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The WHO-commissioned systematic reviews on health effects of radiofrequency radiation provide no assurance of safety

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Abstract
The World Health Organization (WHO) commissioned 12 systematic reviews (SR) and meta-analyses (MA) on health effects of exposure to radiofrequency electromagnetic fields (RF-EMF). The health outcomes selected for those reviews (cancer, electromagnetic hypersensitivity, cognitive impairment, birth outcomes, male fertility, oxidative stress, and heat-related effects) were based on a WHO-conducted international survey. The SR of the studies of cancer in laboratory animal studies was the only one that did not include a MA, because those authors considered it inappropriate due to methodological differences among the available studies, including differences in exposure characteristics (carrier frequency, modulation, polarization), experimental parameters (hours/day of exposure, duration of exposure, exposure systems), and different biological models. MAs in all the other SRs suffered from relatively few primary studies available for each MA (sometimes due to excessive subgrouping), exclusion of relevant studies, weaknesses in many of the included primary studies, lack of a framework for analyzing complex processes such as those involved in cognitive functions, and/or high between-study heterogeneity. Due to serious methodological flaws and weaknesses in the conduct of the reviews and MAs on health effects of RF-EMF exposure, the WHO-commissioned SRs cannot be used as proof of safety of cell phones and other wireless communication devices. However, the animal cancer SR, which was rated as "high certainty of evidence" for heart schwannomas and "moderate certainty of evidence" for brain gliomas, provided quantitative information that could be used to set exposure limits based on reducing cancer risk. The multiple and significant dose-related adverse effects found in the SRs on male fertility and pregnancy and birth outcome should also serve as the basis for policy decisions to lower exposure limits and reduce human reproductive risks. The report of harmful effects (e.g., cancer, reproductive toxicity, etc.) at doses below the adverse health effect threshold claimed by ICNIRP demonstrates that current exposure limits to RF-EMF, which were established by applying arbitrary uncertainty factors to their putative adverse threshold dose, lack scientific credibility.

Keywords World Health Organization, Radiofrequency radiation, Systematic review, Meta-analysis, Cancer risk, Reproductive toxicity, Oxidative stress

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Introduction

The World Health Organization's (WHO) International EMF (Electromagnetic Fields) Project, was established "to assess the health and environmental effects of exposure to static and time varying electric and magnetic fields in the frequency range 0–300 GHz" (https://www.who.int/initiatives/the-international-emf-project). This frequency range includes RF radiation (RFR) generated by modern wireless technologies such as cell phones, Wi-Fi routers, cell towers and 5G.

Twelve systematic reviews and meta-analyses (SR-MA) commissioned by the WHO on health effects of radiofrequency electromagnetic fields (RF-EMF) were published in *Environment International* between October 2023 and May 2025. This paper highlights numerous flaws, significant methodological concerns, as well as likely biases in these reviews which undermine the validity of the authors' conclusions and raises serious doubts about the suitability of most of these reviews for informing policy or risk management decisions. Yet, the reviews of experimental studies on cancer and on reproductive toxicity provide sufficient information for public health agencies to reevaluate current exposure guidelines and promote risk-reducing recommendations.

Longstanding relationship and reliance of the WHO's EMF project on the International Commission on Non-ionizing Radiation Protection (ICNIRP)

The WHO's EMF project was founded in 1996 by Michael Repacholi, who was also one of the founders of the International Commission on Non-Ionizing Radiation Protection (ICNIRP). Because of their common origins, it is not surprising that the WHO's early agendas for EMF research included substantial collaborations with members of ICNIRP (https://iris.who.int/bitstream/handle/10665/64013/WHO_EHG_98.13.pdf? sequence=1). After Repacholi retired from the WHO in 2006, Emilie van Deventer assumed the leadership of the WHO's EMF Project.

In 2010, the WHO published a new research agenda for RF-EMF which included participation by several ICNIRP members in writing that document (https://iris.who.int/bitstream/handle/10665/44396/9789241599948_eng.pdf). In 2013, the WHO announced plans to update its 1993 Environmental Health Criteria (EHC) monograph on health risks related to exposure to RFR (https://www.who.int/news-room/articles-detail/consultation-on-the-scientific-review-for-the-upcoming-who-environmental-health-criteria).

In 2019, the WHO Radiation Programme issued a call for expressions of interest from international research groups in conducting a systematic review of one or more topics that had been prioritized in an international survey (https://www.who.int/news-room/articles-detail/call-for-expressions-of-interest-for-systematic-reviews-(2019), and reiterated its intention to publish an EHC monograph on potential adverse health outcomes in relation to exposure to RFR (https://www.who.int/teams/environment-climate-change-and-health/radiation-and-health/non-ionizing/emf/research-on-radiofrequency-fields). A subsequent paper authored by Jos Verbeek (a consultant to the WHO EMF Project), van Deventer, plus five members (past/present) of ICNIRP specified that the input for this monograph was to be based on systematic reviews of the outcomes prioritized by an international survey: cancer, electromagnetic hypersensitivity, cognitive impairment, birth outcomes, male fertility, oxidative stress, and heat-related effects [1], and would include separate evaluations of the published scientific literature on observational and experimental studies. The review on heat-related effects was never conducted; this was considered to be an "important gap" since exposure limits to RF-EMF are based on heat-related adverse effects (van Deventer: https://www.youtube.com/watch?v=lelHXT3YO2w&t=2101s), A glaring deficiency in the survey [1] was the omission of categories for altered gene expression and genotoxicity. Those effects, which are precursors to numerous adverse health effects including cancer, have been shown to be induced in the preponderance of published studies on RFR [2].

After identification of the prioritized health effects, the WHO commissioned systematic reviews of those topics by selected outside groups in which all members were assessed for conflicts of interest per WHO's declaration of interests (DOI) for experts (https://cdn.who.int/media/docs/default-source/ethics/doifrmen_wlogo_blank.pdf?sfvrsn=799d694_6&download=true). The DOI was the only filter for participation in the review groups; it questioned whether the expert received any financial support from an entity or organization with an interest in the subject matter of the work, and whether the expert consulted for such an organization or made any public statements related to the subject matter. The WHO requires external experts disclose any activity that might be perceived as affecting the individual's objectivity. Because most prioritized topics have numerous publications, published protocols written by these groups before the start of the reviews specified the inclusion of MA, when appropriate, following the PRISMA guidelines [3].

The twelve WHO-commissioned systematic reviews that were published in *Environment International* are shown in Table 1. The table also notes the ICNIRP members (past or present) who participated in these SRs or participated only in writing the SR protocols. The inclusion of ICNIRP members in both the protocol and review groups confirms the strong influence that ICNIRP continues to have on the WHO's EMF Project.

