

Supplementary File S2

The Meta-Analyses in the WHO RF-EMF Systematic Reviews Yielded Unreliable Results

In this appendix we applied the guidelines listed below to each of the meta-analyses reported in eleven WHO RF-EMF systematic reviews (SRs) of health effects of exposure to radiofrequency electromagnetic fields.

Statistical power and heterogeneity of primary studies

None of the WHO systematic reviews (SRs) reported having conducted power analyses. If they had done this, they would not likely have relied upon the results from random-effects meta-analyses with fewer than five studies and would have been cautious about interpretation of results from meta-analyses of ten or fewer studies.

Inadequate statistical power plays an important role in the ability to interpret the results of a meta-analysis when the number of primary studies is limited, especially when the studies are heterogeneous. “Heterogeneity is a vague term which describes any kind of variability among studies included in a systematic review, namely clinical, methodological and statistical between-study heterogeneity” (Kanellopoulou et al., 2025).

Meta-analysts must always account for the variation in the results from the primary studies. The I^2 statistic ([Higgins and Thompson. 2002](#)) is commonly used to quantify the between-study heterogeneity. It is defined as the percentage of variability in the effect sizes that is not caused by sampling error. This statistic is commonly used because there is a “rule of thumb” for its interpretation ([Higgins and Thompson. 2002](#)):

Higgins and Thompson (2002) quantify the proportion of total variability due to true between-study heterogeneity (rather than chance). Higgins (2003) has proposed thresholds for the interpretation of the I^2 index in a meta-analysis, according to which, if I^2 index ranges between:

- 0% and 40%, then heterogeneity might not be important.
- 30% and 60%, then heterogeneity is moderate.
- 50% and 90%, then heterogeneity is substantial.
- 75% and 100%: then heterogeneity is considerable.

Unfortunately, heterogeneity cannot be reliably estimated if very few primary studies are available (Bender et al., 2018). Moreover, “If heterogeneity is too large for a meaningful pooling of the available study results, no quantitative summary of the study results should be performed. In this situation, a merely qualitative evidence synthesis is recommended” (Bender et al., 2018).

Our analysis which appears later in this appendix found that most meta-analyses reported in the WHO SRs showed high between-study heterogeneity which reduced overall precision and statistical power. Due to this heterogeneity the authors followed up their meta-analyses with subgroup analyses or meta-regression which had even less statistical power due to even smaller numbers of primary studies available in each subgroup. According to Richardson et al. (2019), “The Cochrane Handbook advises that it is unlikely that an investigation of heterogeneity will produce useful findings unless there are at least 10 trials included in the

meta-analysis, although even 10 trials may be too few if the covariate is unevenly distributed (i.e. if there is a limited amount of data for a particular subgroup)."

Although the random-effects model enables one to calculate a pooled effect size even if the studies are heterogeneous, it does not inform us whether this pooled effect can be meaningfully interpreted. Many scenarios exist in which the pooled effect does not adequately represent the data.

In a meta-analysis, the pooled effect size should not be interpreted without first examining the heterogeneity of the primary studies on which this average effect is based. If the results of the primary studies differ substantially, the overall effect does not reflect the fact that the true effects in some studies may differ substantially from the overall point estimate.

High heterogeneity can be caused by two or more subgroups of primary studies that have different true effects. For example, some exposures to radio frequency radiation (RFR) may have an adverse effect on a given outcome whereas other exposures may appear to have a positive effect (at least in the short-term) due to an adaptive response. Such information is important to identify. Yet, if one only examines the pooled effect, this information will be missed. High heterogeneity may indicate that the studies have nothing in common, and the pooled effect is not interpretable.

Statistical independence of primary studies

Statistical independence of the effect sizes from the primary studies is a core assumption of meta-analysis. If the effect sizes are correlated, this artificially reduces heterogeneity and can lead to false-positive results. Effect size dependence can stem from different sources ([Cheung 2014](#)):

Examples of primary studies with dependent effect sizes include studies that gathered data from multiple sites, compared multiple interventions to a single control group, or used different questionnaires to measure the same outcome. Such dependencies accounted for by applying a three-level random-effects meta-analysis model to handle the clustered effect size data (Harrer et al., 2021; Kanellopoulou et al., 2025).

Although a meta-analysis can be performed with only two studies, Myung (2023) recommends a minimum of five, and preferably ten primary studies, to draw a conclusion from a meta-analysis. Moreover, if substantial heterogeneity exists among the studies included in a meta-analysis, a minimum of ten studies are required to explore its source.

Guidelines

For a meta-analysis to yield a meaningful summary of the effects of an intervention (or exposure), it should ...

- 1) include studies with similar methodologies (Kanellopoulou et al., 2025);
- 2) include at least five studies If statistical heterogeneity is minor ($I^2 < 50\%$) or at least ten studies if heterogeneity is substantial ($I^2 \geq 50\%$) (Myung, 2023);
- 3) the weights associated with the individual studies should be fairly homogeneous;

- 4) and the meta-analysis should not include studies with multiple comparison groups with a single control group or more than one outcome from each study if a fixed effects or random effects model was employed as this violates the independent observations assumption of these models unless a three-level statistical model was employed to analyze the data (Axon et al., 2023; Kanellopoulou et al., 2025).

For each of the meta-analyses reported in eleven WHO RF-EMF systematic reviews, this appendix provides a summary of the following information: the meta-analytic methodology applied, the number of studies included, and the statistical heterogeneity (I^2 = the percentage of between-study variability) of the pooled result.

Conclusion

Almost all the meta-analyses included in eleven WHO RF-EMF systematic review papers had methodological weaknesses that compromised the interpretability of results due to relatively few primary studies available for each meta-analysis and/or high between-study heterogeneity. Yet in many instances, the authors of these systematic reviews employed these results to draw unreliable conclusions.

The WHO should heed the advice of the Cochrane Collaboration:

“Meta-analysis should only be considered when a group of studies is sufficiently homogeneous in terms of participants, interventions and outcomes to provide a meaningful summary (see MECIR Box 10.10.a).”

“Reliable conclusions can only be drawn from analyses that are truly pre-specified before inspecting the studies’ results, and even these conclusions should be interpreted with caution. Explorations of heterogeneity that are devised after heterogeneity is identified can at best lead to the generation of hypotheses. They should be interpreted with even more caution and should generally not be listed among the conclusions of a review. Also, investigations of heterogeneity when there are very few studies are of questionable value.”

“A systematic review need not contain any meta-analyses. If there is considerable variation in results, and particularly if there is inconsistency in the direction of effect, it may be misleading to quote an average value for the intervention effect.” (Deeks et al., 2025).

Thus, we recommend that the WHO does not use the eleven systematic reviews published in a special issue of *Environment International* for the upcoming “Environmental Health Criteria Monograph on the Effects of Radio Frequency Electromagnetic Fields (RF-EMF).” 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.

