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The effects of radiofrequency exposure on male fertility: A systematic review of human observational studies with dose–response *meta*-analysis

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ABSTRACT

Background: The World Health Organization (WHO) is bringing together evidence on radiofrequency electromagnetic field (RF-EMF) exposure in relation to health outcomes, previously identified as priorities for research and evaluation by experts in the field, to inform exposure guidelines. A suite of systematic reviews have been undertaken by a network of topic experts and methodologists to collect, assess and synthesise data relevant to these guidelines. Following the WHO handbook for guideline development and the COSTER conduct guidelines, we systematically reviewed the evidence on the potential effects of RF-EMF exposure on male fertility in human observational studies.

Methods: We conducted a broad and sensitive search for potentially relevant records within the following bibliographic databases: MEDLINE; Embase; Web of Science and EMF Portal. We also conducted searches of grey literature through relevant databases including OpenGrey, and organisational websites and consulted RF-EMF experts. We hand searched reference lists of included study records and for citations of these studies. We included quantitative human observational studies on the effect of RF-EMF exposure in adult male participants on infertility: sperm concentration; sperm morphology; sperm total motility; sperm progressive motility; total sperm count; and time to pregnancy. Titles and abstracts followed by full texts were screened in blinded duplicate against pre-set eligibility criteria with consensus input from a third reviewer as required. Data extraction from included studies was completed by two reviewers, as was risk of bias assessment using the Office of Health Assessment and Translation (OHAT) tool. We conducted a dose–response *meta*-analysis as possible and appropriate. Certainty of the evidence was assessed by two reviewers using the OHAT GRADE tool with input from a third reviewer as required.

Results: We identified nine studies in this review; seven were general public studies (with the general public as the population of interest) and two were occupational studies (with specific workers/workforces as the population of interest).

General public studies.

Duration of phone use: The evidence is very uncertain surrounding the effects of RF-EMF on sperm concentration (10/6 mL) (MD (mean difference) per hour of daily phone use 1.6 10^6/mL, 95 % CI −1.7 to 4.9; 3 studies), sperm morphology (MD 0.15 percentage points of deviation of normal forms per hour, 95 % CI −0.21 to 0.51; 3 studies), sperm progressive motility (MD −0.46 percentage points per hour, 95 % CI −1.04 to 0.13; 2 studies) and total sperm count (MD per hour −0.44 10^6/ejaculate, 95 % CI −2.59 to 1.7; 2 studies) due to very low-certainty evidence. Four additional studies reported on the effect of mobile phone use on sperm motility but were unsuitable for pooling; only one of these studies identified a statistically significant effect. All four studies

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were at risk of exposure characterisation and selection bias; two of confounding, selective reporting and attrition bias; three of outcome assessment bias and one used an inappropriate statistical method.
Position of phone: There may be no or little effect of carrying a mobile phone in the front pocket on sperm concentration, total count, morphology, progressive motility or on time to pregnancy.
Of three studies reporting on the effect of mobile phone location on sperm total motility and, or, total motile count, one showed a statistically significant effect. All three studies were at risk of exposure characterisation and selection bias; two of confounding, selective reporting and attrition bias; three of outcome assessment bias and one used inappropriate statistical method.
RF-EMF Source: One study indicates there may be little or no effect of computer or other electric device use on sperm concentration, total motility or total count. This study is at probably high risk of exposure characterisation bias and outcome assessment bias.
Occupational studies.
With only two studies of occupational exposure to RF-EMF and heterogeneity in the population and exposure source (technicians exposed to microwaves or seamen exposed to radar equipment), it was not plausible to statistically pool findings. One study was at probably or definitely high risk of bias across all domains, the other across domains for exposure characterisation bias, outcome assessment bias and confounding.
Discussion: The majority of evidence identified was assessing localised RF-EMF exposure from mobile phone use on male fertility with few studies assessing the impact of phone position. Overall, the evidence identified is very uncertain about the effect of RF-EMF exposure from mobile phones on sperm outcomes. One study assessed the impact of other RF-EMF sources on male fertility amongst the general public and two studies assessed the impact of RF-EMF exposure in occupational cohorts from different sources (radar or microwave) on male fertility.
Further prospective studies conducted with greater rigour (in particular, improved accuracy of exposure measurement and appropriate statistical method use) would build the existing evidence base and are required to have greater certainty in any potential effects of RF-EMF on male reproductive outcomes. **Prospero Registration:** CRD42021265401 (SR3A)

1. Introduction

1.1. Background

The technological applications of radiofrequency electromagnetic fields (RF-EMF; frequencies 100 kHz to 300 GHz) have been steadily increasing since the 1950 s. RF-EMF are used in medicine (e.g. magnetic resonance imaging, diathermy, radiofrequency ablation), industry (e.g. heating and welding), domestic appliances (e.g. baby monitors, Wi-Fi), security and navigation (e.g. radar and radio frequency identification, RFID), and especially in telecommunications (e.g. radio and TV broadcasting, mobile telephony). These developments mean that large parts of the global population are now exposed to an increasing range of RF-EMF sources over increasing durations. Concern has been raised regarding the public health consequences from exposure to RF-EMF and it is therefore crucial to perform a health risk assessment to inform exposure guidelines.

The World Health Organization (WHO) has an ongoing project to assess potential health effects of exposure to RF-EMF in the general and working population. To prioritise the assessments of potential adverse health outcomes from exposure to these fields, the WHO conducted a broad international survey amongst RF experts in 2018 (Verbeek et al., 2021). Six priority topics were identified: cancer, adverse reproductive outcomes, cognitive impairment, symptoms, oxidative stress, and heat-related effects.

Survey results showed that 28 % of respondents deemed effects on male fertility critical for decision making. As such, these outcomes were indicated for further investigation (Verbeek et al., 2021). The reasoning given by the respondents (RF-EMF experts) for applying these ratings were public concern, knowledge from animal and human studies, and burden of disease.

WHO subsequently commissioned 10 systematic reviews of observational and experimental studies to collect, assess and synthesise the available evidence on these topics. Two related systematic reviews were commissioned to look at the effect of RF-EMF on adverse reproductive outcomes, one looking at male infertility (SR3A) and the other adverse pregnancy outcomes (SR3B). Each systematic review was registered with PROSPERO (SR3A, CRD42021265401 and SR3B, CRD42021266268) and had its full protocol published (Kenny et al., 2022).Here, we report on the effects of RF-EMF on male fertility outcomes (SR3A). Male infertility is defined as the inability of a man to cause pregnancy in a fertile female after 12 months or more of regular unprotected sexual intercourse (World Health Organization, 2020). Such infertility is strongly correlated with a lack of viable spermatozoa (e.g. reduced sperm concentration or total sperm count) (Levine et al., 2017). Declining sperm concentration has been consistently reported and debated over the past 50 years and can be attributed to a range of environmental and lifestyle exposures, such as pesticides, endocrine disrupters, body mass index (BMI), or type II diabetes (Levine et al., 2017).

Abnormal sperm morphology can also affect a man's ability to cause pregnancy, especially when abnormal morphologies occur in high quantities. Additionally, abnormally shaped sperm are usually associated with other semen irregularities, such as low sperm count or motility (American Society for Reproductive Medicine, 2014). Healthy sperm motility has forward progressions of at least 25 μm per second, containing at least 50 % grade A and B progressively motile sperm. If these factors are not met, the sperm may have difficulty passing though the cervical mucus, leading to failure in fertilisation (Kumar and Singh, 2015).

Evidence exists indicating that male reproductive outcomes (e.g. sperm motility, morphology, viability, and concentration) could potentially be affected by RF-EMF exposure (Kesari et al., 2018). For example, a review combining in vivo and in vitro evidence suggests mobile phone use negatively impacts sperm quality (Adams et al., 2014). Literature reviews have been performed to assess the evidence on RF-EMF regarding potential adverse health effects (International Commission on Non-Ionizing Radiation Protection (ICNIRP) (2020), Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR) (2015)). However, overall, the evidence to date on RF-EMF exposure and male fertility is unclear with conclusions to date drawn from non-systematic reviews.

To our knowledge, there is no existing systematic review of observational studies assessing the effect of localised (e.g. mobile phones) or whole-body (e.g. radio) exposure from RF-EMF in general living and work environments on male reproductive outcomes. We therefore aim to systematically review and synthesise evidence on the possible effect of exposure to RF-EMF sources on sperm outcomes.

2. Objectives

The review question is outlined using the Population (P); Exposure (E); Comparator (C); Outcome (O) criteria (Morgan et al., 2018) as follows:

Within human observational studies, what are the effects of localised and whole-body RF-EMF exposure (E) compared to no or low level exposure (C) in adult males (P) on male infertility, sperm morphology, motility, concentration or count, and time to pregnancy (O)?

A secondary objective of the systematic review was to assess whether a dose–response relationship between RF-EMF exposure and male fertility outcomes exist.

3. Methods

This systematic review was registered in PROSPERO under CRD42021265401 (SR3A) and the full protocol for the systematic review is published (Kenny et al., 2022).

3.1. Eligibility criteria

The PECO criteria are described below (Morgan et al., 2018). For those records deemed eligible for inclusion, the methods of exposure and outcome assessment used were noted during data extraction and then evaluated during risk of bias assessment. No deviations from eligibility criteria listed in full within the protocol were made (Kenny et al., 2022).

3.1.1. Population

We considered for inclusion any studies reporting on adult males exposure to environmental, from occupational and non-occupational sources, RF-EMF and the influence of this on infertility outcomes.