Table 1 WHO-commissioned systematic reviews on health effects of RF-EMF

SR1A: Karipidis et al. [4]. The effect of exposure to radiofrequency fields on cancer risk in the general and working population: A systematic review of human observational studies – Part I: Most researched outcomes. ICNIRP: Karipidis, Baaken, Röösli, Feychting (*P*)
SR1B: Karipidis et al. [5]. The effect of exposure to radiofrequency fields on cancer risk in the general and working population: A systematic review of human observational studies – Part II: Less researched outcomes. ICNIRP: Karipidis, Baaken, Röösli, Feychting (P)
SR2: Mevissen et al. [6]. Effects of radiofrequency electromagnetic field exposure on cancer in laboratory animal studies, a systematic review. ICNIRP: Wood
SR3A: Kenny et al. [7]. The effects of radiofrequency exposure on male fertility: A systematic review of human observational studies with dose–response meta-analysis. ICNIRP: Feychting (P)
SR3B: Johnson et al. [8]. The effects of radiofrequency exposure on adverse female reproductive outcomes: A systematic review of human observational studies with dose–response meta-analysis. ICNIRP: Feychting (P)
SR4A: Cordelli et al. [9]. Effects of radiofrequency electromagnetic field (RF-EMF) exposure on male fertility: A systematic review of experimental studies on non-human mammals and human sperm in vitro. ICNIRP: Marino, Wood
SR4B: Cordelli et al. [10]. Effects of radiofrequency electromagnetic field (RF-EMF) exposure on pregnancy and birth outcomes: A systematic review of experimental studies on non-human mammals. ICNIRP: Marino, Wood
SR5: Benke et al. [11]. The effects of radiofrequency exposure on cognition: A systematic review and meta-analysis of human observational studies. ICNIRP: Karipidis, Feychting (P)
SR6: Pophof et al. [12]. The effect of exposure to radiofrequency electromagnetic fields on cognitive performance in human experimental studies: Systematic review and meta-analyses. ICNIRP: Pophof, Kuhne
SR7: Röösli et al. [13]. The effects of radiofrequency electromagnetic fields exposure on tinnitus, migraine and non-specific symptoms in the general and working population: A systematic review and meta-analysis on human observational studies. ICNIRP: Röösli, Feychting (P)
SR8: Bosch-Capblanch et al. [14]. The effects of radiofrequency electromagnetic fields exposure on human self-reported symptoms: A systematic review of human experimental studies. ICNIRP: Röösli, Oftedal (P)
SR9: Meyer et al. [15]. The effects of radiofrequency electromagnetic field exposure on biomarkers of oxidative stress in vivo and in vitro: A systematic review of experimental studies. ICNIRP: Kuhne

(P) participated only in writing the systematic review protocol

Our evaluation of the WHO's SRs and the conclusions reached by the authors of those reviews are addressed in the following sections: (1) potential biases among working group authors, (2) inclusion/exclusion of studies, (3) adequacy of the designs of the included studies and conduct of the systematic reviews, (4) meta-analyses, and (5) risk of bias and gradings of certainty.

Criticisms of the WHO-commissioned systematic reviews

Potential biases among working group authors

The extensive involvement of present and past members of ICNIRP in the development of the protocols and/or the SRs raises serious concerns regarding potential bias in these SR-MAs. All of the commissioned working groups had at least one ICNIRP member and some had several members (Table 1). For example, for the SR-MAs of human observational cancer studies there were three ICNIRP members. In addition, two ICNIRP members were in multiple groups (Röösli was a co-author of 4 SRs and Karipidis 3 SRs).

Because ICNIRP has long maintained that increased tissue temperature was the only established health effect of this form of radiation, and that "there is no evidence of adverse health effects at exposure levels below the restriction levels in the ICNIRP's 1998 guidelines" [16], the affiliation with ICNIRP may have influenced those reviewers' objectivity in grading and interpreting the results of their analyses. Furthermore, the Radiation and Health Unit of the WHO (https://www.who.int/news-room/questions-and-answers/item/radiation-electromagnetic-fields) held the same opinion as ICNIRP [16].

As part of their critique of the SR on effects of RF-EMF on pregnancy and birth outcomes in experimental animals by Cordelli et al. [10], Nordhagen and Flydal [17] described the extensive participation of ICNIRP-affiliated experts in the WHO's International EMF Project. The flaws in that SR identified by Nordhagen and Flydal [17] "skew the results in support of the review's conclusion that there is no conclusive evidence for nonthermal effects."

A disadvantage of commissioning self-selected working groups to write these SR-MAs is that prior associations are susceptible to "groupthink" bias [18]. This can occur when a tightly knit group of individuals prioritizes a previous interpretation of the data rather than considering alternative possibilities. This situation has been described by Lin [18] for the situation in which ICNIRP, a self-appointed group, dismissed positive cancer findings from experimental and human observational studies [16].

Another concern for the usefulness of the reviews is ICNIRP's ties to major economic industries (telecommunications, military) that have financial interests in exposure standards for RF-EMF. These ties have been described by members of the European Parliament as "conflicts of interest, corporate capture and the push for 5G" (https://ehtrust.org/wp-content/uploads/ICNIRP-report-FINAL-JUNE-2020.pdf), https://www.spandidos-p

ublications.com/https://doi.org/10.3892/ijo.2017.4046). Numerous analyses have found that sources of funding can impact the design and conclusions of health effects studies, including those on effects of nonionizing EMF [19–22]. Industry ties with some authors of the SRs are shown in Supplementary File S1 ("Examples of Working Group Authors' Ties to Industry").

Because the SR-MAs are expected to form the basis for the EHC monograph and could impact international exposure standards for exposures to RF-EMF, it is critical that those reviews be performed in an unbiased manner and without serious methodological flaws. This is critically important for RF-EMF since current exposure limits are based on inadequate experimental studies [23]. As stated by Lin [18], a previous member of ICNIRP, "Biases can impair rational judgment and lead to poor decisions." This cautionary comment should have been followed by the WHO when commissioning working groups to perform these SR-MAs. However, these concerns might have been overlooked by the WHO because of the common origin and longstanding interaction between the WHO's EMF Project and ICNIRP, and because four present or past ICNIRP members were involved in planning these reviews [1].

Inclusion/exclusion criteria

Across multiple reviews, there were issues in the inclusion and exclusion criteria which led to the exclusion of relevant, well-conducted studies, while flawed studies were given disproportionate weight, thereby undermining the reliability of the evidence assessments. Highlighted below are select examples which illustrate the failings in the selection of studies.