References

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Methodological Weaknesses in Meta-Analyses Reported in Eleven WHO RF-EMF Systematic Reviews

SR1A: Karipidis K, Baaken D, Loney T, Blettner M, Brzozek C, Elwood M, Narh C, Orsini N, Rösli M, Paulo MS, Lagorio S. 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. *Environ Int.* 2024 Sep;191:108983. doi: 10.1016/j.envint.2024.108983. Epub 2024 Aug 30. <https://www.sciencedirect.com/science/article/pii/S0160412024005695>

Meta-analytic methods

“For homogenous datasets (in terms of outcome, exposure type/metric, and subjects’ lifestage), we set a minimum size requirement for amenability to a meta-analysis (i.e., at least 3 independent measures of effect). This was a deviation from the protocol whereby, to address concerns about the large uncertainty in heterogeneity statistics from meta-analyses based on few studies ([Fu et al., 2008](#), [Ioannidis et al., 2007](#)), we had planned to calculate the confidence intervals of the I^2 statistics. However, this was not done because the I^2 statistic is considered more a descriptive measure of heterogeneity than a quantity on which to make statistical inference, such as a confidence interval (see § 6.2. *Amendments to the protocol*, point 3). We also assessed the heterogeneity in findings across studies (in terms of direction and magnitude of effects), to decide whether averaging individual measures of effect would produce meaningful results. Possible causes of inconsistency (e.g., design features) were explored through subgroup meta-analyses. In the presence of substantial unexplained heterogeneity, reporting of overall meta-risk estimates was considered inappropriate, and confidence in the body of evidence was reduced (see [section 3.7](#)).”

“The meta-analyses were neoplasm- and exposure-specific, performed separately for glioma, meningioma, acoustic neuroma, pituitary tumours, salivary gland tumours, and paediatric brain tumours, in relation to usage of each type of wireless phone (mobile or cordless).

We used the natural logarithms of the most (appropriately) adjusted point estimates of relative risk (RR, HR, OR), and related 95 % CLs, extracted from the relevant articles as input for the meta-analyses, focusing on the exposure metrics and contrasts below.

- a. For the binary exposure variable “ever vs never” (regular) use, we performed meta-analyses stratified on study design and based on random-effects restricted likelihood (REML) models, using the I^2 statistic ([Higgins et al., 2003](#)) to assess the statistical heterogeneity in results across studies. To describe the degree of heterogeneity detected via the I^2 index, we tried to be consistent with the Cochrane’s guidance ([Deeks et al., 2021](#)), whereby: 0 % to 40 %: might not be important; 30 % to 60 %: may represent moderate heterogeneity; 50 % to 90 %: may represent substantial heterogeneity; and 75 % to 100 %: considerable heterogeneity. Differences between cohort and case-control studies were assessed using the test for group differences (Q_b statistics).
- b. For the categorical variable “time since start of use” (TSS), the across-study variability in cut points was dealt with by aligning (to the possible extent) the original categories to a “standard” classification, namely into short-term (<5 years), mid-term (5–9 years), and long-term use (≥ 10 years). When needed, we combined the original measures of effect

for adjacent categories using the inverse variance weighting method (IVWA, fixed effects model). We performed meta-analyses stratified on category of TSS vs no exposure, based on REML models, using the Q_b statistic to assess the homogeneity in results across TSS subgroups (<5, 5–9, 10+ years). Note that this was a deviation from the protocol, whereby we had planned to perform a meta-regression, assigning increasing numerical values to the three levels of this categorical variable (short-term = 1; mid-term = 2; long-term = 3), in order to approximate an analysis of trend by latency (see § 6.2 *Amendments to the protocol*, point 4). We did carry out neoplasm-specific meta-regressions using a quality of exposure assessment score as moderator variable, but realized that the related findings were more difficult to interpret, compared to those from the subgroup meta-analyses. Therefore, results from the latter are reported in the main paper, while findings from the former are included in the [supplemental online material](#).

- c. We conducted dose–response meta-analyses (DRM) of glioma, meningioma, and acoustic neuroma risks in relation to mobile phone CCT and CNC using weighted mixed effects models ([Crippa et al., 2019](#), [Orsini, 2021](#)). The dependent variable was the study-specific estimates of the log transformed (ln) odds ratio. The independent variable was the midpoint exposure value assigned to each interval. For an upper open-ended category, the assignment was its lower bound plus the width of the previous (second-to-highest) interval ([Il'yasova et al., 2005](#)). Weights for correlated study-specific ORs were derived from the confidence intervals (variances) and crude counts using the Hamling's method (covariances). Restricted cubic splines with 3 knots at fixed percentiles of the exposure distribution were used to estimate a smooth shape ([Orsini, 2021](#), [Orsini and Spiegelman, 2020](#)). The statistical heterogeneity of dose–response gradients across studies was taken into account by using random-effects for the regression coefficients of the exposure transformations using a two-stage approach. A Wald-type test (w) at 5 % confidence level for the hypothesis of overall no summary exposure effect on neoplasm risks was conducted with reference to a χ^2 distribution with degrees of freedom equal to the number of regression coefficients being tested. Point and interval (95 %) estimates for the dose–response relationship (odds ratio) for the average study is shown graphically up to the 95th percentile of the exposure distribution using the 50th percentile (median) exposure as referent.”

Meta-analytic results

Fig.2: Glioma: Ever or regular use vs no use (dataset MA5)

Cohort: 3 studies; $I^2 = 63.1\%$

Case-control: 10 studies; $I^2 = 57.8\%$

Overall: 13 studies; $I^2 = 61.8\%$

Fig.3: Glioma: Time since first use (TSS) vs no use (dataset MA5)

TSS < 5 Yrs: 10 studies (3 cohort); $I^2 = 50.0\%$

TSS 5-9 Yrs: 10 studies (3 cohort); $I^2 = 66.4\%$

TSS 10+ Yrs: 7 studies (3 cohort); $I^2 = 77.3\%$

Fig.4: Glioma: 10+ yrs by Risk of Bias (RoB) (dataset MA1)

Tier 1: 7 studies (3 cohort); $I^2 = 4.1\%$

Tier 2: 4 studies (0 cohort); $I^2 = 64.8\%$

Fig.4: Glioma: 10+ yrs by RoB (dataset MA5)

Tier 1: 4 studies (3 cohort); $I^2 = 5.5\%$

Tier 2: 3 studies (0 cohort); $I^2 = 0\%$

Fig.5: Glioma: 10+ yrs by RoB (dataset MA1) (excludes studies w/ RR $\geq$ 1.5)
Cohort: 3 studies (3 cohort); $I^2 = 21.3\%$ *study weights = 56.1%, 26.1%, 2.6%
Case-control: 4 studies (0 cohort); $I^2 = 0\%$
Overall: 7 studies (3 cohort); $I^2 = 0\%$

Fig.5: Glioma: 10+ yrs by RoB (dataset MA4) (excludes studies w/ RR $\geq$ 1.5)
Cohort: 3 studies (3 cohort); $I^2 = 21.3\%$ *study weights = 50.7%, 24.4%, 2.5%
Case-control: 3 studies (0 cohort); $I^2 = 0\%$
Overall: 6 studies (3 cohort); $I^2 = 1.7\%$

