Assessment of WHO-commissioned systematic reviews on health effects of RF-EMF

Background and Rationale

Between 2023 and 2025, a coordinated series of systematic reviews (SRs) examining the health effects of radiofrequency electromagnetic fields (RF-EMF; frequencies from 100 kHz to 300 GHz) were published in a special issue of "Environmental International" (https://www.sciencedirect.com/special-issue/1092DR596MG). Conducted by over 80 international scientists and accompanied by detailed protocols, the SRs provide a transparent evidence base to inform global health risk assessments and policy development. The SRs were commissioned and overseen by the World Health Organization (WHO) as part of its ongoing assessment of health risks from human exposure to electromagnetic fields (EMF). This work builds on the WHO's Environmental Health Criteria (EHC) Monograph series with the last comprehensive update on RF-EMF relevant to mobile communication systems published in 1993 (WHO EHC Monograph No. 137). Following the establishment of the "International EMF Project" (https://www.who.int/initiatives/the-international-emf-project) and the reintroduction of RF-EMF to the WHO's research agenda in 2010 (WHO research agenda for radiofrequency fields, 2010), this SR project was initiated to update the evidence base. Conducted in line with WHO's *Handbook for Guideline Development*, the SRs adhere to high standards of methodological rigour, transparency, and independence.

The approach to develop the scientific basis for the updated EHC Monograph and the development of these SRs followed a structured, three-step approach, designed to ensure comprehensive and focused evidence synthesis (Verbeek et al., 2025). The prioritisation of relevant health topics for assessment by SRs was informed by a survey conducted by the WHO in 2018, which polled over 300 invited researchers on their anticipated public concerns (Verbeek et al., 2021). The most relevant health-related topics for an evaluation by SRs were identified: RF-EMF experts rated cancer, heat-related effects, male fertility and reproductive outcomes, adverse birth outcomes, electromagnetic hypersensitivity, cognitive impairment, adverse pregnancy outcomes and oxidative stress as outcomes most critical regarding RF EMF exposure (Table 1). This prioritisation of health topics was the basis for the 10 SRs subjects published as an open call by the WHO. They comprise the assessment of human observational and experimental studies as well as in experimental animal and cell studies, for which international research teams were able to apply for conducting SRs on these topics. It resulted in the publication of twelve SRs, which are now available in Environment International's special edition, accompanied by an overview of strategic considerations, methodological procedures and findings by the organisers and editors (Verbeek et al., 2025). These SRs provide an up-to-date evidence synthesis on RF-EMF health effects, serving as the scientific foundation for WHO's ongoing risk assessment and the forthcoming EHC Monograph update.

Table 1: Overview of health subjects of the WHO-commissioned SRs

Topics of WHO survey	**WHO-commissioned SRs**	**SR in Environmental International**
Cancer	SR1 – Cancer (human observational studies)	Karipidis et al., 2024 Karipidis et al., 2025
	SR2 – Cancer (animal studies)	Mevissen et al., 2025
Adverse pregnancy and birth outcome	SR3 – Adverse reproductive outcomes (human observational studies)	Johnson et al., 2024 Kenny et al., 2024

	SR4 – Adverse reproductive outcomes (animal and in vitro studies)	Cordelli et al., 2023 Cordelli et al., 2024
Cognitive impairment	SR5 – Cognitive impairment (human observational studies)	Benke et al., 2024
	SR6 – Cognitive impairment (human experimental studies)	Pophof et al., 2024
Electromagnetic hypersensitivity	SR7 – Symptoms (human observational studies)	Röösli et al., 2024
	SR8 – Symptoms (human experimental studies)	Bosch-Capblanch et al., 2024
Oxidative stress	SR9 – Effect of exposure to RF on biomarkers of oxidative stress	Meyer et al., 2024
Heat-related effects	SR10 – Effect of exposure to heat from any source on pain, burns, cataract and heat-related illnesses	Commissioned but not completed