SR1A: RF-EMF exposure and human cancer. Although this systematic review [4] did not exclude any relevant studies, it relied heavily on the Danish cohort study [24–26] which the International Agency for Research on Cancer (IARC [27]), judged to be uninformative because exposure was based on subscriptions to mobile phone providers as a surrogate for mobile phone use: the study "lacked information on level of mobile-phone use and there were several potential sources of misclassification of exposure." Thus, the exposure proxies used in that study do not provide reliable measures of brain cancer risk.

SR1B: Effect of RF-EMF exposure on less researched human cancers. This SR [5] covered papers published from 1988 to 2019. SR1B did not have sufficient information for any specific neoplasm to perform dose–response MA for either cumulative call time or cumulative number of calls. Nor did it have sufficient studies to perform MA on the intensity or duration of occupational exposures. Because the cutoff for this review was five years prior to its publication, the authors mentioned three studies published since 2020, but dismissed their importance. Yet, one of those studies was the UK Biobank prospective cohort study of 431,861 participants [28], which found statistically significant associations between mobile phone use and higher risks of incident overall cancer and nonmelanoma skin cancer in men and women, urinary tract cancer and prostate cancer in men, and vulva cancer in women. Also, the authors of SR1B did not address other relevant studies published since 2019. For example, Luo et al. [29] found that mobile phone use was significantly associated with thyroid cancer when some genetic variants were present, and the association increased when mobile phone use duration and frequency increased, indicating that genetic susceptibility may modify the association between cell phone use and thyroid cancer risk.

SR5: Effects of RF-EMF exposure on cognition in human observational studies. This systematic review was based on only five studies that met the review's inclusion criteria [11]. The MAs in this SR were based on only two of those studies. With so few studies, the cross-sectional literature could have been included in the review, with each paper assessed for risk of bias on its own merits. SR5 excluded the most comprehensive longitudinal study conducted thus far, which followed children in schools for 10 years [30], and reported significant negative effects (reaction time to light and sound, phonemic perception, detection of sound signals, arbitrary attention and semantic memory, muscle fatigue and working muscle capacity) in children and adolescents due to increases in mobile phone exposure over time.

SR6: Effects of RF-EMF on cognitive performance in human experimental studies., Studies that investigated the effects of RF-EMF on cortical activity alongside cognitive functions should not have been excluded. Cortical effects, e.g., changes in electroencephalography (EEG) (e.g [31, 32]), which are more apparent than effects on cognitive abilities, demonstrate that RF-EMF affects brain activity.

SR7: Human observational studies on effects of RF-EMF exposure on non-specific symptoms. This SR-MA focused on tinnitus, migraine/headache, and sleep disturbance [13]. The only study designs considered by the authors to be relevant and of reasonable quality were traditional cohort or case-control studies. However, the symptoms addressed in this SR are typically recurrent over long periods of time and therefore are not ideally studied in standard cohort or case-control designs. This is because the traditional cohort study design requires the exclusion of subjects with a history of the health outcome at baseline; this exclusion effectively limits the SR's results to the causation of new-onset symptoms only and therefore represents a small proportion of all relevant cases. In addition, subjects who have taken exposure reduction

measures due to their perceived sensitivity to RF-EMF should have been analyzed separately because, due to their reduced exposures, they are less likely to report adverse outcomes in cohort studies.

SR8: RF-EMF exposure and electromagnetic hypersensitivity. The WHO had specified electromagnetic hypersensitivity as a priority topic for systematic review [1]. However, this topic was expanded in SR8 to focus the study on individuals without EHS [14], thereby undermining the utility of the review of EHS. This was particularly evident regarding the review of sleep disturbance, where not one study included participants known to have EHS. Although sleep disturbance is a common symptom in EHS individuals, no conclusion can be drawn regarding this symptom from the SR8 review.

The choice to focus only on radiofrequency and power density (with exclusion of all other frequency ranges and other potential variables such as magnetic fields, pulses, modulations, polarity, data transfer, etc.), limits the utility of the review given that EHS individuals report reacting to a broad range of EMF triggers, and extremely low frequency (ELF) fields are a commonly reported trigger. RF communications are modulated at ELF, and ELF is likely to have contaminated some sham phases due to pollution from monitoring equipment or infrastructure within the test room.

SR9: RF-EMF exposure and biomarkers of oxidative stress. This SR differs from the other SRs in that it addresses a potentially early step in the development of several adverse health effects due to exposure to RF-EMF rather than an adverse effect endpoint. The stated objective of this SR was "to summarize and evaluate the literature on the relation between the exposure to RF-EMF in the frequency range from 100 kHz to 300 GHz and biomarkers of oxidative stress" [15]. The conclusion that "the relation between the exposure to RF-EMF and biomarkers of oxidative stress was of very low certainty" was greatly different than the findings of Yakymenko et al. [33] and ICBE-EMF [23] who reported that induction of oxidative effects was observed in >90% of studies in which biological systems were exposed to low intensity RFR. Much of this discrepancy is due to the excessive exclusion of relevant studies in SR9. Of the 897 articles that Meyer et al. [15] considered eligible for their review, only 52 were included in their MAs; 360 studies were excluded because the only biomarker reported in those articles was claimed to be an invalid measure of oxidative stress [34].

Thiobarbituric acid reactive substances (TBARS) and dihydrodichlorofluorescein diacetate (DCFDA) are commonly used markers of oxidative stress in biological samples [35–37] but were excluded by Meyer et al. [15]. The TBARS assay has been widely used as a measure of lipid peroxidation products, mainly malondialdehyde (MDA). Meyer et al. [15] excluded studies in which TBARS was reported as the sole measure of oxidative stress because according to Henschenmacher et al. [34], non-oxidative stress reactions including metabolism can also produce TBARS. However, there is no evidence that exposure to RF-EMF activates metabolic pathways that can produce TBARS. With the use of appropriate sham exposure groups, elevated TBARS measurements in biological samples after exposure to RF-EMF are most likely the result of lipid peroxidation. In addition, changes in TBARS and 4-HNE-modified protein, an accepted biomarker of oxidative stress due to lipid peroxidation [34], frequently occur in parallel when both markers are measured.