Fig.5: Glioma: 10+ yrs by RoB (dataset MA1) (excludes studies w/ RR $\geq$ 1.5)
Cohort: 3 studies (3 cohort); $I^2 = 21.3\%$ *study weights = 52.7%, 26.1%, 2.7%
Case-control: 2 studies (0 cohort); $I^2 = 0\%$
Overall: 5 studies (3 cohort); $I^2 = 3.6\%$

Fig.7: Meningioma: Ever or regular use vs no use (dataset MA5)
Cohort: 3 studies; $I^2 = 20.7\%$
Case-control: 7 studies; $I^2 = 29.1\%$
Overall: 10 studies; $I^2 = 29.2\%$

Fig.8: Meningioma; Time since first use vs no use (dataset MA5)
TSS < 5 Yrs: 8 studies (3 cohort); $I^2 = 14.4\%$
TSS 5-9 Yrs: 8 studies (3 cohort); $I^2 = 46.2\%$
TSS 10+ Yrs: 6 studies (3 cohort); $I^2 = 0\%$

Fig.10: Acoustic Neuroma: Ever or regular use vs no use (dataset MA5)
Cohort: 2 studies; $I^2 = 76.6\%$
Case-control: 9 studies; $I^2 = 47.4\%$
Overall: 11 studies; $I^2 = 51.2\%$

Fig.11: Acoustic Neuroma; Time since first use vs no use (dataset MA5)
TSS < 5 Yrs: 7 studies (1 cohort); $I^2 = 26.1\%$
TSS 5-9 Yrs: 8 studies (1 cohort); $I^2 = 64.8\%$
TSS 10+ Yrs: 6 studies (2 cohort); $I^2 = 75.9\%$

Fig.12: Acoustic Neuroma: 10+ yrs by RoB (dataset MA1)
Tier 1: 5 studies (2 cohort); $I^2 = 0\%$
Tier 2: 2 studies (0 cohort); $I^2 = 15.8\%$

Fig.12: Acoustic Neuroma: 10+ yrs by RoB (dataset MA5)
Tier 1: 4 studies (2 cohort); $I^2 = 34.7\%$
Tier 2: 2 studies (0 cohort); $I^2 = 68.5\%$

Fig.14: Pituitary Tumor: Ever or regular use vs no use (dataset MA5)
Cohort: 1 study
Case-control: 4 studies; $I^2 = 51.7\%$
Overall: 5 studies; $I^2 = 44.8\%$

Fig.15: Pituitary Tumor; Time since first use vs no use (dataset MA5)
TSS < 5 Yrs: 5 studies (0 cohort); $I^2 = 0\%$

TSS 5-9 Yrs: 4 studies (1 cohort); $I^2 = 61.4\%$
TSS 10+ Yrs: 4 studies (1 cohort); $I^2 = 0\%$

Fig.16: Salivary Tumor: Ever or regular use vs no use

Cohort: 1 study

Case-control: 7 studies; $I^2 = 0\%$ *includes separate malignant & benign tumor results from 2 studies

Overall: 8 studies; $I^2 = 0\%$

Fig.17: Salivary Tumor; Time since first use vs no use

TSS < 5 Yrs: 3 studies (0 cohort); $I^2 = 0\%$ *includes 5 results

TSS 5-9 Yrs: 3 studies (0 cohort); $I^2 = 0\%$ *includes 5 results

TSS 10+ Yrs: 3 studies (0 cohort); $I^2 = 0\%$ *includes 5 results

Fig.18: Pediatric Brain Tumor: Ever or regular use vs no use (all case-control studies)

Overall: 3 studies; $I^2 = 44.5\%$

Fig.19: Glioma, meningioma, acoustic neuroma with cordless phone use: Ever vs no use (all case-control studies)

Glioma (MA1 dataset): 5 studies; $I^2 = 78.9\%$

Glioma (MA5 dataset): 3 studies; $I^2 = 74.4\%$

Meningioma (MA1 dataset): 5 studies; $I^2 = 40.1\%$

Meningioma (MA5 dataset): 3 studies; $I^2 = 58.6\%$

Acoustic Neuroma (MA1 dataset): 5 studies; $I^2 = 48.4\%$

Acoustic Neuroma (MA5 dataset): 4 studies; $I^2 = 63.3\%$

Fig.20: Childhood Leukemia with Fixed-site transmitters (3 radio-TV, 2 base-station studies) by exposure level

Medium exposure: 1 cohort & 4 case-control studies; $I^2 = 15.9\%$

Highest exposure: 1 cohort & 4 case-control studies; $I^2 = 0\%$

Overall: 1 cohort & 4 case-control studies; $I^2 = 0\%$

Fig.21: Pediatric Brain Tumors with Fixed-site transmitters (2 radio-TV, 2 base-station studies) by exposure level

Medium exposure: 1 cohort & 3 case-control studies; $I^2 = 67.8\%$

Highest exposure: 1 cohort & 3 case-control studies; $I^2 = 56.9\%$

Overall: 1 cohort & 3 case-control studies; $I^2 = 57.2\%$

Fig.22: Glioma with Occupational RF by exposure level (studies use different exposure metrics and 2 results from 2 studies)

Lowest exposure: 1 nested case-control & 2 case-control studies; $I^2 = 31.3\%$

Medium exposure: 1 nested case-control & 2 case-control studies; $I^2 = 24.4\%$

Highest exposure: 1 cohort & 2 case-control studies; $I^2 = 18.7\%$

Overall: 1 nested case-control & 2 case-control studies; I^2 missing

Conclusion

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 substantial between-study heterogeneity.

SR1B: Karipidis K, Baaken D, Loney T, Blettner M, Mate R, Brzozek C, Elwood M, Narh C, Orsini N, Rösli M, Paulo MS, Lagorio S. 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. *Environ Int.* 2025 Feb;196:109274. doi: 10.1016/j.envint.2025.109274. Epub 2025 Jan 11.

<https://www.sciencedirect.com/science/article/pii/S016041202500025X>

Meta-analytic methods

“The methods for this systematic review and meta-analysis are described in detail in the published protocol (Lagorio et al., 2021), and summarised below.”

“The small number of studies, and of exposed cases in some instances, hampered the assessment of the statistical heterogeneity in findings across studies in the *meta-analyses*.”

See SR1 Part 1 for more information.