Summary, conclusions, and relevance for human health

The twelve SRs evaluated the scientific evidence of numerous endpoints related to human health topics of concern (Table 1). The number of studies included in each SR varied substantially, ranging from five studies on cognitive function in human observational research to 215 studies on fertility in animals. Carcinogenicity of RF-EMF exposure was addressed in two SRs on human observational studies (Karipidis et al., 2024, Karipidis et al., 2025), and in one SR in laboratory animals (Mevissen et al., 2025). Four SRs addressed the topic of fertility and reproduction, either evaluating human observational studies from the female (Johnson et al., 2024) or male (Kenny et al., 2024) perspective or experimental data on animals and *ex vivo* human sperm (Cordelli et al., 2023, Cordelli et al., 2024). The impact of RF-EMF exposure on human cognition was analysed in two SRs, focusing on observational (Benke et al., 2024) and experimental (Pophof et al., 2024) studies. Two SRs reported on subjective symptoms related to human well-being, based on observational (Röösli et al., 2024) and experimental (Bosch-Capblanch et al., 2024) human studies. In relation to cancer, and also associated to other health topics, oxidative stress markers were at last systematically evaluated for experimental *in vivo* and *in vitro* data (Meyer et al., 2024).

The main findings and conclusions of these SRs are summarised elsewhere (BAFU, BfS). In a nutshell, the SRs on the available human observational studies on cancer, cognition, reproduction and symptoms have not hinted towards potential adverse health impacts of exposure. For the majority of endpoints, however, the available data are limited, and the confidence in the evidence is generally low (Karipidis et al., 2024, Karipidis et al., 2025, Benke et al., 2024, Johnson et al., 2024, Kenny et al., 2024, Röösli et al., 2024). However, for tumours of the brain and head region associated with near-field exposure, the evidence was judged to provide moderate confidence in an absence of an effect. Thus, adverse health impacts of RF-EMFs are not readily discernible in epidemiological studies, reflecting real-life exposure of the general and working populations.

The conclusions of the SRs on observations from human experimental studies and animal studies were more ambivalent, which might be due to prolonged and higher levels of exposure than for the general population typically assessed in observational studies. RF-EMF exposure in humans did not impact volunteers' symptoms, such as headache and most cognitive parameters, with moderate or high confidence in the evidence (Bosch-Capblanch et al., 2024, Pophof et al., 2024). Nevertheless, there were some indications of effects on specific cognitive tasks, albeit with low or very low confidence in the evidence. Similarly, *ex vivo* exposure of human semen has been observed to result in an inconsistent negative impact on sperm quality, yet having assigned low confidence in the evidence (Cordelli et al., 2024). The results of animal experiments on reproduction revealed some evidence, assigned with moderate confidence, for an increased risk that male animals may fail to reproduce and for reduced birth weight following exposure of females. With regard to other reproductive parameters, including fertility and brain development of the offspring, no adverse effects were reported with high

or moderate confidence (Cordelli et al., 2023, Cordelli et al., 2024). However, for a considerable number of the analysed endpoints, the available data is limited, and the confidence in the evidence is low. This renders a firm conclusion about RF-EMF effects on animal reproduction challenging and hampers also the translation of the findings in animals to human reproduction, for which no adverse effects were put forward in observational studies on the general and working population (Johnson et al., 2024, Kenny et al., 2024).

The findings and conclusions of the cancer-related SRs differ between observational human and animal experimental studies, thereby leaving some uncertainties regarding the carcinogenic impact of RF-EMF. As demonstrated by studies conducted in laboratory animals, an elevated incidence of heart schwannomas and gliomas, in addition to tumours of other organs, has been documented. The evidence supporting these findings has been categorised as either high or moderate confidence, as outlined in the SR by Mevissen et al. (2025). It is important to note that these conclusions are based on the findings of two large chronic bioassays conducted by the NTP and the Ramazzini institute (see BERENIS special NL, November 2018). This topic requires further consideration to evaluate potential human health impact, taking into account the direct translation of animal cancer to humans and the utilisation of experimental RF-EMF doses commonly used in toxicological approaches. There is an absence of compelling evidence to suggest that animal models are not a rational basis for potential effects in humans. However, it is imperative to consider the nature of exposure (local or whole body), as well as the duration and intensity of exposure, when translating the effect sizes into cancer risk in humans. In this regard, a mechanistic understanding of the mode of action of RF-EMF, which is typically investigated in cell studies, would be advantageous in evaluating its impact on human health. Yet, a recent SR conducted independently from the WHO initiative pointed with moderate confidence towards no impact of RF-EMF exposure on genotoxicity, which is a well-established driver of mutagenesis and thereby cause of carcinogenesis (Romeo et al., 2024). Concerning carcinogenesis, the SR on oxidative stress markers in animal and cell studies provides evidence that is difficult to rely on. This is because it was mostly rated with low and very low confidence for both a trend towards oxidative stress, for instance in the blood, testis and thymus of rodents, and no consistent changes in other tissues and cell types (Meyer et al., 2024). However, it is important to acknowledge the potential limitations of the included studies, which may contribute to the observed low confidence in the evidence. These limitations include the presence of studies with numerous restrictions, as well as the extensive variety of experimental models and protocols. These studies were grouped and combined in accordance with the protocol of the SR and meta-analysis for experimental outcomes. Levels of oxidative stress markers are subject to alteration in a variety of pathologies as a consequence of response to external stimuli and the action of key cellular mechanisms. The conceptual foundation of the approach was oriented towards molecular damage in the context of cancer (DNA damage); however, it did not encompass considerations such as the experimental purpose, the persistence of oxidative stress, and the functional consequences even though the latter ones were assessed in several studies. It is imperative to acknowledge the significance of these points in determining the biological relevance. However, it is equally crucial to recognise the challenges associated with their incorporation into a SR.