Another exclusion criterion for this SR that resulted in exclusion of 63 studies was "no sufficient exposure contrast" [15]; the external electric field strength (E) field must be greater than 1 V/m or the power flux density (PD) must be greater than 2.5 mW/m^2 [34]. However, when exposure to RF-EMF produces a statistically significant increase in a biomarker (including increase in 8-OHdG) in exposed vs. sham samples, and those effects are reduced in the presence of an inhibitor of oxidative damage, then such changes represent meaningful RF-EMF-induced oxidative effects. Also, since the objective of this SR was to evaluate relationships between exposure to RF-EMF and biomarkers of oxidative stress, there is no justification for excluding studies in non-mammalian animal species that show increases in biomarkers of oxidative stress, such as 8-OHdG (e.g., quail embryos exposed to low intensity RFR [38]),.

Meyer et al. [15] also excluded studies with mobile phones if output power was not reported or controlled, or if the EMF was not generated by a phone in GSM mode with an active call. This restriction excludes all realistic simulations that involve devices that are actually in use.

Meyer et al. [15] also excluded studies that used dihydrochlorofluorescein diacetate (DCFDH) to evaluate oxidative stress in cells (e.g [39])., because this marker "measures iron dependent oxidation of dye" [34]. Again, with use of sham controls, this biomarker is a reliable indicator of cellular oxidative stress and should not have been excluded from this SR. The inclusion/exclusion criteria for SR9 did not mention changes in activity or expression of antioxidant enzymes (e.g., superoxide dismutase, glutathione peroxidase, catalase) that have long been used as biomarkers of oxidative stress [40]. Due to the exclusion of studies relevant to the objective of SR9, we conclude that the authors' conclusions are severely deficient and unreliable.

Adequacy of the designs of the included studies and conduct of the systematic reviews

This topic addresses whether the design and conduct of the included studies as well as the SRs themselves were suitable to achieve the objective stated in each review.

SR1A: RF-EMF exposure and human cancer. The MAs in SR1A [4] relied heavily on surrogate measures of phone use, such as "ever" versus "never," and "time since start of use." These surrogate measures of exposure lack critical information on the extent of phone use. Consequently, they cannot inform dose–response relationships, which reduces their contribution to the assessment of causation [41]. In addition, the updates of the Danish cohort study [24, 42], which were significant contributors to the MAs in SR1A, had several methodological faults that led to invalid results [43]: (1) inclusion of only mobile phone private subscribers in Denmark between 1982 and 1995 in the exposure group; (2) exclusion of the likely most exposed group, consisting of 200,507 corporate users of mobile phones; those individuals were instead included in the unexposed control group if they were not private subscribers; (3) users with mobile phone subscriptions after 1995 were not included in the exposed group and were treated as unexposed, non-users; (4) actual exposure data were unknown and no analysis by laterality (the side where the phone was held in relation to the position of the tumor) was performed; (5) all users of cordless (DECT) phones were treated as unexposed for that exposure although they were also exposed to RFR similar to that of mobile phones. The lack of separate analyses of tumors that are ipsilateral versus contralateral reduce the capacity of these reviews to identify important brain dose–response relationships that are indicative of causation.

In addition to the above factors, the studies cited by Karipidis et al. [4] lacked sufficient follow-up time to detect and diagnose late-developing tumors. Conclusions on cancer risk in SR1 do not resolve uncertainties due to limited follow-up, and run counter to IARC's view on latency [44]: "experience from studies of cancer in humans indicates that the period from first exposure to the development of clinical cancer is sometimes longer than 20 years; therefore, latency periods substantially shorter than about 30 years cannot provide evidence of lack of carcinogenicity."

SR5: RF-EMF exposure and cognition in human observational studies. Each of the five studies included in SR5 [11] provided only weak or no cause-and-effect evidence, due to little change in the causal variable (mobile phone calls per week, e.g., from a median of 2 calls per week at baseline to 2.5 calls per week at follow-up [45]), and failure to analyze temporality (i.e., change in both exposure and effect over time) in three of the studies [46–48]. Since those studies failed to make use of change over time information (cognitive outcomes were assessed against cumulative exposure), the analysis of those studies is no different from cross-sectional analysis. In addition, an analytical framework for classifying cognitive tests (e.g [49]), which would normally be required for investigating a field as complex as cognitive function and potential effects of RF exposures, was not utilized in SR5.

The two primary studies that were included in the MAs in SR5 [45, 50] used baseline populations that contained participants who were not mobile phone owners at baseline, but who had become mobile phone owners by follow-up. The change in ownership of mobile phones by participants in either of the comparison groups would have increased actual exposures for either group due to extra RF-signals from carrying a mobile phone in their pocket. Thus, the actual exposure of group members would have been greater than mere number of calls per week. This contamination would therefore have invalidated the comparison between groups and thus the experiment as a whole.

SR6: Effects of RF-EMF on cognitive performance in human experimental studies. There were several problems with the methods used to collect data and appraise studies in SR6:

1) The simulated signals used in most studies did not include low frequency pulsing and modulations, and therefore, were less likely to have caused effects on the brain or related cognitive processes.
2) Some studies did not provide sufficient time to resolve effects on the brain from exposures prior to the start of the cognitive test.
3) Variations in practice effects among studies could have reduced or eliminated the detection of small effects.
4) Rather than using the appropriate classification system for cognitive abilities, (the Cattell-Horn-Carrol taxonomy of cognitive factors and its adaptation [49]), this review used a classification system from neuropsychiatry [51], which loses information on specific processes that may be affected by exposures because it bundles together different cognitive abilities into broad and overlapping categories.

SR7: Human observational studies on effects of RF-EMF exposure on non-specific symptoms. Major methodological weaknesses in several of the primary studies included in the final MAs of Röösli et al. [27] would normally exclude them from the final list of core studies for an SR [52]. For example, the four-year long COSMOS study of headache and tinnitus as related to cell phone use in Finland and Sweden [53], which contributed a substantial proportion of the data in two of the six MAs of SR7

(35–45% of the overall weight of all pooled studies), suffered from: (1) exclusion at baseline of subjects with a history of tinnitus or weekly headaches; (2) over-adjustment for potential confounding by inclusion in the main multivariable analysis of the covariate "daily painkiller use" (which is likely to reduce observed effect-sizes); and (3) the choice of the reference level of cell phone use as "the bottom 50% of the cell phone use distribution at baseline," rather than a more extreme percentile cutoff. In addition, there is no rationale for a four-year study duration of symptoms, which are usually induced in persons who report them related to RF-EMF exposure after a much briefer latency (typically hours to days). Ascertaining such outcomes so long after baseline exposures were measured risks increasing exposure misclassification substantially, during an era when both cell phone technology and user habits were changing rapidly. These methodological weaknesses create biases in the direction of reducing the observed strengths of association towards the null.