Meta-analytic results

Fig.2: Mobile phone use (Ever or Regular) and Leukemia
Cohort: n=2; I^2 unreported (combined weights = 90.6%)
Case-control: n=2; I^2 unreported (combined weights = 9.4%)
Overall: 4 studies; I^2 = 0%

Fig.3: Long term mobile phone use (10+ years) and Leukemia
Cohort: n=2; I^2 unreported (combined weights = 73.7%)
Case-control: n=1; (weight = 26.3%)
Overall: 3 studies; I^2 = 0%

Fig.4: Mobile phone use (Ever or Regular) and Non-Hodgkins Lymphoma
Cohort: n=2; I^2 unreported (combined weights = 79.8%)
Case-control: n=3; I^2 unreported (combined weights = 20.2%)
Overall: 5 studies; I^2 = 0%

Fig.5: Long term mobile phone use (10+ years) and Non-Hodgkins Lymphoma
Cohort: n=1 (weight = 73.7%)
Case-control: n=3; I^2 unreported (combined weights = 26.3%)
Overall: 3 studies; I^2 = 0%

Fig.6: Mobile phone use (Ever or Regular) and Thyroid Cancer
Cohort: n=2; I^2 unreported (combined weights = 73.0%)
Case-control: n=1 (weight = 27.0%)
Overall: 3 studies; I^2 = 0%

Fig.7: Occupational exposure (Exposed vs Not exposed) and mortality risk of Lymphohematopoietic System Tumors
Cohort: n=4; I^2 =0 (combined weights for 2 of 4 studies = 97.3%)
Case-control: n=0
Overall: 4 studies; I^2 = 0%

Fig.8: Occupational exposure (Exposed vs Not exposed) and mortality risk of Oral Cavity and Pharynx Cancer

Cohort: $n=3$; $I^2=0\%$ (combined weights for 2 of 3 studies = 93.9%)

Case-control: $n=0$

Overall: 3 studies; $I^2 = 0\%$

Conclusion

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 M, Ducray A, Ward JM, Kopp-Schneider A, McNamee JP, Wood AW, Rivero TM, Straif K. Effects of radiofrequency electromagnetic field exposure on cancer in laboratory animal studies, a systematic review. *Environ Int.* 2025 May;199:109482. doi: 10.1016/j.envint.2025.109482. Epub 2025 Apr 25.
<https://www.sciencedirect.com/science/article/pii/S0160412025002338>

This systematic review did not report any meta-analyses: “Studies were not considered suitable for *meta*-analysis due to heterogeneity in study design, species, strain, sex, exposure characteristics, and cancer outcome.”

SR3A: Pw Kenny R, Evelynne Johnson E, Adesanya AM, Richmond C, Beyer F, Calderon C, Rankin J, Pearce MS, Toledano M, Craig D, Pearson F. The effects of radiofrequency exposure on male fertility: A systematic review of human observational studies with dose-response meta-analysis. *Environ Int.* 2024 Aug;190:108817. doi: 10.1016/j.envint.2024.108817. Epub 2024 Jun 11. <https://www.sciencedirect.com/science/article/pii/S0160412024004033>

Meta-analytic methods

Nine studies were reviewed: seven general public and two occupational studies.

“Pairwise *meta*-analyses and dose–response *meta*-analyses were completed using RStudio ([R Core Team, 2020](#); v4.0.4). Where the same outcome was reported on the same scale, a standardised mean difference (SMD) was considered to combine different metrics (e.g. means and regression-coefficients) and scales (e.g. hours and years). However, we did not perform SMD *meta*-analyses as we could not assume that the difference was due only the outcome scale and not differences in the reliability of the outcome measures or variability amongst the study populations. ([Higgins et al., 2023](#)) The studies where a mean difference (MD) could be calculated were then considered using varying degrees of exposure comparisons as per the protocol (e.g. high vs no exposure, all levels of exposure vs no exposure). However, there was significant heterogeneity between the studies, and it was not deemed plausible to include these results in this review.

The dose–response *meta*-analyses was able to be completed as there was less heterogeneity present in the model, thereby providing more meaningful results than the pairwise *meta*-analysis. The package *dosresmeta* was used to perform a *meta*-analysis exploring possible dose–response where at least two studies reported the same exposure quantification and outcomes ([Crippa and Orsini, 2016](#)). All analyses were conducted using linear and non-linear quadratic models. Model fit was assessed by the χ^2 test for goodness-of-fit, log likelihood, [Akaike information criterion](#) and [Bayesian information criterion](#). After assessment the best model fit was used which for each analysis was linear. We therefore used random-effects linear models to assess the MD in dose–response. To do so, we precalculated the MDs between dose–response levels, represented by a proxy of mobile phone minutes usage or talk time and the corresponding standard deviation (SD) for individual categories. To accomplish this, a single exposure value was assigned to each category and for closed categories, the midrange score was used. For the (uppermost) open-ended categories, a value based on the lower bound and the width of the previous (second-to-highest) interval was calculated ([Il'yasova et al., 2005](#)). When studies only reported the regression coefficient (β), they were combined with studies where a MD between groups could be calculated. For this reason, only the unstandardised β were utilised in the analysis.

Due to the limited number of studies in each analysis, we could not perform any subgroup or sensitivity analyses. Between-study heterogeneity (τ) was calculated using the [restricted maximum likelihood](#) (REML) method. We also report the I^2 percentage.”

Meta-analytic results

General Public Studies: Conducted dose-response meta-analyses on seven studies. No Forest plots were presented.

Duration of mobile phone use on sperm: concentration (n=3 studies), morphology (n=3), progressive motility (n=2), total count (n=2)

Mobile phone location on sperm: total motility (n=3), total motile count (n=3)

RF-EMF source on sperm concentration (n=1), total motility (n=1), total motile count (n=1)

Occupational Studies: No meta-analyses were performed on two studies due to heterogeneous populations and exposure sources.

Conclusion

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 EE, Kenny RPW, Adesanya AM, Richmond C, Beyer F, Calderon C, Rankin J, Pearce MS, Toledano M, Craig D, Pearson F. The effects of radiofrequency exposure on adverse female reproductive outcomes: A systematic review of human observational studies with dose-response meta-analysis. *Environ Int.* 2024 Aug;190:108816. doi: 10.1016/j.envint.2024.108816. Epub 2024 Jun 12.
<https://www.sciencedirect.com/science/article/pii/S0160412024004021>

Meta-analytic methods

Eighteen studies were reviewed: eight general public and ten occupational studies.

See methods section in SR3 Part 1.

Meta-analytic results

General public studies:

Mobile phone exposure: preterm birth risk (n=4 studies), low birthweight (n=4), small for gestational age (n=2)

Congenital anomalies and miscarriage risk – no meta-analysis performed

No studies on stillbirth.

Occupational studies:

Shortwave diathermy on miscarriage (n=2), offspring (n=2), congenital malformations (n=2)

RF-EMF on miscarriage (n=2), pre-term births (n=3), low birthweight (n=3)

Stillbirth and small for gestational age – no meta-analysis performed

Conclusion

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 E, Ardoino L, Benassi B, Consales C, Eleuteri P, Marino C, Sciortino M, Villani P, Brinkworth MH, Chen G, McNamee JP, Wood AW, Belackova L, Verbeek J, Pacchierotti F. Effects of Radiofrequency Electromagnetic Field (RF-EMF) exposure on pregnancy and birth outcomes: A systematic review of experimental studies on non-human mammals. *Environ Int.* 2023 Oct;180:108178. doi: 10.1016/j.envint.2023.108178. Epub 2023 Aug 30. Erratum in: *Environ Int.* 2025 Feb;196:109273. doi: 10.1016/j.envint.2025.109273. <https://www.sciencedirect.com/science/article/pii/S0160412023004518?via%3Dihub>

Meta-analytic methods

Eighty-eight papers in this review.