Does the data and study quality allow for firm conclusions about health impact?

While the overall SR project demonstrated scientific quality and transparency, the limitations of the existing primary studies meant that the certainty of evidence for many key outcomes remained low or very low. The methodological quality and completeness of available data generally did not permit firm conclusions regarding the health impacts of RF-EMF exposure across most investigated endpoints. All

twelve SRs reported constraints related to either an insufficient number of studies or methodological weaknesses in existing research, both of which limit the strength of the conclusions that can be drawn. BERENIS concurs with the authors' observations that the frequent methodological limitations documented for the included studies, often involving failures across two or more quality criteria, challenge the certainty of the assessment and the formulation of firm conclusions regarding the potential health effects of RF-EMF exposure. Consequently, despite the existences of numerous studies on RF-EMF effects, many of them are found to be lacking scientific rigour. Such limitations are not only confined to the body of literature assessed in these SRs, but are a pervasive issue in research, particularly in the field of EMF-related topics, where the distinction between thermal and non-thermal effects, along with the establishment of appropriate exposure metrics, are paramount. The reliability of observational studies may be compromised by misclassification resulting from retrospective exposure assessment by proxies. Conversely, insufficiency in the study design and exposure characterisation is a prevalent limitation of experimental studies, resulting in downgrading of the confidence in the evidence (GRADE assessment).

Besides the limitations of the existing primary research, it is necessary to consider the constraints of the SR approach regarding the assessment of the certainty and quality of a body of evidence (GRADE assessment). For this SR project a harmonised approach was used to assess the level of evidence, to ensure that the methods were as similar as possible across the different SRs. In a 2016 publication in Environment International, experts in SR methodology asserted that while the GRADE framework offers many advantages for evidence assessment, it requires further refinement and methodological adaptions to be fully applicable in environmental research. Particularly for studies of cancer in animals, meta-analysis was deemed inappropriate primarily because of substantial methodological and biological heterogeneity between the studies, including differences in animal models (species, genetic modifications, diet, housing conditions), exposure characteristics (far- versus near-field, modulation), and key experimental parameters (onset, timing and duration of exposure, and type of exposure system). Hence, the SR methodology needs refinement to include the evaluation and integration of evidence from human, animal, *in vitro*, and *in silico* studies when determining whether an environmental factor represents a potential health risk. To date, the guidelines have not yet been adapted. However, there are proposals on changing the assessments in the "*Report on Carcinogens",* which is part of the National Toxicology Program. These proposals include incorporating sensitivity issues in the risk of bias evaluation.

The SRs also dealt differently with studies judged to suffer from biases and limitations when it came to meta-analyses, which were performed in eleven out of the twelve SRs. A meta-analysis is recommended when studies included in a SR address a similar question, use comparable interventions and outcomes, and provide sufficient data for meaningful statistical synthesis. However, as stated above, a meta-analysis should not be performed when there is substantial heterogeneity in study design, populations, or outcomes that cannot be satisfactorily explained, or when methodological differences and biases make summary estimates misleading. The quality and number of studies included in most of the SRs were limited, and the way in which biased studies were handled may have influenced the overall conclusions. This issue must be given due consideration in the forthcoming evaluation of the health implications for humans, which will be informed by the systematic collection and assessment of the current body of literature by these SRs.