3.1.2. Exposures

In summary, we included studies of the effect of both whole-body and comparatively more localised RF-EMF exposure. Specific absorption rate (SAR), expressed in watts per kilogram (W/kg), was the idealised exposure metric of interest for the systematic review. However, as it was unlikely SAR at the reproductive organs would be readily used within studies, we also included epidemiological studies using surrogate RF-EMF exposure measures when reliant on measured or modelled levels of electric or magnetic fields or power density (e.g. at the participants' residence) or other similar exposure proxies.

Studies of mobile phone use were included when exposure assessments were based on self-reporting of proxy measures such as hours of phone use. We included studies which objectively measured and/or self-reported phone use as these measurements are known to be well correlated (compared to network provider data), although with some variation dependent on the study design, participants ages and outcome measures used (Vanden Abeele et al., 2013, Samkange-Zeeb et al., 2004).

Studies assessing exposure from base stations, were only included when distance to source assessment was measured objectively (e.g. derived from geocodes) and were excluded when distance to source assessment was self-reported, as these measures are not well correlated (Martens et al., 2017).

Studies using spot measurements, personal exposimeters and prediction models were included.

As indicated in the protocol, we expected a large proportion of studies to investigate occupational RF-EMF exposure sources (Kenny et al., 2022). Occupational RF-EMF exposure occurs from use of; navigation systems, broadcast and telecommunication equipment, security and access controls, plasma discharge equipment, tape erasers, welding equipment, and radar (Advisory group on Non-ionising radiation, 2003). For studies of occupational exposure, measurement data based on observations, expert assessment or any combination of these were included (Bondo Petersen et al., 2018). We also included studies of occupational exposure to RF-EMF within which exposure level was modelled based on job-exposure matrices (JEMs) but not when exposure was modelled based on job title alone.

We did not include studies where exposure to an RF-EMF source was assessed as "exposed versus unexposed" through response to a dichotomous question (e.g. "*have you ever owned a mobile phone?*" yes/no). This is due to the high level of imprecision created when assessing RF-EMF exposure using this approach.

We excluded studies of RF-EMF exposure from medical technologies when the population of interest were patients rather than workers using the technology. This is because the review aims to assess the impact of RF-EMF on workers exposed on a regular basis over a longer time duration than we would see within a patient population exposed at low and, or, acute levels over a short period of time. Timing of RF-EMF exposure comparative to outcome assessment was not used as an exclusion criterion but was considered in risk of bias assessments (Bonde et al., 2019, Anand-Ivell et al., 2018, Selevan et al., 2000, Cohen Hubal et al., 2014, Wigle et al., 2007, Porpora et al., 2019).

3.1.3. Comparators

We included studies comparing RF-EMF exposure in a low exposure or non-exposure group to a "high" exposure group (i.e. utilising categorical data), as per study authors' definition. We also included studies comparing at least two different levels of RF-EMF of varying exposure and duration, as well as studies presenting dose–response data with a continuous scale of varying RF-EMF exposure.

3.1.4. Outcomes

We included studies assessing fertility and time to pregnancy outcomes in a dichotomous manner. We included studies in which newly diagnosed cases of male infertility were an outcome of interest when this outcome was based on a physician's diagnosis and in agreement with the definition of male infertility as "the inability to cause pregnancy in a fertile female after a specific period of follow-up".

Studies with sperm concentration or total sperm count, morphology, or motility as outcomes of interest were included if assessment of the outcomes was undertaken in a quantitative manner. Studies with other sperm parameters as outcomes of interest were excluded, as the validity of these broader sperm outcomes as diagnostic measures for infertility have not been established. We included studies that assessed sperm concentration and total sperm count, sperm morphology and motility both categorically and/or continuously. The WHO reference ranges were used to establish normal values for these outcomes of interest (World Health Organization, 2021).

Studies using self-reported outcomes of male infertility were excluded.

3.1.5. Types of studies

3.1.5.1. Inclusion criteria. We considered cohort (including analysis conducted using dose–response methods) and case-control studies to be eligible for inclusion.

3.1.5.2. Exclusion criteria. Cross-sectional studies of male infertility were excluded because in these studies no temporality can be inferred between exposure and outcomes, meaning no inference on causality can be made. Studies with self-selection of participants from an unidentified study population, e.g. through advertisement, were excluded. Preclinical and in vitro studies were excluded.

3.1.5.3. Years considered. We did not exclude any studies based on year of publication. Searches, as outlined below, were designed to include publications from inception of databases to the search conduct date.

3.1.5.4. Publication language. We included studies written in any

language, provided that an English translation could be obtained.

3.1.5.5. Publication types. We aimed to include published and unpublished reports of studies which adhered to the eligibility criteria already outlined. Given this, conference proceedings, abstracts, theses/dissertations, guidelines and reports from public health and radiation protection bodies as well as research publications were included. Case reports were excluded.

3.2. Information sources and search strategy

Eligible studies were identified by literature searches through MEDLINE and Embase. The EMF Portal, a dedicated database of the scientific literature on the health effects of exposure to electromagnetic fields (https://www.emf-portal.org/en) was also searched. The search strategy was developed iteratively based upon concepts integral to the review question and incorporates keyword terms and subject headings as well as outcome measures identified by clinical experts (see Supplementary File 1). No language or date restrictions were applied to the search, which was originally ran in November 2020, updated in December 2021 and then in January 2023. The search results were exported into EndNote and duplicates removed before screening commenced.

Grey literature was identified during April 2021 through searching of OpenGrey, focusing on guidelines and reports from public health and radiation protection bodies, theses and EMF conferences. Web of Science (conference abstracts) and IEEE Xplore® were searched to identify grey literature of relevance at this time, and these searches were updated in January 2022 and January 2023. OpenGrey was no longer available at the time of the update searches in lieu of which an internet search using advanced search functionality in Google was conducted. The updated search yielded a single study in this review and we therefore believe the current trajectory of the research would not require further literature searching updates.

These searches were supplemented by screening reference lists of previous systematic and narrative reviews of RF-EMF exposure on male fertility and female reproductive outcomes, as far as such reviews were available. Screening of references and citations of included studies was also completed. Individual reports of studies highlighted by topic experts were also evaluated for inclusion.

3.3. Selection process

De-duplicated search results were exported from EndNote to Rayyan for screening (Ouzzani et al., 2016). Pairs of reviewers independently checked the relevance of the identified records based on titles and abstracts (from RPWK, EEJ, AMA). We excluded irrelevant records that did not fulfil at least one of the inclusion criteria. Full texts of records included at this stage were then sourced. Pairs of reviewers (from RPWK, EEJ, AMA) then independently assessed included records based on full texts. This resulted in a final list of included and excluded studies. We undertook the same screening process for results of grey literature searches.

Across all steps, disagreements between reviewers were resolved by discussion. A third reviewer was consulted if no consensus could be reached (CC, FP).

3.4. Data collection process

A standardised set of details were extracted from included studies, full details on which is reported in the protocol (Kenny et al., 2022).

Using mutually agreed piloted Excel forms for data extraction, one reviewer (of RPWK, EEJ and AMA) extracted and recorded the relevant features of each included study. A second reviewer (of RPWK, EEJ and AMA) checked the extracted study information against the accompanying record(s) for completeness and accuracy flagging any discrepancy using the Excel comments feature. The reviewers then resolved any discrepancy by discussion; and where needed a third reviewer was involved to resolve conflict. We contacted study authors for missing information or data as required.

3.5. Risk of bias assessment

Risk of bias assessments were conducted at study and outcome level using the "Risk of Bias Rating Tool for Human and Animal Studies" developed by the National Toxicology Program Office of Health Assessment and Translation (Office of Health Assessment and Translation (OHAT) (2019), Rooney et al., 2014). Seven domains were assessed: selection/participation bias; exposure measurement errors; inaccurate outcome assessment; uncontrolled confounding; incomplete outcome assessment due to attrition/exclusion; selective outcome reporting; and other potential threats to internal validity. Each domain was rated with one of four options: definitely low, probably low, probably high, and definitely high risk of bias. Assessments were documented within mutually agreed piloted Excel forms using the Excel comments feature as required.

The following critical confounder relationships have been identified by experts in the RF-EMF field and were assessed: age, ethnicity, body mass index (BMI), socioeconomic status (SES), smoking status, and alcohol intake. The following confounders were considered important, but not critical: geographical location, co-exposures (e.g., occupation exposure to hazardous substances and heat), environmental noise, and air pollution. Lack of confounding control was not a reason for exclusion. The importance of any further confounders identified during data extraction were considered.

3.6. Synthesis methods

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.

Where it was not possible to perform *meta*-analysis, we have solely conducted a narrative synthesis to give a summary of the current state of knowledge in relation to the review questions to the best of our ability given published data (Popay et al., 2006). We have utilised the Synthesis Without Meta-analysis (SWiM) reporting guidelines to record our narrative synthesis and approach transparently (Campbell et al., 2020).

3.7. Reporting bias assessment

Due to a lack of data identified, no analyses for publication or reporting bias were undertaken (see deviations from protocol for further information).

3.8. Certainty assessment

Where possible, we examined the certainty of evidence for outcomes with a dose–response analysis using the OHAT GRADE method (Office of Health Assessment and Translation (OHAT) (2019)). OHAT GRADE rates the certainty of the evidence in epidemiological and toxicological studies by assessing the following domains: imprecision; indirectness; inconsistency; publication bias; risk of bias; magnitude of effect; plausible confounding; dose response. However, we did not assess the domain of consistency across models or study design. As indicated in the protocol and after extensive discussion with the OHAT and - GRADE experts, Dr Rooney and Dr Morgan, we decided that the use of the extra domain was not appropriate for this review. In accordance with OHAT GRADE guidance, a single reviewer (EEJ) made an initial assessment of what level the evidence assessment would start at for each outcome (very low, low, moderate or high), which was checked by another reviewer (RPWK). Two reviewers (RPWK and EEJ) then independently assessed the certainty of evidence based on each domain. Disagreements were resolved by discussion and where needed with input from a third reviewer (FP) before a final confidence rating was assigned to each outcome. We used the phrasing recommended by Santesso et al (2020) to frame results in terms of their overall OHAT GRADE rating.(Santesso et al., 2020) Where dose–response *meta*-analysis was not possible, we considered the risk of bias across studies reporting on an outcome.