“Study results were pooled in a random effects *meta*-analysis comparing average exposure to no-exposure and in a dose–response *meta*-analysis using all exposure doses, after exclusion of studies that were rated at “high concern” for RoB. Subgroup analyses were conducted for species, [Specific Absorption Rate](#) (SAR) and temperature increase.”

According to the protocol, subgroup analyses were only interpreted when subgroups included at least 3 studies. Most analyses combined studies with different species. Averaged exposures used for studies with multiple levels of exposure:

Effects on fecundity: litter size, resorbed and dead fetuses.

Offspring health at birth: fetal weight, fetal length, percentage of fetuses with malformations, incidence of litters with malformed fetuses.

Delayed effects on offspring health: brain weight, learning and memory functions, motor activity functions, motor and sensory functions, litter size conceived by F2 female offspring neurobehavioural effects based on few studies.

Meta-analytic results

Fig.3: Pre-implantation loss
Low/some concern (n=1 study)
High concern (n=4; $I^2=37.5\%$)
Overall (n=5; $I^2=16.7\%$)

Fig.4: Litter size (excludes 8 studies)
Low/some concern (n=24; $I^2=15.2\%$)
High concern (n=12; $I^2=40.1\%$)
Overall (n=36; $I^2=35.6\%$)

Fig.5: Resorbed or dead fetuses (excludes 2 studies)
Low/some concern (n=21; $I^2=55.2\%$)
High concern (n=6; $I^2=45.8\%$)
Overall (n=27; $I^2=51.8\%$)

Fig.6: Fetal weight (excludes 7 studies)
Low/some concern (n=48; $I^2=72.5\%$)
High concern (n=14; $I^2=75.9\%$)

Overall (n=62; $I^2=72.9\%$)

Fig.7: Fetal length

Low/some concern (n=13; $I^2=77.0\%$)

High concern (n=2; $I^2=90.1\%$)

Overall (n=15; $I^2=78.6\%$)

Fig.8: Fetal malformations

Low/some concern (n=13; $I^2=47.2\%$)

High concern (n=9; $I^2=0\%$)

Overall (n=22; $I^2=29.3\%$)

Fig.9: Incidence of litters with malformed fetuses (excludes 8 studies)

Low/some concern (n=28; $I^2=42.2\%$)

High concern (n=2; $I^2=35.2\%$)

Overall (n=30; $I^2=41.6\%$)

Fig.10: Sex ratio

Low/some concern (n=13; $I^2=0\%$)

High concern (n=0)

Overall (n=13; $I^2=0\%$)

Fig.11: Offspring brain weight

Low/some concern (n=12; $I^2=33.5\%$)

High concern (n=1)

Overall (n=13; $I^2=36.8\%$)

Fig.12: Offspring behavioral ontogeny - age of first righting

Low/some concern (n=0)

High concern (n=4; $I^2=81.2\%$)

Overall (n=4; $I^2=81.2\%$)

Fig.13: maze escape latency time

Low/some concern (n=2; $I^2=0\%$)

High concern (n=9; $I^2=66.0\%$)

Overall (n=11; $I^2=59.3\%$)

Fig.14: endurance time

Low/some concern (n=4; $I^2=57.8\%$)

High concern (n=9; $I^2=27.1\%$)

Overall (n=13; $I^2=60.2\%$)

Fig.15: magnitude of startle to stimulus

Low/some concern (n=2; $I^2=0.2\%$)

High concern (n=1)

Overall (n=3; $I^2=0\%$)

Fig.16: Female offspring infertility

Low/some concern (n=4; $I^2=30.4\%$)

High concern (n=0)

Overall (n=4; $I^2=30.4\%$)

Conclusion

The majority of the 14 meta-analyses had methodological weaknesses due to substantial between-study heterogeneity (Figs. 5,6,7,12,13,14) or a small number of studies (Figs. 15, 16).

SR4B: Cordelli E, Ardoino L, Benassi B, Consales C, Eleuteri P, Marino C, Sciortino M, Villani P, H Brinkworth M, Chen G, P McNamee J, Wood AW, Belackova L, Verbeek J, Pacchierotti F. 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*. *Environ Int.* 2024 Mar;185:108509. doi: 10.1016/j.envint.2024.108509. Epub 2024 Feb 19. <https://www.sciencedirect.com/science/article/pii/S0160412024000953>

Meta-analytic methods

The review included 117 experimental animal studies and 10 human sperm *in vitro* studies.

“We pooled study results in a random effects *meta*-analysis comparing average exposure to no-exposure and in a dose–response *meta*-analysis using all exposure doses. For experimental animal studies, we conducted subgroup analyses for species, Specific Absorption Rate (SAR) and temperature increase. We grouped studies on human sperm exposed *in vitro* by the fertility status of sample donors and SAR.”

Meta-analytic results

Fig.4: Rate of infertile males

Low/some concern (n=4 studies; $I^2=0\%$)

High concern (n=0)

Overall (n=4; $I^2=0\%$)

Fig.5: Number of nonpregnant females over paired females

Low/some concern (n=19; $I^2=60.0\%$)

High concern (n=4; $I^2=0\%$)

Overall (n=23; $I^2=53.9\%$)

Fig.6: Litter size

Low/some concern (n=16; $I^2=0\%$)

High concern (n=4; $I^2=97.3\%$)

Overall (n=20; $I^2=92.3\%$)

Fig.7: Sperm count

Low/some concern (n=80; $I^2=71.4\%$)

High concern (n=7; $I^2=58.6\%$)

Overall (n=87; $I^2=70.4\%$)

Fig.8: % of abnormal sperm

Low/some concern (n=65; $I^2=89.6\%$)

High concern (n=5; $I^2=87.2\%$)

Overall (n=70; $I^2=91.2\%$)

Fig.9: % dead or immobile sperm

Low/some concern (n=32; $I^2=95.8\%$)

High concern (n=6; $I^2=89.2\%$)

Overall (n=38; $I^2=95.3\%$)

Fig.10: sperm DNA/chromatin alterations

Low/some concern (n=6; $I^2=66.0\%$)

High concern (n=1)

Overall (n=7; $I^2=59.5\%$)

Fig.11: % dead or immotile sperm

Low/some concern (n=23; $I^2=64.7\%$)

High concern (n=1)

Overall (n=24; $I^2=69.2\%$)

Fig.12: human sperm *in vitro* studies: DNA/chromatin alterations

Low/some concern (n=13; $I^2=52.7\%$)

High concern (n=0)

Overall (n=13; $I^2=52.7\%$)

Fig.13: testis/epididymis weight

Low/some concern (n=68; $I^2=52.6\%$)

High concern (n=13; $I^2=62.5\%$)

Overall (n=81; $I^2=54.6\%$)

Fig.14: testis histomorphometry

Low/some concern (n=24; $I^2=81.5\%$)

High concern (n=17; $I^2=78.2\%$)

Overall (n=41; $I^2=79.8\%$)

Fig.15: testis histopathology (Johnsen score)

Low/some concern (n=17; $I^2=93.5\%$)

High concern (n=7; $I^2=81.6\%$)

Overall (n=24; $I^2=99.2\%$)

Fig.16: testicular cell death

Low/some concern (n=23; $I^2=85.0\%$)

High concern (n=8; $I^2=92.5\%$)

Overall (n=31; $I^2=90.2\%$)

Fig.17: testicular sperm production

Low/some concern (n=36; $I^2=69.0\%$)

High concern (n=4; $I^2=68.4\%$)

Overall (n=40; $I^2=70.1\%$)

Fig. 18: testosterone level

Low/some concern (n=29; $I^2=85.2\%$)

High concern (n=11; $I^2=80.4\%$)

Overall (n=40; $I^2=83.9\%$)

Conclusion

All meta-analyses had methodological weaknesses due to substantial between-study heterogeneity and/or few studies.

