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The effects of radiofrequency exposure on adverse female reproductive outcomes: A systematic review of human observational studies with dose–response *meta*-analysis

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ABSTRACT

Background: To inform radiofrequency electromagnetic field (RF-EMF) exposure guidelines the World Health Organization (WHO) is bringing together evidence on RF-EMF in relation to health outcomes prioritised for evaluation by experts in this field. Given this, a network of topic experts and methodologists have conducted a series of systematic reviews collecting, assessing, and synthesising data of relevance to these guidelines. Here we present a systematic review of the effect of RF-EMF exposure on adverse pregnancy outcomes in human observational studies which follows the WHO handbook for guideline development and the COSTER conduct guidelines.

Methods: We conducted a broad, sensitive search for potentially relevant records within the following bibliographic databases: MEDLINE; Embase; and the EMF Portal. Grey literature searches were also conducted through relevant databases (including OpenGrey), organisational websites and via consultation of RF-EMF experts. We included quantitative human observational studies on the effect of RF-EMF exposure in adults' preconception or pregnant women on pre-term birth, small for gestational age (SGA; associated with intrauterine growth restriction), miscarriage, stillbirth, low birth weight (LBW) and congenital anomalies. In blinded duplicate, titles and abstracts then full texts were screened against eligibility criteria. A third reviewer gave input when consensus was not reached. Citation chaining of included studies was completed. Two reviewers' data extracted and assessed included studies for risk of bias using the Office of Health Assessment and Translation (OHAT) tool. Random effects *meta*-analyses of the highest versus the lowest exposures and dose–response *meta*-analysis were conducted as appropriate and plausible. Two reviewers assessed the certainty in each body of evidence using the OHAT GRADE tool.

Results: We identified 18 studies in this review; eight were general public studies (with the general public as the population of interest) and 10 were occupational studies (with the population of interest specific workers/workforces).

General public studies.

From pairwise *meta*-analyses of general public studies, the evidence is very uncertain about the effects of RF-EMF from mobile phone exposure on preterm birth risk (relative risk (RR) 1.14, 95% confidence interval (CI): 0.97–1.34, 95% prediction interval (PI): 0.83–1.57; 4 studies), LBW (RR 1.14, 95% CI: 0.96–1.36, 95% PI: 0.84–1.57; 4 studies) or SGA (RR 1.13, 95% CI: 1.02–1.24, 95% PI: 0.99–1.28; 2 studies) due to very low-certainty evidence. It was not feasible to *meta*-analyse studies reporting on the effect of RF-EMF from mobile

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phone exposure on congenital anomalies or miscarriage risk. The reported effects from the studies assessing these outcomes varied and the studies were at some risk of bias. No studies of the general public assessed the impact of RF-EMF exposure on stillbirth.
Occupational studies.
In occupational studies, based on dose–response *meta*-analyses, the evidence is very uncertain about the effects of RF-EMF amongst female physiotherapists using shortwave diathermy on miscarriage due to very low-certainty evidence (OR 1.02 95% CI 0.94–1.1; 2 studies). Amongst offspring of female physiotherapists using shortwave diathermy, the evidence is very uncertain about the effects of RF-EMF on the risk of congenital malformations due to very low-certainty evidence (OR 1.4, 95% CI 0.85 to 2.32; 2 studies). From pairwise *meta*-analyses, the evidence is very uncertain about the effects of RF-EMF on the risk of miscarriage (RR 1.06, 95% CI 0.96 to 1.18; very low-certainty evidence), pre-term births (RR 1.19, 95% CI 0.32 to 4.37; 3 studies; very low-certainty evidence), and low birth weight (RR 2.90, 95% CI: 0.69 to 12.23; 3 studies; very low-certainty evidence). Results for stillbirth and SGA could not be pooled in *meta*-analyses. The results from the studies reporting these outcomes were inconsistent and the studies were at some risk of bias.
Discussion: Most of the evidence identified in this review was from general public studies assessing localised RF-EMF exposure from mobile phone use on female reproductive outcomes. In occupational settings, each study was of heterogenous whole-body RF-EMF exposure from radar, short or microwave diathermy, surveillance and welding equipment and its effect on female reproductive outcomes. Overall, the body of evidence is very uncertain about the effect of RF-EMF exposure on female reproductive outcomes.
Further prospective studies conducted with greater rigour (particularly improved accuracy of exposure measurement and using appropriate statistical methods) are required to identify any potential effects of RF-EMF exposure on female reproductive outcomes of interest.