3.9. Deviations from protocol

No additional data was gained from study authors and no imputation of missing data was conducted.

It was not feasible to statistically assess publication bias conducting the Egger's test for categorical outcomes, or the method proposed by Doleman *et al* for continuous outcomes (Doleman et al., 2020) or the arcsine test for dichotomous outcomes (Rücker et al., 2008).

RF-EMF exposure from differing sources was considered separately rather than similarly in the narrative synthesis. It was not possible to statistically combine study findings and present sub-group analyses to explore exposure source.

When sufficient data was available, we conducted dose response analyses and did not perform traditional *meta*-analysis as doses in studies were not consistently reported at similar levels allowing for standardised comparison of high and low/no exposure. Had we conducted traditional *meta*-analysis we could have presented assessment of MDs per hour with heterogeneity visually. Between-study heterogeneity and the I^2 percentage were calculated and reported but other assessments of statistical heterogeneity were not conducted.

No sensitivity analyses were conducted to test review process assumptions or the effect of risk of bias on review findings.

4. Results

4.1. Results of the search

Database searching lead to 20,329 records (after de-duplication) being screened at the title and abstract stage. Of these, 278 were sought for full text assessment and nine were not retrievable. Other documented search methods lead to a further 43 records being identified and assessed.

Eight studies were included in this review: six were related to general public exposure to RF-EMF, while the remaining two studies assessed exposure in occupational settings. The PRISMA diagram provides a breakdown of the study selection process (See Fig. 1). A full list of excluded studies can be seen in Supplementary File 2.

4.2. Excluded studies

This section reports exclusion reasons for both the male and female reviews as literature searching and screening was conducted simultaneously. Studies were excluded for the following reasons: wrong population (e.g. cancer patients, animal studies, n = 23); wrong exposure (e.g. not RF-EMF, ELF, n = 67); wrong outcome (e.g. cancer risk, motor development, n = 16); wrong study design (e.g. cross-sectional, n = 86); and wrong publication type (e.g. conference abstracts that lacked detail and results, n = 92).

4.3. Study characteristics

General characteristics of the studies reporting on male fertility outcomes are presented in Table 1.

Seven studies were focused on the general public (Chen et al., 2022, Feijo et al., 2011, Hatch et al., 2021, Jurewicz et al., 2014, Lewis et al., 2017, Rago et al., 2013, Zhang et al., 2016), while two were occupational studies (Lancranjan et al., 1975, Ye et al., 2007). For the occupational studies, men were seamen exposed to radar (Ye et al., 2007) or described as technicians exposed to microwaves (Lancranjan et al., 1975).

Seven studies were cohorts (Chen et al., 2022, Feijo et al., 2011, Hatch et al., 2021, Jurewicz et al., 2014, Lewis et al., 2017, Rago et al., 2013, Ye et al., 2007, Zhang et al., 2016). Lancranjan et al. (1975) appeared to be a case-control study, but its reporting regarding study design was unclear. The smallest study recruited 31 participants (Lancranjan et al., 1975), while the largest recruited 3100 (Hatch et al., 2021).

The studies were conducted in: China (Chen et al., 2022, Ye et al., 2007, Zhang et al., 2016); both the USA and Denmark (Hatch et al., 2021); Brazil (Feijo et al., 2011); Poland (Jurewicz et al., 2014); the USA (Lewis et al., 2017); Romania (Lancranjan et al., 1975); and Italy (Rago et al., 2013). In general, the age of participants was between 30 and 39 in five studies (Hatch et al., 2021, Jurewicz et al., 2014, Lancranjan et al., 1975, Lewis et al., 2017), between 20 and 29 in two (Zhang et al., 2016), and was not reported in one (Feijo et al., 2011). In one study Rago et al. (2013), mean ages ranged from 27.5 to 30 while in another Ye et al. (2007), the youngest participant was 22 and the oldest was 46.

The education level, alcohol intake, smoking status and abstinence rate of participants were either not reported or reported heterogeneously across the studies; details are reported in Supplementary Table 2.

4.4. Exposure characteristics

General characteristics of exposures assessed within the studies reporting on male fertility outcomes are presented in Table 2.

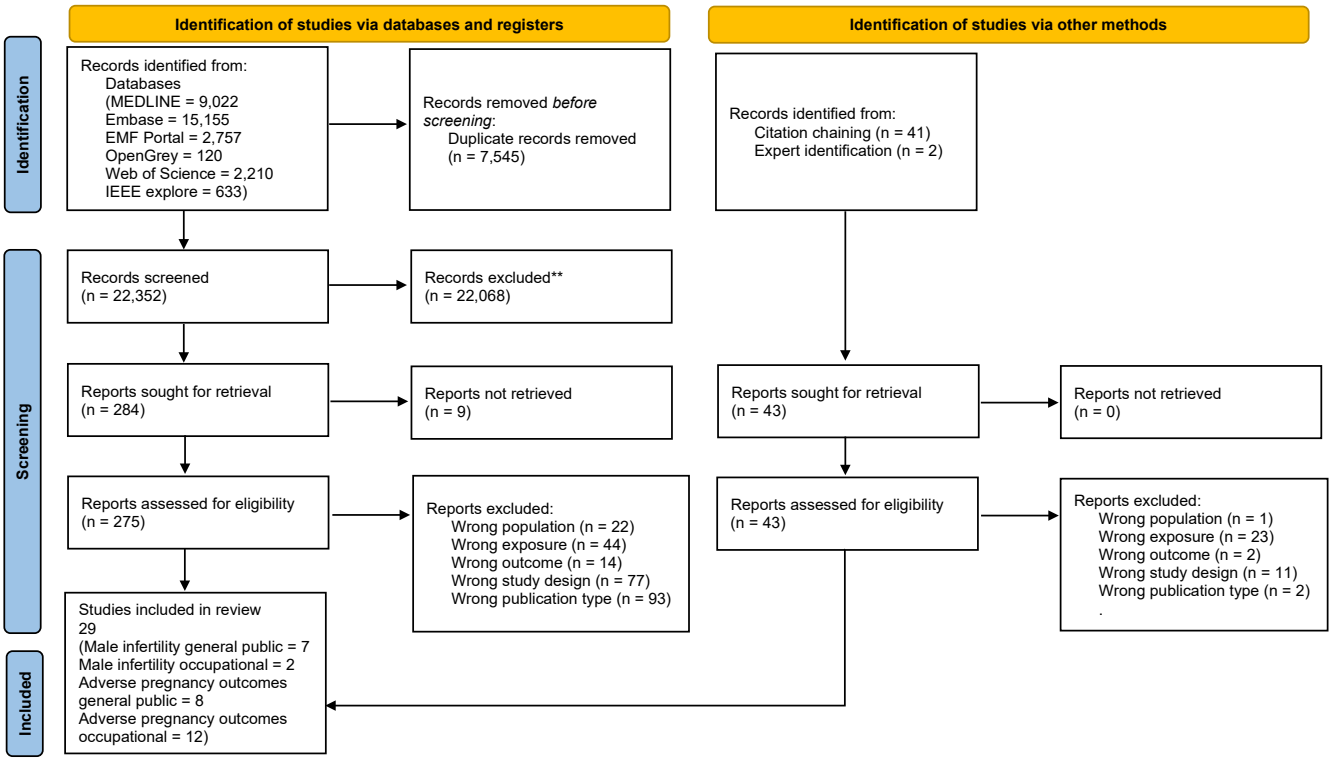

Fig. 1. PRISMA flow diagram.

The source of EMF exposure was: mobile phones in six studies (Feijo et al., 2011, Hatch et al., 2021, Jurewicz et al., 2014, Lewis et al., 2017, Rago et al., 2013, Zhang et al., 2016); mobile phones, computers and other electronic equipment in one (Chen et al., 2022); radar equipment in one (Ye et al., 2007); and was not reported in one (Lancranjan et al., 1975). The exposure metric was: hours or minutes of mobile phone use in two studies (Lewis et al., 2017, Zhang et al., 2016); hours of usage per day in one (Chen et al., 2022); hours/minutes of talking on a mobile phone in two (Feijo et al., 2011, Rago et al., 2013); years of mobile phone use in one (Jurewicz et al., 2014); hours of keeping a mobile phone in the front pocket of trousers in one (Hatch et al., 2021); number of participants who kept a phone in trouser pocket in two (Lewis et al., 2017, Rago et al., 2013); and both hours of daily mobile phone use and data traffic in terms of gigabytes (GB) of data used monthly in one (Zhang et al., 2016). No studies reported on exposure distribution or background exposure levels, while exposure location across the body, strength and the co-exposures considered by studies were either not reported or were reported heterogeneously; see Table 1.