SR5: Benke G, Abramson MJ, Brzozek C, McDonald S, Kelsall H, Sanagou M, Zeleke BM, Kaufman J, Brennan S, Verbeek J, Karipidis K. The effects of radiofrequency exposure on cognition: A systematic review and meta-analysis of human observational studies. *Environ Int.* 2024 Jun;188:108779. doi: 10.1016/j.envint.2024.108779. Epub 2024 May 28. <https://www.sciencedirect.com/science/article/pii/S0160412024003659>

Meta-analytic methods

This systematic review included 5 studies that reported data from 4 cohorts. Four studies examined effects on children.

According to the protocol:

“We will conduct a *meta*-analysis of similar studies with a random effects model in Stata or similar software if two or more studies are available for a given exposure-outcome combination. We will consider studies that have included only children or adolescents separately from those that include only adults (in subgroups within each analysis). For these analyses, we will consider RF EMF from all sources as similar.”

“Meta-analyses of incremental RRs will be performed using the generalized least squares for trend estimation of summarized dose–response (gls) method ([Orsini et al., 2006](#), [Orsini et al., 2012](#)).”

Meta-analytic results

Complex Attention:

Mobile phone use (change vs no change in calls/week) and Detection Accuracy

Overall (n=2; $I^2=0\%$) *one of the two studies had a weight of 99.9%

Mobile phone use (change vs no change in calls/week) and Detection Response

Overall (n=2; $I^2=0.01\%$) *one of the two studies had a weight of 84.5%

Mobile phone use (change vs no change in calls/week) and Identification Accuracy

Overall (n=2; $I^2=0.04\%$) *one of the two studies had a weight of 64.8%

Mobile phone use (change vs no change in calls/week) and Identification Response

Overall (n=2; $I^2=0\%$) *one of the two studies had a weight of 61.0%

Executive Function:

Mobile phone use (change vs no change in calls/week) and Time Ratio (B-A/A) Response

Overall (n=2; $I^2=76.0\%$)

Mobile phone use (change vs no change in calls/week) and Time Ratio (D-C/C) Response

Overall (n=2; $I^2=17.7\%$)

Learning and Memory:

Mobile phone use (change vs no change in calls/week) and One back Memory Accuracy

Overall (n=2; $I^2=31.3\%$)

Mobile phone use (change vs no change in calls/week) and One back Memory Response

Overall (n=2; $I^2=0.04\%$) *one of the two studies had a weight of 87.7%

Mobile phone use (change vs no change in calls/week) and One Card Learning Accuracy
Overall (n=2; $I^2=0.01\%$) *one of the two studies had a weight of 64.0%

Mobile phone use (change vs no change in calls/week) and One Card Learning Response
Overall (n=2; $I^2=25.1\%$) *one of the two studies had a weight of 72.5%

Conclusion

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 reported above the Forest plots for the random effects meta-analyses from 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 B, Kuhne J, Schmid G, Weiser E, Dorn H, Henschenmacher B, Burns J, Danker-Hopfe H, Sauter C. The effect of exposure to radiofrequency electromagnetic fields on cognitive performance in human experimental studies: Systematic review and meta-analyses. *Environ Int.* 2024 Sep;191:108899. doi: 10.1016/j.envint.2024.108899. Epub 2024 Jul 22.
<https://www.sciencedirect.com/science/article/pii/S0160412024004859>

Meta-analytic methods

“Random effects *meta*-analyses of Hedges’s *g* were conducted separately for accuracy- and speed-related performance measures of various cognitive domains, for which data from at least two studies were available.”

“Quantitative data from 50 studies (52 reports) with 2433 participants were included into the *meta*-analyses.”

“For the synthesis we defined a specific outcome as described above and summarized all studies investigating this outcome. Additionally, we considered accuracy- and speed-related outcome measures separately for each outcome. When a study reported multiple outcome measures per domain and/or subclass, in order to best inform the overall synthesis and to avoid *meta*-analysing highly correlated outcomes ([Higgins et al. 2023](#)), we considered in the *meta*-analyses those outcome measures that were reported in most other studies.”

Meta-analytic results

Fig. S13.1: D1: Orientation and Attention – Attention - Vigilance - MA Speed (n=7 studies)

Fig. S13.2: D1: Orientation and Attention – Attention - Selective Attention - MA Speed (n=13)

Fig. S13.3: D1: Orientation and Attention – Attention - Selective Attention - MA Accuracy (n=10)

Fig. S13.4: D1: Orientation and Attention – Attention - Divided Attention - MA Accuracy (n=4)

Fig. S13.5: D1: Orientation and Attention – Processing Speed – 2-Choices Reaction Time Task - MA Accuracy (n=3)

Fig. S13.6 D1: Orientation and Attention – Processing Speed – Other Tasks - MA Speed (n=6)

Fig. S13.7: D3: Memory - – Verbal and Visual Memory - MA Accuracy (n=10)

Fig. S13.8: D6: Concept Formation and Reasoning - Mathematical Procedures - MA Accuracy (n=5)

Conclusion

Supplementary Data 12 contained a spreadsheet with eight subgroup analyses for outcome measures with high heterogeneity between studies. Hence, these eight meta-analyses had methodological weaknesses.

Forest plots were presented only in Supplementary Data 13 for meta-analyses with at least moderate heterogeneity ($I^2 > 30\%$) for which subgroup analyses were performed. I^2 values were

not reported. Two of the eight meta-analyses in this supplement had methodological weaknesses (Fig. S13.4, S13.5).

Overall, the majority of meta-analyses had methodological weaknesses due to substantial between-study heterogeneity or few primary studies available for meta-analysis.

SR7: Rösli M, Dongus S, Jalilian H, Eysers J, Esu E, Oringanje CM, Meremikwu M, Bosch-Capblanch X. 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. *Environ Int.* 2024 Jan;183:108338. doi: 10.1016/j.envint.2023.108338. Epub 2023 Dec 6.
<https://www.sciencedirect.com/science/article/pii/S0160412023006116>

Meta-analytic methods

“For the five primary symptoms, we performed a random-effects *meta*-analysis if at least two study results were available, which were comparable in terms of exposure source. Only one eligible study on migraine was available and thus no *meta*-analysis was conducted for this symptom. Some cohort studies used several analyses approaches. In this case priority was given to [cohort analysis](#) compared to other approaches such as change analyses. For all *meta*-analyses, we used random-effect methods weighted with inverse variance weighting.”