BERENIS's overall evaluation of the extant evidence, as presented and analysed in the SRs, is that it is insufficient and too ambivalent to draw firm conclusions about human health impacts of RF-EMF. This is partly due to the SR methodology employed, which has been designed for clinical studies to assess the advantage of a new treatment. Conversely, although high-confidence findings in the SRs of human

observational studies are lacking, there is hardly any indication for substantial health impacts by RF-EMF exposure in healthy individuals, suggesting that the regulatory measures offer a precautionary level of protection.

Are there more vulnerable people?

The current scientific data available does not allow for the drawing conclusions about the existence of more sensitive and vulnerable individuals when compared to the general population. To date, the analysis of observational and experimental data from electromagnetic hypersensitive and multiple sclerosis patients did not advance our understanding (Bosch-Capblanch et al., 2024, Röösli et al., 2024). Observational studies generally include data from the entire population. It is therefore unlikely that a small, highly vulnerable subpopulation would have a significant impact on the overall public health, especially if the genetic, physiological or disease-based predispositions are not identified. *Vice versa*, an effect in this subpopulation may have been masked, using this study design. SRs on observational human studies did predominantly not allow for stratification by vulnerability or demography (Karipidis et al., 2024, Kenny et al., 2024, Karipidis et al., 2025), while the SR on cognition included predominantly studies on children and only one study on elderly people (Benke et al., 2024). Similarly, human experimental studies on cognition mostly assessed children and adolescents, who are widely regarded as more vulnerable. Notably, only a single study on elderly people has been described (Pophof et al., 2024). Thus, it is challenging to draw conclusions about the vulnerability of subgroups, and there is a particular lack of data for older individuals. It is important to note that the insights derived from human experimental studies often lack generalisability, as these studies typically involve healthy and young volunteers.

In toxicology, developing organisms, such as foetuses and children, are recognised as being particularly vulnerable. In this context, the assessment of birth outcomes in human observational (Johnson et al., 2024) and experimental animal (Cordelli et al., 2023) studies is meaningful. A number of studies have been conducted on the effects of RF-EMF exposure on the general public and in the occupational settings. These studies have not identified any impact on foetal development, birth weight or premature birth. In contrast, there is evidence with moderate confidence for a reduced birth weight in laboratory mammals and with low confidence for an impact on the development of embryos and the neural system of the offspring. Yet, it remains unclear whether the RF-EMF exposure directly affects foetal development or acts indirectly through maternal changes. At this time, the possibility cannot be discounted that RF-EMF exposure has an impact on foetuses. Consequently, pregnant females and their unborn offspring should be considered a potentially vulnerable group.

Knowledge gaps and directions of future research

The authors of each SR provided commentary on the implications of their results and conclusions for future research. Overall, there was a common demand that more research is needed, especially studies of higher quality. BERENIS concurs with these statements, which concern not only the health topics addressed in these WHO-SRs but are generally observed in the body of literature on EMF-related research, being a main cause for the existing uncertainties. Although this series of SRs supports the evaluation of potential human health impacts on cancer, reproduction, cognition and well-being, many health topics remain insufficiently explored and require further research on both the experimental level and evidence evaluation by SRs. For instance, there is some, but hardly compelling evidence, for effects on the cardiovascular and immune system as well as for influences on the metabolism and

neurodegenerative processes. However, there is a need for adaption and refinement of the approach for future SRs on health-related EMF effects. This is crucial for the meaningful assessments of potential environmental health impacts, especially when including cell and animal studies but also human studies lacking homogeneity. The combination of data in a meta-analysis without consideration of homogeneity is questionable; nevertheless, this practice has been adopted by most of SRs, despite the possibility of a narrative synthesis approach in accordance with the OHAT SR methodology. It is evident that SRs serve as a potent instrument for evaluating the body of evidence. Yet, it is essential to recognize the fundamental principles and the knowledge of toxicology, which remain highly relevant and should not be overlooked.

BERENIS emphasised that for the majority of research and health topics, there is a necessity for well-conducted mechanistic investigations to facilitate a more profound comprehension of the impact of RF-EMF exposure on the molecular level. This is ultimately required to achieve a comprehensive understanding of the potential impact on human health. This also holds true for the health topic "cancer", for which the conclusions of the WHO-SRs differ between human observational and animal studies (Karipidis et al., 2024, Karipidis et al., 2025, Mevissen et al., 2025). This discrepancy necessitates heightened scrutiny and further research to elucidate the underlying implications. However, in order to advance our understanding, it is essential that these investigations are conducted in a way that minimises study limitations and biases, thus avoiding further uncertainties and concerns as raised in the WHO-SRs. Apart from mechanistic and toxicological investigations that address both thermal and non-thermal influences, as well as current and forthcoming technologies, the health impacts of RF-EMF exposure need to be continuously monitored by observational studies on cancer but also other health topics. The primary focus should be on the conduct of prospective studies of long-term exposure of the general public, as well as the working population. These studies should involve improved exposure assessments, as recommended in several SRs (Johnson et al., 2024, Karipidis et al., 2024, Kenny et al., 2024, Röösli et al., 2024, Karipidis et al., 2025).