4.5. Risk of bias in studies

Table 3 shows the risk of bias for all studies reporting on male fertility outcomes, ranked from the study with the most assessments of "definitely low" to the study with the most "probably and, or, definitely high and, or, N" assessments. For all studies, concerns were noted across all domains of the OHAT tool, with no single domain being mostly free from risk of bias. However, there are specific concerns about exposure characterisation bias, with no studies assessed as being at definitely low risk and only two judged to be at probably low risk of bias (Feijo et al., 2011, Hatch et al., 2021); the remaining studies were judged as at probably high (Chen et al., 2022, Lewis et al., 2017, Lancranjan et al., 1975, Rago et al., 2013, Ye et al., 2007, Zhang et al., 2016) or definitely high risk of bias (Jurewicz et al., 2014) for this domain. There are also specific concerns about outcome assessment bias, with only two studies judged to be at definitely low risk of bias (Jurewicz et al., 2014, Lewis et al.,), the rest judged to be at probably high risk of bias (2017 Chen et al., 2022, Feijo et al., 2011, Hatch et al., 2021, Lancranjan et al., 1975, Rago et al., 2013, Ye et al., 2007, Zhang et al., 2016). Three studies were deemed to have used inappropriate or insufficient statistical methods (e.g. they did not appropriately adjust for confounders in statistical analysis) (Feijo et al., 2011, Lancranjan et al., 1975, Ye et al., 2007).

4.6. Certainty of the evidence

Table 4 shows the OHAT GRADE evidence profile across all outcomes where dose–response and pairwise *meta*-analyses were possible. In general, all outcomes were judged to be of very low-certainty, with concerns regarding inconsistency due to large amounts of statistical heterogeneity on I^2 and indirectness, given that talk time is a proxy for overall minutes used and exposure may be too far away from the genitalia.

4.7. Synthesis

4.7.1. General public studies

All seven general public studies reported the effect of mobile phone exposure on sperm outcomes but not all were sufficiently comparable to include in individual dose–response analyses. Only one study assessed time to pregnancy (Hatch et al., 2021). The study by Zhang et al. (2016) could not be included in the dose–response analyses and is not included further in the narrative report as it did not clearly state a comparator or reference group. A list of all outcomes reported in the individual studies can be found in Table 1.

4.7.1.1. Sperm concentration (10^6/mL). Five studies reported the effects of mobile phone exposure on sperm concentration (Feijo et al., 2011, Jurewicz et al., 2014, Hatch et al., 2021, Lewis et al., 2017, Rago et al., 2013). One study reported the effects of mobile phone, computers, and other electronic devices on sperm concentration (Chen et al., 2022).

Duration of phone use.

Three studies could be combined for dose response *meta*-analysis

Table 1
Characteristics of studies focusing on male fertility.

Study ID	Groups	Number per group	Age	Occupation(s)	Education	Alcohol intake	Smoking	Abstinence
Feijo 2011	Non-users	23	NR	NR	NR	NR	NR	NR
	Talk time < 120 mins	266						
	Talk time 120–240 mins	88						
	Talk time > 240 mins	120						
Grajewski 2000	Exposed	12	32.3 ± 7.5	Water mattress manufacturer workers	NR	NR	NR	NR
	Unexposed	34	34.5 ± 9.3	Workers at a nearby communications equipment manufacturing facility (inspectors, technicians, assemblers in quality assurance and fiber-optic assembly departments				
Hatch 2021	SF: 0 h of mobile phone in front pants pocket	89	30 ± 4	NR	≥ College education: 71.7 %	Drinks per week: 4.5	Current smoker: 9 %	NR
	SF: ≥ 8 h of mobile phone in front pants pocket	278			≥ College education: 77.6 %	Drinks per week: 5.1	Current smoker: 8.2 %	
	PRESTO: 0 h of mobile phone in front pants pocket	375	32 ± 5		≥ College education: 54.6 %	Drinks per week: 5.7	Current smoker: 12.2 %	
	PRESTO: ≥ 8 h of mobile phone in front pants pocket	707			≥ College education: 67.4 %	Drinks per week: 6.2	Current smoker: 7 %	
Jurewicz 2014	0–5 years of mobile phone use	55	32.5 ± 4.8	NR	Primary and vocational education: 22.09 %	NR	Not smoking: 143	< 3 abstinence days: 18
	6–10 years of mobile phone use	179					Ex-smoker: 91	3–7 abstinence days: 250
	11–25 years of mobile phone use	82			Secondary education: 37.21 %		Smoker: 110	> 7 abstinence days: 22
					Higher education: 40.7 %			Missing: 54
Lancranjan 1975	Exposed	31	33 (SD not reported)	Technicians (no other information)	NR	NR	NR	NR
	Not exposed	30						
Lewis 2017	No use of phone	47	Median 36 (IQR 33 to 40.3)	NR	NR	Alcohol consumer: 97 (86 %)	Never smoked: 100 (65 %)	NR
	Use of headset or earpiece	31					Past or current smoker: 53 (35 %)	
	No headset or earpiece use	75				Not an alcohol consumer: 16 (14 %)		
	< 2 h per day use	81						
	2 + hours of use per day	25						
	Carried in pants pocket	84						
	Carried in other location	22						
Malini 2017	1–5 h of mobile phone use and contact with body	20	Range: 20 to 55	NR	NR	NR	NR	NR
	6–10 h of mobile phone use and contact with body	22						
	10 + hours of mobile phone use and contact with body	5						
Rago 2013	< 2 h mobile use per day	16	27.5 ± 5.5	NR	NR	NR	NR	NR
	2–4 h mobile use per day	17	30 ± 5					
	> 4 h mobile use per day	20	30 ± 4					
	No use	10	28.5 ± 6					
Schrader 1998	Radar use	33	24.2 ± 5.4	Radar operators: 33	NR	Drinks per day: 2.9 ± 5.2	Cigarettes, cigars or chews per day: 5.1 ± 8.6	Days of abstinence: 2.8 ± 1.14

(*continued on next page*)

Table 1 (*continued*)

Study ID	Groups	Number per group	Age	Occupation(s)	Education	Alcohol intake	Smoking	Abstinence
	Artillerymen	57	24.4 ± 4.1	Artillerymen: 57		Drinks per day: 7.6 ± 12	Cigarettes, cigars or chews per day: 2.8 ± 6.3	Days of abstinence: 2.8 ± 1.49
	Control	103	24 ± 4.2	Other: 103		Drinks per day: 8.4 ± 16.2	Cigarettes, cigars or chews per day: 8 ± 10.8	Days of abstinence: 2.84 ± 1.68
Ye 2007	Exposed for 12–36 months (mean 20.4 months)	128	25.5 (range 22–43)	Seamen	NR	NR	NR	NR
	Exposed for 37–72 months (mean 51.6 months)	58	26.5 (range 24–42)					
	Exposed for 73–108 months (mean 86.4 months)	47	27.5 (range 27–46)					
	Exposed for ≥ 109 months (mean 124.8 months)	19	27.2 (range 26–41)					
	Free from exposure for ≥ 6 months, but used to exposure for ≥ 48 months	96	NR					
Zhang 2016	2013	794	20.4 ± 1.2	NR	NR	Never drinks: 409 (51.6 %) Quit drinking: 10 (1.3 %) Current drinker: 374 (47.2 %) Missing: 2	Never smoked: 593 (74.7 %) Quit smoking: 30 (3.8 %) Current smoker: 171 (21.5 %)	Abstinence duration (days): 4.3 ± 1.7
	2014	666	21.4 ± 1.2			Never drinks: 130 (19.5 %) Quit drinking: 41 (6.2 %) Current drinker: 495 (74.3 %)	Never smoked: 483 (72.5 %) Quit smoking: 35 (5.3 %) Current smoker: 147 (22.1 %) Missing: 1	Abstinence duration (days): 4.2 ± 1.4
	2015	568	22.4 ± 1.2			Never drinks: 122 (21.5 %) Quit drinking: 22 (3.9 %) Current drinker: 423 (74.5 %) Missing: 2	Never smoked: 414 (72.9 %) Quit smoking: 26 (4.6 %) Current smoker: 128 (22.5 %)	Abstinence duration (days): 4.1 ± 1.2
Zilberlicht 2015	Abnormal sperm Normal sperm	34 45	34.9 ± 5.6	NR	12 years or less: 37 (46.3 %) Above 12 years: 43 (53.8 %)	NR	Never smoked: 43 (53.8 %) Ever smoked (less than 10 pack years): 37 (46.3 %)	NR

(Feijo et al., 2011, Lewis et al., 2017, Rago et al., 2013). The dose–response analysis, based on time of usage/contact with mobile phone, was categorised between 0 and 300 min. The evidence is very uncertain about the effect of using a mobile phone for one hour per day compared with no usage on sperm concentration (MD 1.6 10^6/mL; 95 % CI −1.7 to 4.9, n = 713, P = 0.34, see Fig. 2; very low-certainty evidence). Heterogeneity was observed to be high (I^2 = 89.9 %, τ = 0.0472). It is worth noting that Rago et al. (2013) report sperm concentration as sperm density, with their definition of sperm density matching our definition for sperm concentration. As such, this study was included in the analysis of the effect of mobile phone exposure on sperm concentration.

Two other studies reported on sperm concentration but looked at the impact of exposure sources using alternate metrics and could not be included in the *meta*-analysis (Jurewicz et al., 2014, Chen et al., 2022). In an adjusted analysis, Jurewicz et al reported that there was no statistically significant difference between using a mobile phone for 0–5 years or using for 11–25 years in terms of sperm concentration per 10^6/mL (β = –0.33, P = 0.14) (Jurewicz et al., 2014). In an adjusted analysis Chen et al reported 3.1 to 4.5 h of use and > 4.5 h of use per day were not statistically significantly different to using 3 h or less per day (percentage change −1.2, 95 % CI −10.2 to 8.7; and −2.5, 95 % CI −10.5 to 6.2 respectively) (Chen et al., 2022). However, data in this study was not reported at participant level, rather as an average across all semen samples provided by each individual patient.

