Pei et al. [173]	1.j
Mohamed et al. [174]	1.j
Migdal et al. [175]	4.c
Matei et al. [176]	1.j
Krivova et al. [177]	1.j
Khira et al. [178]	1.j
Kizilçay et al. [179]	1.j
Karaman et al. [180]	1.j
Karadayi et al. [181]	4.c
Jing X et al. [182]	1.j
Jiang et al. [183]	1.j
Ibrahim et al. [184]	1.j
Hoghoughizadeh et al. [185]	1.j
Hajinejad et al. [186]	1.j
Gupta et al. [187]	1.j
Gautam et al. [188]	1.j
Gao et al. [189]	1.j, 4.c
Fatahi et al. [190]	1.j
Azimzadeh et al. [191]	1.j
Altaib et al. [192]	1.j, 4.d
Aghaa et al. [193]	1.j
Jaffar et al. [194]	1.j
Maluin et al. [195]	1.j
Koç et al. [196]	1.j
Nik et al. [197]	1.j
Zhang et al. [198]	1.j
Zhang et al. [199]	1.d
Zhang et al. [200]	1.d
Viana et al. [201]	1.d
Sun et al. [202]	1.d
Kim et al. [203]	1.d
Hernandez et al. [204]	1.d
Guo et al. [205]	1.d
Bokhari et al. [206]	1.d
Jiao et al. [207]	1.d
Jiao et al. [208]	1.d

Dione et al. [209]	1.d
Abtin et al. [210]	1.h
Dehdari et al. [211]	1.h
Dieper et al. [212]	1.h
Liu et al. [213]	1.h
Manville et al. [214]	1.h

Excluded systematic reviews

Dione et al. [215]	Misses important aspects of a systematic review; No PECO, unclear RoB assessment, no systematic assessment of the confidence in the body of evidence (like GRADE)
Assefa et al. [216]	Misses important aspects of a systematic review; No PECO, no RoB assessment, no systematic assessment of the confidence in the body of evidence (like GRADE)

Excluded Cell studies

ELF

Reference	Reason for exclusion
Cios et al., 2024 [217]	number of independent experiments not reported and exposures at room temperature

IF

Reference	Reason for exclusion
Chow et al. [218]	No dosimetry performed (1.j)
Szilágyi Z, Pintér B, Szabó E, Kubinyi G, Le Drean Y, Thuróczy G. [219]	No sham control (2.c)

RF

Reference	Reason for exclusion
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Al-Ghamdi FH et al. [220]	No Sham control; no dosimetry performed; medical device (1.j; 2.c)
Bertuccio MP et al. [221]	No Sham control (2.c)
Butković I et al. [222]	No dosimetry performed (1.j)
Byun KA et al. [223]	No Sham control; no dosimetry performed; medical device (1.j; 2.c)
Costantini E et al. [224]	no dosimetry performed; medical device (1.j)
Deena K et al. [225]	Cell phone as source of RF; no Sham control (1.j; 2.c)
Jangid P et al. [226]	Cell phone as source of RF; no Sham control (1.j; 2.c)
Jooyan N et al. [227]	No Sham control (2.c)
Keskin I et al. [228]	No dosimetry, no sham control (1.j; 2.c)
Kim et al. [229]	No dosimetry, no sham control (1.j; 2.c)
Koohestanidehaghi et al. [230]	Cell phone as source of RF; no Sham control (1.j; 2.c)
Lei M et al. [231]	No dosimetry, no sham control (1.j; 2.c)
Zahumenska R et al. [232]	No Sham control (2.c)
Žaja IŽ et al. [233]	No dosimetry. Not clear if sham is properly provided (1.j; 2.c)

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