“Step 1 *meta*-analysis: Many studies used categorized exposure values for their analysis. Thus, if studies have not reported linear-exposure response trends, we calculated first within each study for each outcome and exposure combination the linear exposure–response trends per unit increase of exposure following the methods of [Orsini et al. \(2006\)](#). Indicator for RF-EMF exposure of the brain is wireless phone use and unit of exposure was set to 100 min call duration per week. Indicator for whole-body exposure was measured or modelled electric field strength and unit of exposure for analysis was 1 V/m. For closed categories, the [geometric mean](#) of the [upper and lower bounds](#) of the exposure categories was used; for the (uppermost and lowest) open-ended categories, we assigned an estimated median value as proposed by [Ilyasova et al., 2005](#)).

Step 2 *meta*-analysis: Subsequently, the exposure–response trends from each study were *meta*-analysed across studies together with the estimated confidence intervals using random effects and inverse variance weighting. With this approach, we assumed a linear exposure–response relationship. Given the limited number of studies, we refrained from exploring non-linear relationships. However, in sensitivity analyses we conducted *meta*-analyses of the original categorical estimates to search for indications of non-linearity, which was not the case.

In each *meta*-analysis, we did not combine results from completely or partially overlapping populations. We conducted separate analyses for exposure surrogates related to the brain (operator recorded mobile phone use, self-reported mobile and cordless phone use) and for exposure surrogates representing whole-body exposure (total personal exposure, fixed site transmitters or mobile phone base stations).”

Meta-analytic results

Fig. 3. Tinnitus in relation to brain exposure using best available evidence (n=3 studies; $I^2=85.6\%$)

Fig. 4. Headache in relation to brain exposure using best available evidence (n=4; $I^2=100.0\%$)

Fig. 5. Sleep disturbances in relation to whole body exposure using best available evidence (n=3; $I^2=99.8\%$)

Fig. 6. Composite symptom scores in relation to whole body exposure using best available evidence (n=3; $I^2=99.7\%$)

Fig.7: Non-specific symptoms in relation to modelled and self-perceived exposure

Modelled exposure (n=2; $I^2=63.2\%$) *2 outcomes per study (i.e., interdependent outcomes)

Self-perceived exposure (n=2; $I^2=43.6\%$) *2 outcomes per study (i.e., interdependent outcomes)

Overall (n=2; $I^2=91.9\%$) *only 2 studies with 4 related outcomes (i.e., interdependent outcomes)

Conclusion

All meta-analyses had methodological weaknesses due to few studies and substantial between-study heterogeneity.

SR8: Bosch-Capblanch X, Esu E, Oringanje CM, Dongus S, Jalilian H, Eysers J, Auer C, Meremikwu M, Rösli M. The effects of radiofrequency electromagnetic fields exposure on human self-reported symptoms: A systematic review of human experimental studies. *Environ Int.* 2024 May;187:108612. doi: 10.1016/j.envint.2024.108612. Epub 2024 Apr 2. Erratum in: *Environ Int.* 2024 Aug;190:108892. doi: 10.1016/j.envint.2024.108892.

<https://www.sciencedirect.com/science/article/pii/S0160412024001983>

Meta-analytic methods

“For symptoms and the O/E ratios, we used random-effects model meta-analyses, using R (rma with DerSimonian-Laird estimator, [R Core Team, 2020](#)). For EMF perception, we used random effect meta-analysis to pool study specific sensitivity and specificity rating and to obtain a pooled ROC curve ([Nyaga and Arbyn, 2022](#)). To test whether O/E ratio, sensitivity and specificity of the RF-EMF perception differ between IEI-EMF and general population samples, we added the corresponding information as a covariate into the model.

Because we re-estimated the effects of exposure and could not take into account individual correlations existing in cross-over trials, we carried out sensitivity analyses repeating the meta-analyses of the primary outcomes re-calculating the SE ([Higgins et al., 2019](#)) of the effect using a correlation of 0.5 (Follmann et al., 1992 as cited in [Fu et al., 2013](#)) for cross-over trials.”

Meta-analytic results

Fig.3: EMF exposure to head exposures on [headache](#) in the general population (n=7 studies; $I^2=0\%$)

Fig.4: EMF exposure to whole body exposures on [headache](#) in the general population (n=2; $I^2=24\%$)

Fig.5: EMF exposure to head exposures on sleep disturbances in the general population (n=8; $I^2=7\%$)

Fig.6: EMF exposure to whole body field exposures on sleep disturbances in the general population (n=1)

Fig.7: EMF exposure to head exposures on composite symptoms in the general population (n=3; $I^2=36\%$)

Fig. 8: EMF exposure to whole body exposures on composite symptoms in the general population (n=4; $I^2=0\%$)

Fig. 9: EMF exposure to head exposures on [headache](#) in IEI-EMF individuals (n=3; $I^2=0\%$)

Fig.10: EMF exposure to whole body exposure on [headache](#) in IEI-EMF individuals (n=1)

Fig.11: EMF exposure to whole body exposure on composite symptoms in IEI-EMF individuals (n=2; $I^2=64\%$)

Fig.12: EMF exposure to head exposure on composite symptoms in IEI-EMF individuals (n=3; $I^2=0\%$)

Conclusion

All but two (Fig.3, 5) of the 9 meta-analyses had methodological weaknesses due to few primary studies available for meta-analysis.

SR9: Meyer F, Bitsch A, Forman HJ, Fragoulis A, Ghezzi P, Henschenmacher B, Kellner R, Kuhne J, Ludwig T, Sachno D, Schmid G, Tsaion K, Verbeek J, Wright R. The effects of radiofrequency electromagnetic field exposure on biomarkers of oxidative stress in vivo and in vitro: A systematic review of experimental studies. *Environ Int.* 2024 Dec;194:108940. doi: 10.1016/j.envint.2024.108940. Epub 2024 Aug 14.

<https://www.sciencedirect.com/science/article/pii/S0160412024005269>

Meta-analytic methods

“We synthesized study results using a random effects meta-analysis when study characteristics were judged sufficiently similar to be combined and heterogeneity (I^2) was lower than 75 %, otherwise we describe the findings narratively.”

“Fifty-six (56) studies, 45 *in vivo* and 11 *in vitro*, in which cells (in vitro) or animals (in vivo) were exposed to frequencies in the range 800–2450 MHz, were included in the systematic review after eliminating 12,353 publications because they did not meet the criteria defined in the published protocol (Henschenmacher et al., 2022). Of 56 studies 52 studies with 169 individual results were included in the meta-analysis. Together, these studies examined six human *in vitro* samples and fifty animal samples, including rodents (mice, rats, hamsters, and guinea pigs, (n = 46)) and rabbits (n = 4). RF-EMF were predominantly applied as continuous wave exposures in these studies.”