Phone position.

Hatch et al. (2021) reported that keeping the mobile phone in the front pocket for 3–7 h and eight or more hours was not statistically significantly different to keeping the mobile phone in the front pocket

Table 2
Exposure characteristics of studies focusing on male fertility.

Study ID	Case definition	Control definition	Exposure location	Exposure distribution	Exposure strength	Background exposure levels	Listed co-exposures	Metric
Feijo 2011	Any users of cell phones, divided into 3 groups (talk time < 120 min, 120–240 min and > 240 min)	No use of mobile phone	NR	NR	Talk time < 120 min, 120–240 min and > 240 min	NR	NR	Minutes of talk time on mobile phone
Grajewski 2000	Workers at 4 water mattress manufacturers in Maryland	Workers at a nearby communications equipment manufacturing facility	Eye, chest, groin, feet	NR	Machine operating frequencies ranged from 12 to 57 mHz; 93 % of the machines had operating frequencies between 20.3 and 32 mHz	NR	1,1,1-trichloroethane, toluene, decane, 2-ethyl-1-hexanol, undecane, dodecane, remaining total hydrocarbons, formaldehyde, hydrochloric acid, sulfuric acid	mHz
Hatch 2021	Mobile phone exposure > 2 h	0–2 h of mobile phone in front pants pocket	Front pants pocket	NR	800–900 mHz for Danish cohort 800–2600 mHz for American cohort	NR	Alcohol, sweetened drinks	mHz
Jurewicz 2014	Mobile phone use for 6 + years	Mobile phone use 0–5 years	NR	NR	NR	NR	Smoking, past disease, alcohol usage, coffee consumption, leisure time activity, boxer shorts (yes/no), sauna (yes/no)	Years of mobile phone use
Lancranjan 1975	NR	"men without exposures"	NR	NR	Between 3 and 12 cm and frequencies between 10,000 and 3600 mHz	NR	NR	mHz
Lewis 2017	< 2 h per day on mobile phone or > 2 h per day on mobile phone; using headset or earpiece and not using a headset or earpiece	No mobile phone use	Pants pocket or other location, head	NR	NR	NR	NR	NR
Malini 2017	Users of mobile phones	Non-users of mobile phones	In trousers close to testis	NR	1–5, 6–10 and more than 10 h of exposure to mobile phones per day	NR	NR	Hours per day of mobile phone use
Rago 2013	Either using a mobile phone for < 2 h a day, 2–4 h a day or > 4 h per day	No use of mobile phone	In shirt or in trousers	NR	850, 900, 1900, 2100 mHz	NR	NR	mHz
Schrader 1998	Radar operators	Artillerymen or controls with neither exposure	NR	NR	Low, moderate or high	NR	Ethanol, tobacco	NR
Ye 2007	Infertile men with a history of radar exposure due to work	Men who were not occupied as seamen	NR	NR	Exposed for a minimum of 12–36 months (in Group 1) to ≥ 109 months (in Group 4)	NR	NR	Time on boat in months
Zhang 2016	2014 or 2015 questionnaire respondents	2013 questionnaire respondents	NR	NR	2G or 3G mobile phones	NR	NR	Hours of mobile phone use daily; GB of data used monthly
Zilberlicht 2015	Abnormal sperm concentration (according to WHO 2010 criteria)	Normal sperm concentration (according to WHO 2010 criteria)	≤ 50 cm or > 50 cm from the groin	NR	NR	NR	NR	Minutes of usage, number of phones used

for 0–2 h (adjusted percentage difference 9.6 % (95 % CI: −13.7 to 39.2 %), 13.8 % (95 % CI: −7.4 to 39.7 %) respectively). Additionally, Chen et al found no statistically significant effects of carrying the mobile phone in the pants on sperm concentration (percentage change −0.3, 95 % CI: −7.6 to 7.7) (Chen et al., 2022). Two other studies also reported no statistically significant effects on sperm concentration when comparing carrying a phone in the pocket to other locations (e.g., shirt, belt) or to non-users (Lewis et al., 2017, Rago et al., 2013). However, these studies only reported on the number of people carrying their phone in different locations, rather than on exposure time from a phone kept in such locations.

4.7.1.2. Sperm morphology. Four studies reported the effects of mobile phone exposure on sperm morphology in terms of percentage of normal forms (Feijo et al., 2011, Jurewicz et al., 2014, Lewis et al., 2017, Rago et al., 2013).

Table 3
Risk of bias assessments across male studies.

Study ID	Selection bias	Confounding bias	Attrition bias	Exposure characterisation bias	Outcome assessment bias	Selective reporting bias	Appropriate statistics
Hatch 2021	PH	DL	DL	PL	PH	DL	Y
Chen 2022	PL	PL	DL	PH	PH	DL	Y
Rago 2013	DL	PL	DL	PH	PH	DL	Y
Jurewicz 2014	PL	PL	PL	DH	DL	PH	Y
Lewis 2017	PL	PH	PL	PH	DL	PH	Y
Zhang 2016	PL	DL	DH	PH	PH	PL	Y
Ye 2007	DL	PH	DL	PH	PH	DL	N
Feijo 2011	PH	PL	PH	PL	PH	PL	N
Lancranjan 1975	PH	PH	PH	PH	PH	DH	N

Assessed using the OHAT tool.
Key: DL: definitely low; PL: probably low; PH: probably high; DH: definitely high; Y: yes; N: no.

Duration of phone use.

A dose–response *meta*-analysis was conducted on three studies (Feijo et al., 2011, Lewis et al., 2017, Rago et al., 2013), based on time of usage/contact with the mobile phone, categorised between 0 and 300 min. The evidence is very uncertain about the effects of using a mobile phone for one hour per day compared with no use on sperm morphology (MD 0.15 percentage points of abnormal sperm; 95 % CI −0.21 to 0.51, n = 713, P = 0.41, see Fig. 3; very low-certainty evidence). Heterogeneity was observed to be high (I^2 = 83.3 %, τ = 0.0044).

One study reported sperm head, neck and tail abnormalities as opposed to normal forms, so was not included in the analyses (Jurewicz et al., 2014). This study showed a positive association between more than 11 years mobile phone use when compared to zero up to five years use and: the percentages of atypical sperm (beta co-efficient = 19; p = 0.002), the percentage of sperm head abnormalities (beta co-efficient = 17.58; p = 0.01) but not neck or tail abnormalities (Jurewicz et al., 2014) nor when comparing 6–10 years mobile phone use to 0–5 years use (Jurewicz et al., 2014).

Phone position.

When considering the number of people carrying their phone in different locations, rather than on exposure time from a phone kept in such locations Rago et al. (2013) and Lewis et al. (2022) found no significant differences in sperm morphology. Respectively, carrying a mobile phone in the trousers (n = 12; mean = 9 % normal forms) compared with carrying in the shirt (n = 8; mean = 11 % normal forms) (Rago et al., 2013) and carrying a mobile phone in a trouser pocket compared to no use (beta co-efficient = 0.96, 95 %, CI 0.77–1.18) (Lewis., 2022).

4.7.1.3. Sperm total motility (%). Four studies reported the effects of mobile phone exposure on sperm total motility (Chen et al., 2022, Hatch et al., 2021, Jurewicz et al., 2014, Lewis et al., 2017).

Duration of phone use.

No studies were suitable for statistical pooling. A study conducting adjusted analysis suggested that there may be little difference in sperm motility between men who did not use a mobile phone, those who use one for less than two hours per day (β = 6.38 percentage points, 95 % CI: −1.2 to 14), and those who use one for one to two hours or more per day (β = 3.59 percentage points, 95 % CI: −6.61 to 13.79) (Lewis et al., 2017). Another study conducting adjusted analysis also suggested little difference in sperm motility between men who use a mobile phone from 3.1 to 4.5 h and > 4.5 h per day when compared to those who use for 3 h or less per day (percentage change 1.7, 95 % CI −3.1 to 6.8; −0.9, 95 % CI: −5.2 to 3.5, respectively) (Chen et al., 2022). However, another study conducting an adjusted analysis, (Jurewicz et al., 2014) indicated there may be a statistically significant difference in the level of sperm motility between men who have been using mobile phones for 0–5 years compared to those who have been using for 11–25 years (β = –11.08 percentage points, P = 0.02).

Phone position.

Hatch et al. (2021) suggested there may be little difference in sperm motility between those keeping their phone in their pocket for 3–7 h (adjusted mean difference –3.6 percentage points, 95 % CI: 4.6 to 8.8) or more than eight hours (adjusted mean difference –0.3 percentage points, 95 % CI: 11.9 to 12.9) when compared to those keeping their phone in their pocket for 0–2 h.

Chen et al. found no statistically significant effects of carrying the mobile phone in the pants on total motility (percentage change 1.4, 95 % CI −2.5 to 5.4).

Lewis et al. (2017) also reported no statistically significant changes in adjusted analysis between non-users and those carrying a mobile phone in the trouser pocket (β = 6.2 percentage points, 95 % CI: −1.32–13.71) or other locations (β = 3.56 percentage points, 95 % CI: −7.38–14.5). They did report a statistically significant increase in total motile sperm count for those carrying in the trouser pocket compared with no use (β = 1.65 percentage points, 95 % CI: 1.02–2.67).

4.7.1.4. Sperm progressive motility (%). Two studies reported the effects of mobile phone exposure on sperm progressive motility (Feijo et al., 2011, Rago et al., 2013). One study reported the effects of mobile phone, computers, and other electronic devices on sperm progressive motility (Chen et al., 2022).

Duration of phone use.