BERENIS recommendations for precautionary and regulatory measures

As previously stated in special newsletters, BERENIS underpins the importance of the precautionary principle, as specified in Switzerland by the "installation limit value" for emissions from stationary transmitters (e.g., mobile phone base stations and radio transmitters) in the Ordinance on Protection against Non-Ionising Radiation (NISV). Despite the tremendous effort expended on the WHO-commissioned SRs, it remains impossible to draw definitive conclusions on potential health effects of RF-EMF exposure. For a considerable proportion of the assessed endpoints, the confidence in the supporting evidence was mainly categorised as low or very low. This conclusion was drawn in particular for health impacts investigated by the SR on human experimental and observational studies. The authors posit that the prevailing low confidence in the accumulated scientific evidence is attributable to a combination of different factors. These include the paucity and/or inconsistency of findings, as well as the lack of reliable studies with few limitations and potential risk of biases. This notion is in line with the evaluations and judgement set out by BERENIS, overseeing the scientific literature of the last decade. Consequently, within the established regulatory limits, it proved impossible to definitively ascertain putative health impacts of RF-EMF exposure with high confidence. Nevertheless, a systematic collection and evaluation of the body of literature is an important step towards the health risk assessment of RF-EMF. It is evident that the multitude of biological and experimental disparities appears to be incongruent with the methodological constraints of the highly standardised SR approach, which has been designed for evaluation of clinical studies. It is a common occurrence, particularly in the context of experimental studies, that meta-analyses exhibit a paucity of biological or statistical

rationale. A wide variety of factors are combined including, but not limited to, the combination of different animal species, different strains, different sexes, different experimental models, studies targeting specific organs or cells with toxicity studies, different exposures such as pulsed with continuous fields, different frequencies, intensities and exposure duration, different study length and endpoints, different statistical analysis methods, and many more. In addition, experimental groups within studies were treated as independent when in fact there is a dependency based on a common control group, violating a fundamental assumption of the meta-analysis methods.

In respect to precautionary and regulatory measures, it also important to note that the WHO-SRs only cover a selection of previously proposed potential biological effects regarding health impacts. In addition, pooled analyses of a broad frequency range were performed in some instances, especially when occupational exposure was involved. However, the included data is dominated by RF-EMF exposure in the frequency range of 0.8-2.5 GHz, which is related to older mobile communication standards. Whether the conclusions of the SRs are extendable on the forthcoming higher frequency bands of future mobile communication standards remains speculative and poorly explored (see BERENIS special NL, May 2025). There is also a knowledge gap when it comes to potential combinatory effects with other environmental factors as well as genetic or physiological pre-conditions, which may not be readily discernible in observational and experimental studies. Despite the absence of a definitive mechanistic concept for RF-EMF impact, the potential for this to be a contributing factor within a vulnerability-stress model is conceivable. This model delineates the manner in which genetic, biological, and environmental factors interact and influence the risk and extent of stress reactions. The ability to cope with stress is determined by a combination of innate and acquired vulnerabilities, in addition to further stressful events. Consequently, in certain individuals, the most trivial overload or negligible pressure to perform can induce symptoms, while in others, it remains asymptomatic.

It is worthy to note that the authors of the WHO-commissioned SRs were encouraged to discuss the implications of their findings for practice and policy. It has been asserted by some authors that there is no need to adjust the regulatory guidelines, on the grounds that the evidence is too uncertain for informed decisions to be made at the regulatory level. Furthermore, the limitations of translating the findings from animal and cell studies to humans were emphasised. Overall, BERENIS can relate to these appraisals and recommends the consequent application of the precautionary principle and current guidelines.

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Note: All WHO-commissioned SRs, as well as the respective protocols and additional articles, can be found in the corresponding special edition of *Environment International*: https://www.sciencedirect.com/special-issue/1092DR596MG

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BERENIS - Swiss expert group on electromagnetic fields and non-ionising radiation

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List of abbreviations (pdf)