“If more than one result was identified for the same PECO(S) element, the results were synthesized in a random-effects meta-analysis. Sometimes two or more results of one publication fell into the same PECO(S) element and originated from using the same control group. In these cases, the results included into one meta-analysis were not independent of each other and a unit-of-analysis error occurs (Higgins et al., 2023). Therefore, an aggregation procedure was performed (for details on the aggregation procedure see [Appendix 4](#)).”

“Considering the diversity of study designs used by the included studies, a DerSimonian-Laird random-effect model was applied to calculate the pooled effect size measure and the corresponding confidence interval (DerSimonian and Laird, 1986). Heterogeneity was quantified by calculating I^2 (Higgins and Thompson, 2002, Higgins et al., 2003) for each meta-analysis. In cases where $I^2 > 75$ %, the individual results were not synthesized. Confidence intervals (CI) were calculated at the $\alpha = 0.05$ level. Individual study results, as well as pooled results, were reported as forest plots.

All analyses were conducted using R version 4.2.2 (2022-10-31) (R Core Team, 2022) and the packages meta (Schwarzer, 2007, Balduzzi et al., 2019) and metafor (Viechtbauer, 2010).”

“The planned dose–response meta-analysis (Henschenmacher et al., 2022) was not carried out. The high RoB in reported exposure levels, the high heterogeneity in exposure parameters, and the lack of sufficient reporting of exposure metrics would have rendered such an analysis meaningless.”

Meta-analytic results

Fig.3A: Oxidized DNA bases (8-OHdG) in the brain of rodents, *in vivo* sorted by 4 exposure levels (I^2 not reported by level)
Overall (n=5 studies; $I^2=86\%$)

Fig.3B: Oxidized DNA bases in the brain of rodents, *in vivo* sorted by 2 RoB levels (I^2 not reported by level)
Overall (n=5; I^2 =86%)

Fig.4: Oxidized DNA bases (8-OHdG) in the brain of rabbits, *in vivo* sorted by 2 exposure levels (I^2 not reported by level)
Overall (n=2; I^2 =94%)

Fig. 5A: RF-EMF on modified proteins and amino acids in the brain of rodents, *in vivo* sorted by biomarker (I^2 not reported by level)
Overall (n=15; I^2 =86%)

Fig. 5B: RF-EMF on modified proteins and amino acids in the brain of rodents, *in vivo* sorted by exposure level (I^2 not reported by level)
Overall (n=15; I^2 =86%)

Fig. 5C: RF-EMF on modified proteins and amino acids in the brain of rodents, *in vivo* sorted by risk of bias (I^2 not reported by level)
Overall (n=15; I^2 =86%)

Fig.6: RF-EMF on oxidized lipids in brain of rodents, *in vivo*
Overall (n=1)

Fig.7: RF-EMF on oxidized DNA bases (8-OHdG) in liver of rodents, *in vivo* sorted by exposure level (I^2 not reported by level)
Overall (n=2; I^2 =85%)

Fig.8: RF-EMF on oxidized DNA bases (8-OHdG) in liver of rabbits, *in vivo* sorted by exposure level
Overall (n=2; I^2 =71%)

Fig.9A: RF-EMF on modified proteins and amino acids in liver of rodents, *in vivo* sorted by biomarker (I^2 not reported by level)
Overall (n=6; I^2 =54%)

Fig.9B: RF-EMF on modified proteins and amino acids in liver of rodents, *in vivo* sorted by exposure level (I^2 not reported by level)
Overall (n=6; I^2 =54%)

Fig.10: RF-EMF on oxidized DNA bases (8-OHdG) in blood of rodents, *in vivo* sorted by exposure level (I^2 not reported by level)
Overall (n=4; I^2 =77%)

Fig.11A: RF-EMF on modified proteins and amino acids in blood of rodents, *in vivo* sorted by biomarker (I^2 not reported by level)
Overall (n=3; I^2 =70%)

Fig.11B: RF-EMF on modified proteins and amino acids in blood of rodents, *in vivo* sorted by exposure level (I^2 not reported by level)
Overall (n=3; I^2 =70%)

Fig.12: RF-EMF on oxidized DNA bases (8-OHdG) in plasma of rodents, *in vivo* sorted by exposure level (I^2 not reported by level)
Overall (n=2; I^2 =17%)

Fig.13A: RF-EMF on oxidized DNA bases (8-OHdG) in testis of rodents, *in vivo* sorted by exposure level (I^2 not reported by level)

Overall (n=2; $I^2=0\%$)

Fig.13B: RF-EMF on oxidized DNA bases (8-OHdG) in testis of rodents, *in vivo* sorted by risk of bias (I^2 not reported by level)

Overall (n=2; $I^2=0\%$)

Fig.14A: RF-EMF on oxidized DNA bases (8-OHdG) in ovary of rodents, *in vivo* sorted by exposure level (I^2 not reported by level)

Overall (n=3; $I^2=87\%$)

Fig.14B: RF-EMF on oxidized DNA bases (8-OHdG) in ovary of rodents, *in vivo* sorted by risk of bias (I^2 not reported by level)

Overall (n=3; $I^2=87\%$)

Fig.15: RF-EMF on oxidized DNA bases (8-OHdG) in rodent cells, *in vivo*

Overall (n=1)

Fig.16: RF-EMF on oxidized lipids in rodent cells, *in vivo*

Overall (n=1)

Fig.17: RF-EMF on thymus in rodents, *in vivo*

Overall (n=1)

Fig.18A: RF-EMF on oxidized DNA bases (8-OHdG) in human cells, *in vitro* sorted by exposure level (I^2 not reported by level)

Overall (n=3; $I^2=78\%$)

Fig.18B: RF-EMF on oxidized DNA bases (8-OHdG) in human cells, *in vitro* sorted by risk of bias (I^2 not reported by level)

Overall (n=3; $I^2=78\%$)

Fig.19: RF-EMF on modified proteins and amino acids in) in human cells, *in vitro* sorted by exposure level

Overall (n=1)

Fig.20A: RF-EMF on oxidized DNA bases (8-OHdG) in rodent cells, *in vitro* sorted by exposure level (I^2 not reported by level)

Overall (n=3; $I^2=72\%$)

Fig.20B: RF-EMF on oxidized DNA bases (8-OHdG) in rodent cells, *in vitro* sorted by risk of bias (I^2 not reported by level)

Overall (n=3; $I^2=72\%$)

Fig.21A: RF-EMF on modified proteins and amino acids in rodent cells, *in vitro* sorted by biomarker

Overall (n=2; $I^2=0\%$)

Fig.21B: RF-EMF on modified proteins and amino acids in rodent cells, *in vitro* sorted by exposure level

Overall (n=2; $I^2=0\%$)

Fig.21C: RF-EMF on modified proteins and amino acids in rodent cells, *in vitro* sorted by risk of bias

Overall (n=2; $I^2=0\%$)

Conclusion

All meta-analyses had methodological weaknesses due to substantial between-study heterogeneity and/or few studies.