Two studies were included in the dose–response analysis (Feijo et al., 2011, Rago et al., 2013). Time of usage was categorised between 0 and 300 min. The evidence is very uncertain on the effects of using a mobile phone for one hour per day compared with no use on sperm progressive motility (MD −0.46 percentage change; 95 % CI −1.04 to 0.13, n = 560, P = 0.1307, see Fig. 4; very low-certainty evidence). There was no observable heterogeneity in the analysis (I^2 = 0 %, τ = 0).

Chen et al., 2022 presented adjusted analyses showing no statistically significant differences in sperm progressive motility when assessed by number of semen samples between hours of use for mobile phones, 3.1 to 4.5 h of use and > 4.5 h of use per day were not statistically significantly different to using 3 h or less per day (percentage change 1.2, 95 % CI −3.8 to 6.4; and −0.9, 95 % CI −5.3 to 3.7, respectively).

Phone position.

Additionally, Chen et al found no statistically significant effects of carrying the mobile phone in the pants on total motility (percentage change = 1.4, 95 % CI: −2.5 to 5.4).

4.7.1.5. Total sperm count (10^6/ejaculate). Three studies reported the effects of mobile phone exposure on total sperm count (Hatch et al., 2021, Lewis et al., 2017, Rago et al., 2013). One study reported the effects of mobile phone, computers, and other electronic devices on sperm concentration (Chen et al., 2022).

Duration of phone use.

Two studies were included in the dose–response analysis (Lewis

Table 4
GRADE evidence profile.

Certainty assessment								Summary of findings		Certainty	Comments
No of studies	Starting level[1]	Risk of bias	Inconsistency	Indirectness	Imprecision	Publication bias	Upgrading Domains	Participants No of participants	Effect Relative (95 % CI)		
Effects of RF-EMF exposure on sperm concentration (10^6/mL) in the general public											
3	Moderate	Downgrade[2]	Downgrade twice[3]	Downgrade twice[4]	No downgrade	No downgrade	No upgrades	713	MD 1.6 10^6/Ml (95 % CI −1.7 to 4.9)	Very low-certainty	Dose-response *meta*-analysis based on time of use/contact with mobile phone, categorised between 0 and 300 min
Effects of RF-EMF exposure on sperm morphology in the general public											
3	Moderate	Downgrade[2]	Downgrade twice[3]	Downgrade twice[4]	No downgrade	No downgrade	No upgrades	713	MD 0.15 (95 % CI −0.21 to 0.51)	Very low-certainty	Dose-response *meta*-analysis based on based on time of use/contact with mobile phone, categorised between 0 and 300 min
Effects of RF-EMF exposure on sperm progressive motility (%) in the general public											
2	Moderate	Downgrade[2]	No downgrade	Downgrade twice[4]	No downgrade	No downgrade	No upgrades	560	% change −0.46 (95 % CI −1.04 to 0.13)	Very low-certainty	Dose-response *meta*-analysis based on time of use categorised between 0 and 300 min
Effects of RF-EMF exposure on total sperm count (10^6/ejaculate) in the general public											
2	Moderate	Downgrade[2]	Downgrade twice[3]	Downgrade twice[4]	No downgrade	No downgrade	No upgrades	216	MD −0.44 (95 % CI −2.59 to 1.7)	Very low-certainty	Dose-response *meta*-analysis based on time of use categorised between 0 and 300 min

Footnotes: [1]Features of design assessed, all cohort studies start at moderate certainty level; [2] High risk of bias across included studies; [3] Substantial amount of statistical heterogeneity on I^2; [4] Talk time/usage may be too far away from the genitals; talk time is a proxy for overall minutes of use.

et al., 2017, Rago et al., 2013). Time of usage was categorised between 0 and 300 min of use. The evidence is very uncertain regarding the effects of using a mobile phone for one hour per day led compared with no use on total sperm count (MD −0.44 10^6/ejaculate; 95 % CI −2.59 to 1.7, n = 216, P = 0.6833, see Fig. 5; very low-certainty evidence). Heterogeneity was observed to be high (I^2 = 90 %, τ = 0.0246).

In the other study not *meta*-analysed (Chen et al., 2022), an adjusted analyses showed no statistically significant differences (when assessed by number of semen samples rather than by individuals) between hours of use for mobile phones, 3.1 to 4.5 h of use and > 4.5 h of use per day were not statistically significantly different to using 3 h or less per day (percentage change −7.6, 95 % CI −18.2 to 4.3 and −5.6, 95 % CI −15.4 to 5.2, respectively).

Phone position.

One study suggested that, when compared to those keeping their mobile phone in a front pocket for 0 to 2 h, there may be some decrease in total sperm count per 10^6/ejaculate compared to 3–7 h (adjusted % difference –10.6, 95 % CI –13.7 to 41.8) or for more than eight hours (adjusted % difference –8.7, 95 % CI –12.2 to 34.7) (Hatch et al., 2021).

Neither of the analysed studies observed any significant effects on total sperm count related to carrying location (Lewis et al., 2017, Rago et al., 2013). Adjusted regression coefficients showed no statistically significant differences in total sperm count between non-users and pants pocket carriers (β 1.25, 95 % CI 0.94 to 1.67) or other carrying locations (β 1.02, 95 % CI 0.68 to 1.55) (Lewis et al., 2017). No statistically significant differences were observed for total sperm count between trouser carriers (n = 12; mean = 182.8 10^6/ejaculate) versus shirt carriers (n = 8; mean = 205.5 10^6/ejaculate) (Rago et al., 2013).

4.7.1.6. Time to pregnancy. One study assessed the impact of carrying a phone in the front pocket on time to pregnancy (Hatch et al., 2021).

Phone position and duration of phone use.

Compared with men who did not keep their phone in their front pocket (reference value), the adjusted fecundability ratio for those with their mobile phone in their front pocket for < 1 to 2 h was 0.89 (95 % CI 0.78 to 1.02), 1.00 for 3–7 h (95 % CI 0.88 to 1.14), and 0.92 for > 8 h (95 % CI 0.8 to 1.06) (Hatch et al., 2021).

4.7.2. Occupational studies

Due to heterogeneity in population assessed, exposure source and outcome assessment, neither of the two occupational studies were able to be pooled into a dose–response analysis (see Table 2 for further details) (Lancranjan et al., 1975, Ye et al., 2007).

4.7.2.1. Sperm concentration (10^6/mL). Both studies suggested there may be a statistically significant difference between exposed and unexposed participants, with those unexposed to EMF generally having a higher sperm concentration (Lancranjan et al., 1975, Ye et al., 2007). In one study, male technicians had a mean concentration per 10^6/mL of 50 (SD 24), while those not exposed had a mean of 60 (SD 34; P < 0.02) (Lancranjan et al., 1975). In the other study, male seamen working across five submarines had a mean concentration ranging from 22.06 (SD 2.38; submarine 2) to 25.16 (SD 2.07; submarine 5) (Ye et al., 2007). In the two non-exposed groups, sperm concentration per 10^6/mL was 32.61 (SD 2.94) and 22.61 (SD 2.34) respectively.

4.7.2.2. Sperm morphology. One study suggested that there may be a statistically significant difference in sperm morphology between groups, with technicians exposed to microwaves having fewer normal forms (70 %, SD 6) compared to non-exposed controls (82 %, SD 7; P < 0.001) (Lancranjan et al., 1975).

4.7.2.3. Sperm motility (%). Both studies suggested there may be a statistically significant difference between exposed and unexposed in terms of percentage of motile sperm (Lancranjan et al., 1975, Ye et al.,

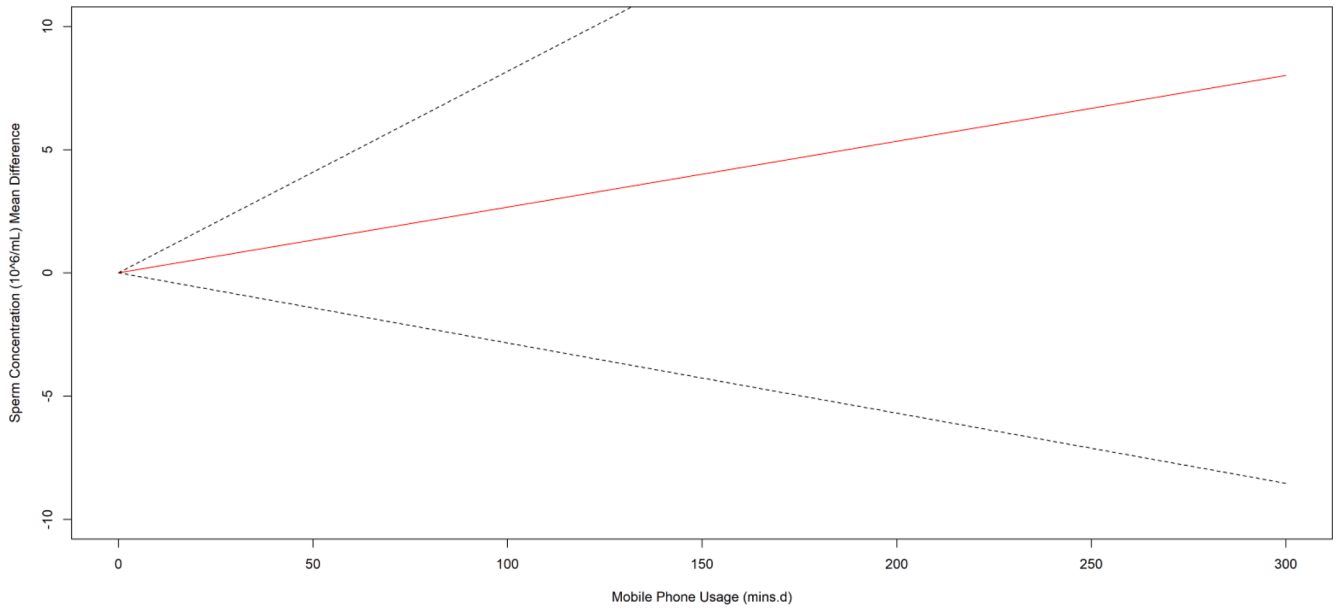

Fig. 2. Dose-response *meta*-analysis between the association of mobile phone usage and sperm concentration (106/mL) based on the linear model. The solid red line represents the fitted linear trend; dashed lines represent the 95% confidence intervals. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