SR8: RF-EMF exposure and electromagnetic hypersensitivity. The reactions of EHS individuals are known to be highly heterogeneous in terms of reaction onset, washout, trigger type, target symptom and symptom severity. By failing to adequately accommodate both inter- and intra-participant variability in terms of their symptomatic reactions, group studies included in this review are heavily biased towards the null.

Many studies used signal generation systems that did not necessarily emulate the real nature of the reported triggers of EHS in terms of near- or far-field pulses, modulation, data transfer etc. Also, because the clinically-reported average onset and washout of reactions were not sought from the potential participants in most studies, volunteers' reactions may not have been encompassed by or restricted to the observation time. Most studies selected for this SR were inadequate for drawing any reliable conclusions on self-reported symptoms from exposures to RF-EMF.

SR9: RF-EMF and biomarkers of oxidative stress. As noted above, the SR on biomarkers of oxidative stress is unique among these reviews because it addresses biological processes rather than a disease endpoint. Indicators of oxidative stress may occur in all organs of all animal species, and are not necessarily specific to only the brain, liver, blood, testis, or ovary of exposed rodents or rabbits, nor is it specific to only in vivo or in vitro studies, and most certainly it is not specific to measurements of only oxidized DNA bases, oxidized lipids, or certain modified proteins or amino acids. Subdividing the 52 primary studies into 19 subgroups resulted in very few studies in most categories; this diluted the overall effect and weakened the significance of the MAs reported by the authors of SR9 [15].

To address the stated objective of this SR, the authors should have first combined studies with the three different types of biomarkers. Further, combining biomarker responses in different organs of a given species would have provided a better representation of the effect of RF-EMF on biomarkers of oxidative stress. If such analyses still showed high heterogeneity likely due to methodological differences, then a narrative review would have been more appropriate than a series of flawed MAs.

SR4A, SR4B, SR8 Corrigenda. The authors of three systematic reviews (SR4A, SR4B, and SR8) submitted corrigenda after their articles had been published due to the detection of inconsistencies. For SR4A, the changes resulted in a slightly weaker, but still significant reduction in pregnancy rate, which is a measure of male fertility [54]. In addition, the certainty GRADE was changed from moderate to "high certainty of evidence that RF-EMF exposure reduces rate of pregnancy" in experimental animal studies. For SR4B, Cordelli et al. [55] wrote that "none of these issues has produced any significant change in the quantitative outputs of the effects estimates or in the interpretation and conclusions of the systematic review." However, these changes did result in a slightly stronger effect of RF-EMF exposure on fetal weight. For SR8, the authors [56] reported "a few inconsistencies detected in the article after its publication due to some dysfunctionalities in the proofreading process," and claimed that none of the changes "produced any significant change in the quantitative outputs of the effects estimates."

Meta-analyses

MAs aim to combine quantitative results from multiple studies to estimate overall effects, but their usefulness depends on methodological consistency, sufficient statistical power, low heterogeneity, and statistical independence of the effect sizes—criteria that were frequently unmet in the WHO's SRs on RF-EMF health effects, as identified by our evaluations.

Our evaluations of the MAs reported in the SRs are summarized in Table 2. See Supplementary File S2 ("The Meta-Analyses in the WHO RF-EMF Systematic Reviews Yielded Unreliable Results") for a critique of the meta-analytic methodology applied in each SR; and for each of the meta-analyses, the number of studies included, and the statistical heterogeneity (I^2 = the percentage of between-study variability) of the pooled result.

Almost all of the MAs included in eleven WHO RF-EMF SR papers had methodological weaknesses that compromised the interpretability of results due to relatively few primary studies available for each MA and/or high between-study heterogeneity. High levels of heterogeneity across primary studies results in MAs that are unreliable and risk producing biased pooled results due

Table 2 Evaluations of the meta-analyses used in the WHO's systematic reviews on health effects of RF-EMF

SR1A: Karipidis et al. [4]	Almost all meta-analyses had methodological weaknesses. Most meta-analyses combined data from studies that employed very different methodologies (cohort vs. case-control) which contributed to high between-study heterogeneity.
SR1B: Karipidis et al. [5]	All meta-analyses had methodological weaknesses. Most combined data from fewer than five studies and employed different methodologies (cohort and case-control studies) that resulted in substantial between-study heterogeneity and disproportionate weighting of studies.
SR2: Mevissen et al. [6]	This systematic review did not report any meta-analyses.
SR3A: Kenny et al. [7]	Each of the dose-response meta-analyses contained fewer than five studies (median = two studies)—too few to yield meaningful results. The paper did not report how well the models fit the data.
SR3B: Johnson et al. [8]	Each of the dose-response meta-analyses contained fewer than five studies (median = two studies)—too few to yield meaningful results. The paper did not report how well the models fit the data.
SR4A: Cordelli et al. [9]	The majority of meta-analyses had methodological weaknesses due to high between-study heterogeneity (Figs. 5, 6, 7, 12, 13 and 14) or a small number of studies (Figs. 15 and 16).
SR4B: Cordelli et al. [10]	All meta-analyses had methodological weaknesses due to high between-study heterogeneity and/or few studies.
SR5: Benke et al. [11]	Contrary to the study protocol, the body of this paper reported results from fixed effects meta-analyses. To be consistent with the other systematic reviews, we examined Forest plots for the random effects meta-analyses reported in Supplementary Data 6. The paper did not report dose-response results. Since only two studies were available for each meta-analysis, all meta-analyses had methodological weaknesses.
SR6: Pophof et al. [12]	Overall, the majority of meta-analyses had methodological weaknesses due to high between-study heterogeneity or few studies available for meta-analysis.
SR7: Röösli et al. [13]	All meta-analyses had methodological weaknesses due to few studies with high between-study heterogeneity.
SR8: Bosch-Capblanch et al. [14]	Eight of the ten meta-analyses had methodological weaknesses due to few studies available for meta-analysis.
SR9: Meyer et al. [15]	All meta-analyses had methodological weaknesses due to high between-study heterogeneity and/or few studies.

to the excessive influence of just one or two larger studies. Another consequence of pooling studies with heterogeneous results is that it might dilute the findings from studies with larger effect-sizes by adding in smaller studies, which typically tend to suffer from biases that underestimate the association strength.

SR2: RF-EMF exposure and cancer in experimental animals. The authors of SR2 [6] considered MAs to be inappropriate for any of the tumor responses due to methodological differences among the available studies, including differences in exposure characteristics (frequency, modulation, hours/day of exposure, duration of exposure, exposure systems), different animal models and sources of animals, animal age/life stage at start of exposure, etc., and because too few studies with similar experimental design were available for any subgroup analysis. Consequently, a narrative approach was used to describe the evidence regarding relationships between tumor response in laboratory animals and exposure to RF-EMF. In addition, the authors calculated BMD01 values for glioma and heart schwannoma for those studies in which a significant positive trend was identified. BMD01 is the dose, expressed as whole-body SAR (specific absorption rate), that is estimated to result in 1% extra risk, and serves as the starting point for extrapolation of cancer risk to lower doses.