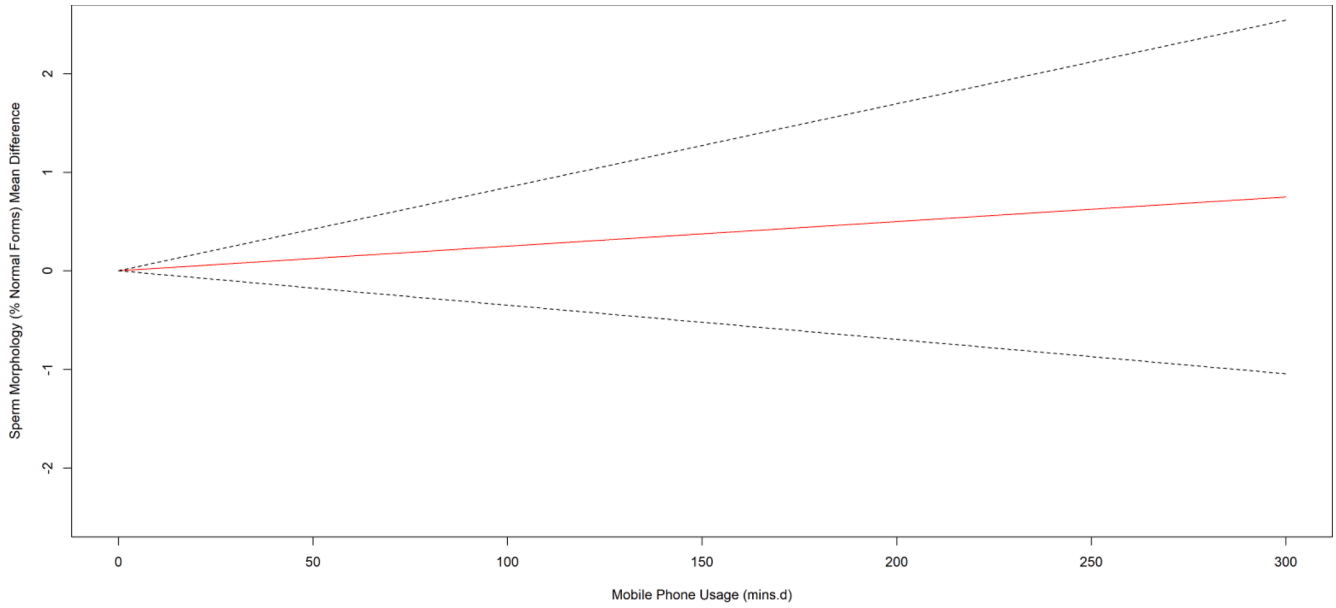

Fig. 3. Dose-response *meta*-analysis between the association of mobile phone usage and sperm morphology (percentage of normal forms) based on the linear model. The solid red line represents the fitted linear trend; dashed lines represent the 95% confidence intervals. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2007). In the first study, male technicians had a mean percentage motility of 36 % (SD 10), while those unexposed had a mean of 54 % (SD 19, $P < 0.001$) (Lancranjan et al., 1975). In the second study, male seamen working across five submarines had a mean percentage motility ranging from 31.22 % (SD 2.26; submarine 4) to 47.2 % (SD 1.95; submarine 1) (Ye et al., 2007). In the two non-exposed groups, mean percentage of motile sperm was 76.8 % (SD 1.59) and 40.97 % (SD 1.96) respectively, with the difference between groups being statistically significant ($P < 0.05$).

4.7.2.4. Total sperm count (10^6/ejaculate). No occupational study reported on total sperm count.

4.7.2.5. Time to pregnancy. No occupational study reported on time to pregnancy.

5. Discussion

5.1. Summary of the evidence and interpretation of the results

In total, nine studies were identified; seven general public studies and two occupational studies. The evidence is very uncertain regarding the effects of RF-EMF from mobile phones on sperm concentration, morphology, progressive motility and total sperm count in the general public due to very low-certainty evidence. We did not pool findings from

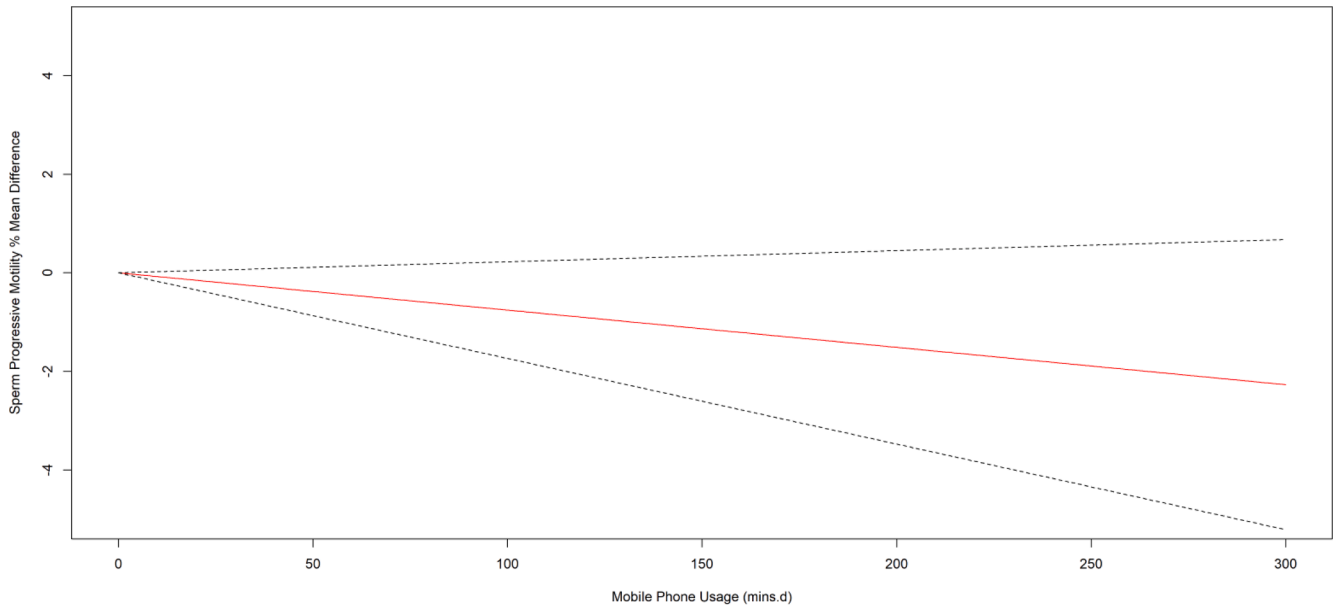

Fig. 4. Dose-response *meta*-analysis between the association of mobile phone usage and sperm progressive motility (percentage) based on the linear model. The solid red line represents the fitted linear trend; dashed lines represent the 95% confidence intervals. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

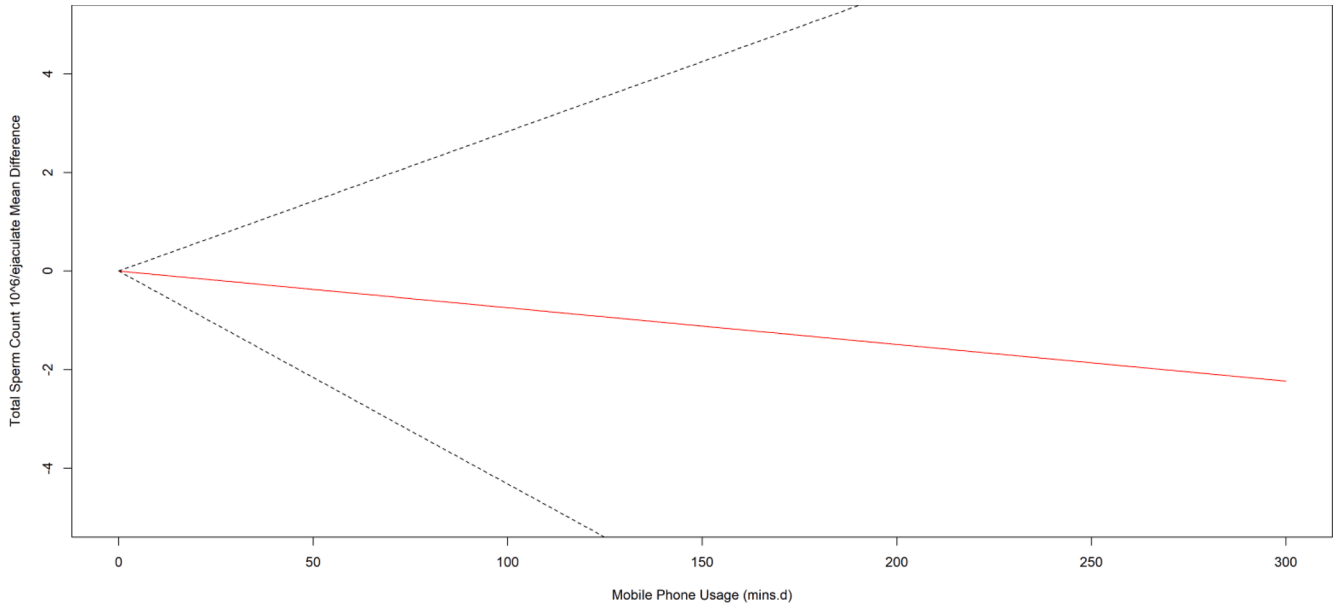

Fig. 5. Dose-response *meta*-analysis between the association of mobile phone usage and total sperm count (106/ejaculate) based on the linear model. The solid red line represents the fitted linear trend; dashed lines represent the 95% confidence intervals. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the two occupational studies identified due to the differences in populations and exposures assessed in each study (technicians exposed to microwaves and seamen exposed to radar equipment). Given the lack of data and the high risk of bias across several domains in the two studies, the effect of RF-EMF on male workers' fertility is uncertain.