SR5: RF-EMF exposure and cognition in human observational studies. The MAs that were included in this review were based on only two of the five reviewed studies. Although it is technically possible to conduct MAs with only two studies, it does not make sense to do this unless the studies were designed to be independent replication studies; however, that was not the case for these two studies. With only two primary studies that were rated as probably high risk of bias included in the MAs in Benke et al. [11], and the strongest paper excluded, the authors should have conducted a narrative analysis instead of a numerical MA.

SR6: Effects of RF-EMF on cognitive performance in human experimental studies. The data from persons with EHS (electromagnetic hypersensitivity) and those without EHS were pooled rather than treated separately. This is problematic because these are two different populations, and cognitive functioning such as memory difficulties are common EHS symptoms [57]. A narrative analysis should have been conducted to describe points of divergence of the EHS population from the non-EHS populations. Also, results of low and high exposure conditions were pooled together, as were the results of pulsed and continuous exposures and different frequency ranges. Pooling the data across these factors or just ignoring them was not justified because of the limited understanding within this field of the effects of these factors on human cognition. Results from visual and verbal memory tasks were grouped into a single category for MA. These are two different abilities that are centered in different parts of the brain and may be differentially affected by RF exposures. These factors present logical sources of heterogeneity separate from statistical variability in effect sizes. These tasks should have been grouped according to the cognitive neuroscience-based classification system [52].

Risk of bias (RoB) and gradings of certainty (GRADE)

There are many aspects of both SRs and MAs which, despite the use of widely recommended tools such as the OHAT Risk of Bias (RoB) scale and GRADE scheme for assessing strength of evidence, involve inherently subjective decisions. Such subjectivity can lead to significant variation across such reviews, even when the same primary studies are being assessed. The potential for subjectivity requires clearcut independence of such reviews' co-authors from all influences that might lead to bias related to conflicts of interest, conditions that were clearly not met in the WHO-commissioned SRs.

SR4A: RF-EMF exposure and male fertility in experimental animals. The MAs of the studies in SR4A revealed statistically significant adverse effects due to RF-EMF exposures for multiple male reproductive parameters, including, decreases in male fertility, sperm count, sperm vitality (immobile or dead sperm), testis or epididymis weight, sperm production and testosterone level, and increases in sperm DNA/chromatin alterations, testicular histological alterations and testicular cell death [9]. Significant adverse effects were identified in studies in which risk of bias was rated as low or some concern. The authors downgraded the certainty of findings where RoB identified some concern, and where there was inconsistency due to variability between individual studies. Factors that were suggested to possibly contribute to inconsistency of results were carrier wave frequency and modulation, level and duration of exposure, animal temperature, and life stage at exposure. However, the finding of significant adverse effects despite these factors strengthens the certainty of the evidence; it does not undermine it. Since the authors considered those factors to downgrade the certainty of their findings, then a narrative review should have been developed to describe the evidence about relationships between male fertility parameters and exposure to RF-EMF. In the recently published corrigendum to SR4A [54], the authors concluded that the certainty of evidence in their revised analysis was high that RF-EMF exposure reduces the rate of pregnancy (i.e. decreases male fertility) in experimental animal studies.

SR4B: RF-EMF exposure and pregnancy and birth outcomes in experimental animals. The MAs of studies rated as low or "some concern for risk of bias" revealed several statistically significant adverse effects associated with exposure to RF-EMF; these included an increase in resorbed and dead fetuses, decrease in fetal weight, decrease in fetal length, increase in the percentage of fetuses with malformations, and a detrimental effect on motor activity functions [10]. For several parameters (resorbed or dead fetuses, decreased fetal weight, decreased fetal length, fetal malformations) a significant, linear dose-response relationship was demonstrated. The rating of "some concern" for RoB was mainly due to lack of blinding during some experiments and "lack of confidence in outcome assessment." Note: this SR did not include the results from the NTP study of RF-EMF in rats that found exposure-related decreases in male and female birth weights after *in utero* exposures to GSM- or CDMA-modulated RFR [58]. Significant adverse effects were identified in studies in which risk of bias was rated as low. The authors downgraded the certainty of studies that were rated as "some concern" for RoB because of inconsistency due to variability between individual studies. Since the authors considered those factors to downgrade the certainty of their findings, then a narrative review should have been developed to describe the evidence regarding relationships between adverse fetal effects and exposure to RF-EMF.

SR5: RF-EMF exposure and cognition in human observational studies. That the only primary studies included in the MAs were co-authored by some authors of Benke et al. [11] represents an unreported conflict of interest that might have biased the review to their own weaker studies.

SR6: Effects of RF-EMF on cognitive performance in human experimental studies [12]. Given the uncertainty of the primary studies and the outcomes of the MAs, the grading of certainty was not warranted or able to produce reliable ratings. The review needed to recognize the extent to which Type II errors (failure to detect a significant effect) had been carried over from the risk of bias assessment stage into the MAs, along with the further Type II errors created by the uncertainty of pooling heterogeneous studies in the MA. For example, the visual memory task that showed effects was nested inside the visual and verbal memory category group that had high heterogeneity and was therefore given a lower grade for the certainty of evidence. Thus, visual memory effects were masked in the overall conclusions.

SR8: RF-EMF exposure and electromagnetic hypersensitivity. The adapted OHAT risk of bias (RoB) tool used in Bosch-Capblanch et al. [14] was inadequate for the subject matter of that review. For example, participant selection and matching to study design is a crucial component, yet none of the RoB assessment criteria reviewed this element. As a result, there was no assurance that a subject would report having reactions to the exposures provided within the planned observation period. The RoB for many studies is much higher than the level of bias that was allocated within this review. The narrative entries in the RoB assessments provided little rationale on how ratings were assigned. In contrast to those ratings, there are noticeable and serious flaws in the most highly rated papers, such as failure to fully match the exposure to the clinically reported trigger [59, 60], failure to clinically assess reliability, onset or offset of symptoms [61–63],

and failure to shield or mitigate all types of background EMF contamination during the experiment [64].

Due to inadequate critiquing, many of the primary outcome groups were listed with "no concerns" regarding RoB at the grading stage. This, together with inadequate scrutiny of indirectness and funding, led to over-grading of each of the primary outcome groups. The conclusion of high or moderate certainty of evidence in support of no effects for most of the primary outcomes is not credible.

Discussion and conclusions

Methodological flaws and limited evidence weaken the value of most of the meta-analyses

It is both inaccurate and misleading for SR-MAs with methodological flaws and limited evidence to conclude that there was no evidence of adverse effects from exposure to RF-EMF below ICNIRP's guideline values. In such cases, it would have been more appropriate to conclude that due to relatively few primary studies available for each MA and/or high between-study heterogeneity, the interpretability of results was severely compromised. For those SRs, a narrative review would have been more informative than a flawed MA.

The SR on the effects of RF-EMF on cognitive performance in human experimental studies [12] used a weak classification system and did not address several cognitive ability categories. This review was unable to comment on several important cognitive abilities such as executive function, learning/encoding efficiency and visual short-term memory. Furthermore, the review gave no insight into the effects of different RF-EMF exposure levels or signal characteristics and provided no insight into the cognitive effects of exposure within the EHS population. Rather than inferring there is little evidence of risk from short-term exposures, the review should have concluded that the field is too complex with too many unknowns for any reliable conclusions to be drawn at this time. The overall certainty in the results of this review should be rated as low.

The methods used to analyze oxidative stress created uncertainty

For SR9, the exclusion of relevant studies on biomarkers of oxidative stress and the splitting of the 52 selected studies into 19 subgroups resulted in a meaningless analysis of the effects of RF-EMF exposure on biomarkers of oxidative stress. Consequently, the conclusion by Meyer et al. [15] that "the evidence on the relation between the exposure to RF-EMF and biomarkers of oxidative stress was of very low certainty" is unreliable and appears to be a predetermined outcome by the authors of this review. The authors of SR9 did not demonstrate uncertainty for the induction of reactive oxygen species by RF-EMF exposure; instead, they created uncertainty by excessively subdividing the available data. An unbiased review of oxidative stress associated with RF-EMF exposure is needed since there is consistent evidence of EMF-induced formation of reactive oxygen species in numerous experimental studies [33, 65] and because oxidative stress is a key characteristic of many human carcinogens [66].

Most SRs improperly inferred safety based on low certainty of evidence

Eight of the 12 WHO-sponsored SRs (SR1A, SR1B, SR3A, SR4A, SR4B, SR6, SR7, and SR8) concluded that exposure to RF-EMF does not likely cause or increase the risk of the health conditions that the authors reviewed. These conclusions were made even though the evidence evaluated by these systematic reviews was rated as low or very low certainty in most cases. Rather than evaluate the strength of the evidence of an increase in risk, most of the present SRs rated the certainty of evidence for the absence of risk. However, because of limitations and variations in human exposures to RF-EMF due to factors such as the intensity of mobile phone emissions, differences in how people use and hold their phones, differences in frequency and modulation patterns of those emissions, as well as interindividual differences in human responses to these exposures, it is not possible to make any reasonable conclusion about the lack of cancer risk or non-cancer effects based on the flawed MAs in the WHO-commissioned SRs.

Several reviews (SR1A, SR1B, SR4A, SR5, SR8) compared the presumed higher exposures in the studies included in their respective SRs to RF exposure limits in ICNIRP's 2020 guidelines [16], while acknowledging that the SRs were not intended to evaluate the validity of the ICNIRP guidelines. In our view, reference to those exposure guidelines in relation to reviews with very low certainty evidence was done to infer safety from exposure to RF emissions from wireless devices and to support ICNIRP's RF exposure limits.

Since eleven SRs that included MAs had serious methodological weaknesses, we recommend that the WHO does not use these reviews for the upcoming "Environmental Health Criteria Monograph on the Effects of Radio Frequency Electromagnetic Fields (RF-EMF)." (Mevissen et al. [6] opted to conduct a narrative review for SR2 due to heterogeneity of the primary studies.) Rather, the WHO should commission narrative systematic reviews of the relevant peer-reviewed literature conducted by teams of experts who have no current or prior conflicts of interest.

The SR on cancer in experimental animals provides quantitative information that could be used to set exposure limits based on cancer risk

When human data are limited but animal data demonstrate adverse health effects, regulatory agencies use animal data to establish health protective exposure limits because every known human carcinogen is carcinogenic in experimental animals when adequately tested [44]. Also, controlled exposures in experimental studies eliminate potential confounders, and animal studies can eliminate the need to wait for the availability of sufficient human cancer data before implementing public health protective strategies. ICNIRP's and FCC's RF-EMF exposure limits are based on acute animal studies, which were inadequate to identify and characterize adverse effects of RFR, especially after long-term exposures [23]. The SR on cancer in laboratory animal studies (SR2) provides quantitative information that should be used to set exposure limits based on cancer risk.

For cancer risk of RF-EMF exposure, the concordant results from the animal carcinogenicity studies on RF-EMF and the increased risk of brain gliomas and Schwann cell tumors from the case-control studies point to a potential cancer risk in humans that was ignored in the overall conclusions in SR1. To analyze the results of the cancer case-control studies, the authors of SR1 provided graphs of the predicted dose-response relationship between cumulative call-time and risk of brain cancer in humans, without providing details of the model and its parameters, analyses of parameter sensitivity and statistical fit of the model to the data, or analyses of alternative dose-response approaches. In addition, there was no mention of whether latency, a critical aspect in cancer assessments, was factored into their analyses. SR1 downplayed the nearly linear increase in the risk for glioma with cumulative call time above about 500 h. In contrast, and based on the same primary studies, Moon et al. [67] reported that higher levels of cumulative call time (greater than 896 h) are associated with a statistically significantly higher relative risk of brain tumors. The methodology in SR1 was not transparent for the dose-response MA of the cancer case-control data.

The SRs on studies of reproductive toxicity in experimental animals showed significant adverse effects on multiple parameters in both the male and female reproductive systems

The reviews on the reproductive effects of RF-EMF exposures were separated into human observational studies on male fertility (SR3A [7]), and female reproductive outcomes (SR3B [8]), and experimental studies on male fertility parameters (SR4A [9]), and on pregnancy and birth outcomes (SR4B [10]). Animal studies can provide data to set exposure limits for reproductive toxicity when human studies are insufficient.

Only nine studies (7 general public and 2 occupational) on male infertility were included in SR3A. Due mainly to the small number of studies reported for each outcome, statistical heterogeneity between studies, and the use of proxy measures of exposure (e.g., minutes of mobile phone usage) when the wireless device may be located too far from the male reproductive organs to provide a reliable assessment of the impact of RF-EMF on male fertility, the authors concluded: "Overall, the evidence is very uncertain about the effect of RF-EMF on male fertility outcomes" [7] in humans.