5.2. Limitations of the evidence

The are multiple limitations with the evidence base of human observational studies assessing the effect of localised and whole-body RF-EMF exposure in adult males on their fertility, sperm morphology, motility, concentration or count, and time to conception. There are a lack of studies assessing the effect of RF-EMF on male fertility outcomes of interest. Most general public studies did not assess sources of RF-EMF exposure other than mobile phones (such as WiFi, local wireless networks or base stations). There were only two occupational studies each looking at a single exposure source (microwave and radar). This means we cannot assess the effects of the many other RF-EMF occupational exposure sources on male infertility (e.g. medical scanners, broadcasting and telecommunication devices, security and remote sensing devices).

All included studies were rated as probably or definitely at high risk of bias for at least two domains on the OHAT risk of bias tool. Seven of the nine included studies were at probably or definitely high risk of exposure characterisation bias (Lancranjan et al., 1975, Lewis et al.,

2017, Jurewicz et al., 2014, Rago et al., 2013, Ye et al., 2007, Zhang et al., 2016, Chen et al., 2022), while another seven were also at risk of outcome assessment bias (Hatch et al., 2021, Rago et al., 2013, Feijo et al., 2011, Ye et al., 2007, Lancranjan et al., 1975, Zhang et al., 2016, Chen et al., 2022). In three studies, issues surrounding the identification and handling of confounders were present (Lancranjan et al., 1975, Lewis et al., 2017, Ye et al., 2007), while three were also at risk of selective reporting (Jurewicz et al., 2014, Lewis et al., 2017, Lancranjan et al., 1975). Reporting on exposures characterisation across studies was often inconsistent and lacking in detail (see Table 2). Specific absorption rate (SAR), expressed in watts per kilogram (W/kg) was not utilised as the exposure metric in any study. Instead, most studies used a proxy exposure, such as time spent on mobile phone or mobile phone usage (which was not always clearly defined), with heterogeneity in methods of measurement. The studies identified often lacked appropriate adjustment for confounding (i.e. no multivariate analysis was performed) (Feijo et al., 2011, Lancranjan et al., 1975, Rago et al., 2013) and statistical methods were otherwise inappropriately used (Feijo et al., 2011, Ye et al., 2007, Lancranjan et al., 1975).

For general public studies that could be pooled, indirectness was an issue as the studies often used talk time as the measurement of exposure; this surrogate measure of exposure, while still localised and close to the body, may be located too far from the male reproductive organs to give an accurate, non-biased assessment of the impact of RF-EMF on fertility outcomes. Imprecision was also a major concern, as 95 % CIs were often very wide. In many of the analyses, there was also a large amount of unexplained statistical heterogeneity present. As demonstrated by the OHAT GRADE assessments, our confidence in the results of the dose–response analyses are very low with all analyses downgraded to very low-certainty evidence due to combinations of risk of bias, unexplained inconsistency, indirectness and imprecision.

5.3. Strengths and limitations of the review process

We conducted a comprehensive search for literature, conducted both forwards and backwards citation chaining and sought information from topic experts to limit the possibility of relevant eligible studies being missed. Screening was completed in blinded duplicate, with piloting of screening across all screening pairs to reduce the chance of inconsistent decision making on study eligibility. However, the use of different screening pairs means there could have been inconsistency in judgements made. Data extraction was completed by a single reviewer, which when compared to double data extraction may have increased errors (Buscemi et al., 2006). However, a second reviewer checked the data for accuracy to ameliorate this risk. All OHAT risk of bias and OHAT GRADE assessments were conducted by two independent reviewers with ratings agreed through consensus across the authorship team.

We expected many more studies to assess the effect of occupational exposure to RF-EMF on male fertility. However, numerous studies were excluded from this systematic review due to the way the measurement of the exposure was conducted or reported; for example, because exposure was reported based on job title alone.

5.4. Implications for biological plausibility

One of the main concerns with the dose–response *meta*-analysis was that the assessment of RF-EMF exposure within the included studies was via an indirect proxy measure (minutes or hours of usage of mobile phone devices when the device is some distance from the reproductive organs). Results of mobile phone studies included in this review suggest that exposure to RF-EMF from mobile phone usage, voice call and, or, other functions, or from being idle in a pocket does not lead to a reduction in sperm parameters linked to male fertility. The included studies assess very low levels of RF-EMF exposure to the reproductive organs, either due to the distance to the source or the infrequent transmissions during idle mode. The discussion of the effect of RF-EMF on non-human mammals and human sperm in vitro was beyond the scope of the current review. However, the WHO commissioned series also included a systematic review assessing these models (Cordelli et al., 2024).

5.5. Implications for research

The dose–response analyses conducted in this review are of very low-certainty and demonstrate a need for higher-quality, more robust prospective research to evaluate the effects of RF-EMF in both general public and occupational settings. In a general public setting, researchers should assess a greater range of technologies, with the majority of evidence currently being on exposure to RF-EMF from mobile phones. For example, far-field exposures (e.g. base stations) should be considered. Detail of exposure metrics assessed, and clear units of measurement should be provided. For example, the strength of mobile phone RF-EMF has varied over time and, where possible, this should be objectively quantified and reported. Additionally, when using metrics such as phone usage, this should be more specifically defined with reporting identifying clearly what it encompasses (e.g. talk time, app usage). In an occupational setting, greater effort should be made to complete prospective studies where multiple job roles, with varying RF-EMF exposure levels and duration of exposure are assessed. All studies should consider how the reproductive organs are exposed by the equipment being assessed and the biological plausibility of the effect given the distance, duration and strength of the exposure. Studies could use the core outcome set for infertility research to improve the consistency of outcome selection, collection and reporting across studies and, or, the emergent core outcome set for male fertility both part of the Core Outcome Measure for Infertility Trials (COMMIT) initiative (DUFFY, 2022, Rimmer et al., 2022). All studies should also collect and report all available demographic, exposure and analysis data transparently. Finally, any potential confounders (e.g. age or other environmental exposures) should be included in a multivariate analysis. Such research would enhance the quality of evidence available and allow for further evaluation of the potential effects of RF-EMF on male fertility from localised and whole-body exposures in which we could have greater certainty.

5.6. Conclusions

Overall, the evidence is very uncertain about the effect of RF-EMF on male fertility outcomes. Where dose–response *meta*-analysis was possible, the evidence was rated as very low-certainty on OHAT GRADE, while the majority of included studies were at risk of bias and only a small number of studies reported on each outcome of interest. Given this, we cannot be confident in what the current body of research concludes about the effect of RF-EMF on male fertility.

Further prospective studies conducted with greater rigour (in particular, improved accuracy of exposure measurement and appropriate statistical method use) are required to build on the existing evidence base and provide greater certainty in any potential effects of RF-EMF on male reproductive outcomes.

6. Other information

6.1. Registration and protocol

The protocol was published in Environment International (Kenny et al., 2022) and an abridged version is also available on PROSPERO (CRD42021265401; referred to as SR3A).

6.2. Funding support

All authors are salaried staff members of their respective institutions. The publication was prepared with financial support from the World

Health Organization.

6.3. Competing interests

Carolina Calderon was involved in both MOBI-Kids (risk of brain cancer from exposure to radiofrequency fields in childhood and adolescence) and GERoNIMO, Tsarna et al. 2019 was one of the outcomes of this project. Although Carolina was not involved in the publication, with her involvement being in the intermediate frequency exposure assessment.

Mireille Toledano has been involved in funded research assessing mobile phone and other wireless technologies usage on health outcomes. The SCAMP (study cognition adolescents and mobile phones) prospective cohort study which is currently ongoing (2015–2021). The COSMOS (cohort study of mobile phone use and health) a longitudinal cohort study which is completed (2019).

Author contributions.

- Conceptualisation: DC, FP.
- Data curation: CR, FB.
- Investigation: RPWK, EEJ, AMA.
- Formal analysis: RPWK, EEJ.
- Validation: RPWK, EEJ, AMA, CC, JR, MSP, MT.
- Writing – Original draft: RPWK, EEJ, CR.
- Writing – Review & Editing: RPWK, EEJ, FP.
- Supervision: FP.
- Project administration: FP.
- Funding acquisition: DC, FP.

CRediT authorship contribution statement

Ryan PW Kenny: . **Eugenie Evelynne Johnson:** Writing – review & editing, Writing – original draft, Validation, Investigation, Formal analysis. **Adenike M. Adesanya:** Validation, Investigation. **Catherine Richmond:** Writing – original draft, Data curation. **Fiona Beyer:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization. **Carolina Calderon:** Validation. **Judith Rankin:** Validation. **Mark S Pearce:** Validation. **Mireille Toledano:** Validation. **Dawn Craig:** Funding acquisition, Conceptualization. **Fiona Pearson:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Availability of other material.

None.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2024.108817.

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