In contrast to the human observational studies, the SR and MAs on the effects of RF-EMF exposure on male reproductive parameters in experimental studies of laboratory animals and human sperm in vitro (SR4A) found statistically significant adverse effects on most endpoints evaluated, including decreases in male fertility, sperm count, sperm vitality (immobile or dead sperm), testis or epididymis weight, sperm production and testosterone level, and increases in sperm DNA/chromatin alterations, testicular histological alterations and testicular cell death [9]. However, to minimize the impact of these findings for concern of human health and international exposure limits to RF-EMF, the authors wrote "most studies evaluated RF-EMF exposure levels were higher than the levels to which human populations are typically exposed, and the limits set in international guidelines," namely ICNIRP 2020. The statement [54] that 32–53% of studies tested exposures above 4 W/kg, ICNIRP's threshold SAR level for adverse health effects, indicates that 47–68% of studies were tested below 4 W/kg. The multiple adverse effects of RF-EMF on male reproductive parameters at SARs below ICNIRP's putative threshold exposure level support the ICBE-EMF's [23] contention that 4 W/kg is not a threshold for adverse effects of RF-EMF exposures. Since the ICNIRP exposure limits are based on applying uncertainty factors to this putative threshold dose, ICNIRP's guideline exposure limits are clearly not adequate for protecting against adverse reproductive effects. Despite their comments aimed at minimizing concerns of exposure to RF-EMF on male reproductive parameters, Cordelli et al. [9] warn that the results of their MAs showing detrimental effects on pregnancy rate and sperm count "should not be overlooked at a policy level." Considering the multiple effects on male fertility parameters in experimental animals, the authors of SR4A should have promoted precautionary recommendations for users of wireless devices on how to reduce the risk of RF-EMF exposure on male fertility. While commenting that the SAR levels in the studies included in this SR were "well above" ICNIRP's exposure limits for the general public, they neglected to note that the linear

dose-response relationship with a potency of 0.03 per W/kg increase reported in this review can be used to establish health-protective limits, similar to how that is done for other hazardous environmental agents [68, 69].

The authors of SR3B of human observational studies on the effects of RF-EMF exposure on adverse reproductive outcomes from studies of the general public and occupational studies [8] concluded: "Overall, the body of evidence is very uncertain about the effect of RF-EMF exposure on female reproductive outcomes." This was because only a small number of studies were available for each outcome, and those were rated as very low certainty. In addition, the use of surrogate measures of exposure, e.g., "hours of mobile phone usage", do not provide reliable information on exposure to the genitalia or the developing fetus. However, to minimize concerns of risk, Johnson et al. [8] claimed "overall, the majority of evidence suggest that there is little to no effect of RF-EMF on female reproductive outcomes." The comment that evidence on the effects of RF-RMF on female reproductive outcomes is too uncertain to draw any implications for biological plausibility was made without consideration of the extensive literature on increased oxidative stress due to RF-EMF exposures and the report (SR4B) of statistically significant adverse effects of RF-EMF exposure on birth outcomes in experimental animals [10].

The SR-MA results on the effects of RF-EMF exposure on pregnancy and birth outcomes in experimental animals (SR4B) found statistically significant adverse effects including increase in resorbed and dead fetuses, decrease in fetal weight, decrease in fetal length, and increase in fetal malformations [10]. The authors noted that the detrimental effect of RF-EMF exposure on fetal weight did not correlate with increase in dam temperature and acknowledged that *in utero* exposure to RF-EMF "likely affects offspring health at birth." Thus, contrary to the view expressed by Cordelli et al. [10], their review *did* "provide conclusions certain enough to inform decisions at a regulatory level," and should serve as the basis for policy decisions to lower exposure limits and reduce human risks. Based on the evidence presented in SR4B, Cordelli et al. [10] should have provided precautionary recommendations for pregnant women about how to reduce the risk of RF-EMF exposure to the developing fetus.

Conclusions

Instead of assessing the scientific evidence on human health risks from RF-EMF exposures comprehensively, these SRs create a false sense of safety that undermines public health protection. In light of the mounting scientific evidence from research studies published over the past 30 years, including the studies on cancer and on reproductive effects in experimental animals reported in SR2, SR4A, and SR4B, and the widespread and increasing exposure of populations to RF-EMF, there is a clear need to reduce exposures and strengthen safety limits, especially for pregnant women, children, and people with chronic health conditions. Because the FCC and ICNIRP exposure limits are outdated and based on invalid health assumptions [23], revised science-based guidelines that are protective of human health and the environment are urgently needed.

Due to serious flaws in the reviews and MAs, the WHO-commissioned SRs cannot be used as proof of safety of cell phones or other wireless communication devices and should not be relied upon for the forthcoming WHO EHC monograph.

Abbreviations

BMD01	Benchmark dose, 1% extra risk
COSMOS	Cohort Study of Mobile Phone Use and Health
DOI	Declaration of Interests
CDMA	Code Division Multiple Access
DCFDH	Dihydrochlorofluorescein diacetate
DECT	Digital Enhanced Cordless Telecommunications
[E]	Electric field strength
EHC	Environmental Health Criteria
EEG	Electroencephalography
EHS	Electromagnetic hypersensitivity
ELF	Extremely low frequency
EMF	Electromagnetic Fields
GSM	Global System for Mobile Communications
FCC	Federal Communications Commission
GRADE	Grading of Recommendations Assessment, Development and Evaluation
8-OHdG	8-hydroxy deoxyguanosine
IARC	International Agency for Research on Cancer
ICBE-EMF	International Commission on the Biological Effects of EMF
ICNIRP	International Commission on Non-Ionizing Radiation Protection
MA	Meta-analyses
PD	Power density
RF-EMF	Radiofrequency Electromagnetic Fields
RFR	Radiofrequency radiation
RoB	Risk of Bias
SAR	Specific absorption rate
SR-MA	Systematic Review Meta-Analysis
TBARS	Thiobarbituric acid reactive substances
WHO	World Health Organization

Supplementary Information

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Supplementary Material 1.

Supplementary Material 2.

Authors' contributions

RLM, JMM, PH, EMB, MH, LH, AP, JWF, TS, EK made significant contributions to the conception of the work. RLM, JMM, EMB, JEM, TS, and MH wrote the main manuscript text. All authors (RLM, JMM, PH, EMB, JEM, MH, LH, AP, FB, JWF, TS, EK) made significant revisions to the work and approved the submitted version.

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Declarations

Competing interests
The authors declare no competing interests.

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