1. Introduction

1.1. Background

Radiofrequency electromagnetic fields (RF-EMF; frequencies 100 kHz to 300 GHz) technological application has steadily been 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). Given which, large parts of the global population are exposed to an increasing range of RF-EMF sources over longer durations. Concern has been raised regarding the public health consequences from exposure to RF-EMF and performing a health risk assessment to inform exposure guidelines is crucial.

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).

The WHO subsequently commissioned systematic reviews of observational and experimental studies to collect, assess and synthesise the available evidence on these topics. Survey results showed that 32 % of respondents deemed adverse pregnancy outcomes as critical for decision making. As such, these outcomes were indicated for further investigation (Verbeek et al., 2021).

The term “adverse reproductive outcomes” encompasses a heterogenous set of endpoints from a clinical perspective: “adverse pregnancy outcomes” such as spontaneous miscarriage which occurs in 25 % of pregnancies (Wang et al., 2021); pre-term birth occurring in 10 % of pregnancies; stillbirth occurring in 2 % of births; congenital anomalies occurring in up to 5 % of newborns and low birth weight occurring in 14.6 % of births (Blencowe et al., 2019).

These reproductive outcomes are linked with other detrimental events over the lifecourse, impacting health beyond their own occurrence. Spontaneous miscarriage is indicative of premature mortality in mothers (before age 70), particularly due to an increased risk of death from cardiovascular disease (Wang et al., 2021). Pre-term birth, especially in very early stages of gestation, is a serious condition that can lead to life-long complications for the child. For example, babies born before 37 weeks’ gestation are at a higher risk of neurodevelopmental disorders and respiratory and gastrointestinal impairments (Etzel, 2020). Intrauterine growth restriction may be associated with pre-term birth through medically indicated pre-term induction of labour but may also carry separate health consequences (Malhotra et al., 2019). Intrauterine growth is indicated by small for gestational age (SGA) or low birth weight adjusted for gestational age (Sharma et al., 2016). A low birth weight has been reported as an important predictor of morbidity and mortality in neonates, childhood, and adults (Lee et al., 2020). Epidemiological evidence demonstrates that environmental exposures can influence fetal growth and development via induction of changes in fetal growth patterns (Lee et al., 2020).

Exposure to RF-EMF could have a detrimental effect on pregnancy outcomes (e.g. miscarriage, congenital anomalies, low birth weight, and pre-term birth (Shah and Farrow, 2014, Mahmoudabadi et al., 2015, Kesari et al., 2018)). However, there is also evidence suggesting that mobile phone use does not negatively impact birth weight or foetal growth (Tsarna et al., 2019). Literature reviews have been performed to assess the body of evidence on RF-EMF regarding potential adverse health effects (International Commission on Non-Ionizing Radiation Protection (ICNIRP), 2020, Advisory group on Non-ionising radiation, 2012, Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR), 2015). Comparative to a literature review, a systematic review adheres to strict scientific design based on pre-defined, explicit, and reproducible methodology (Gopalakrishnan and Ganeshkumar, 2013). As such, their findings are generally less biased with more certainty than those from literature reviews. To our knowledge, there is no existing systematic review including articles assessing the effect of multiple sources of RF-EMF in general living and work environments on female reproductive outcomes. We therefore aim to systematically review and synthesise evidence on the possible effect of exposure to RF-EMF on adverse pregnancy outcomes (SR3B). A systematic review of observational studies assessing the effect of exposure from RF-EMF in general living and work environments on male reproductive outcomes (SR3A) is presented in an allied publication.

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) on pre-term birth; SGA; miscarriage; still birth and, or, congenital anomalies (O) compared to no or low level exposure (C) in preconception or pregnant adults (P)?

A secondary objective of the systematic review was to assess whether an exposure dose–response relationship between the RF-EMF exposure and adverse reproductive outcomes exists.

3. Methods

The protocol for the review was registered in PROSPERO under CRD42021266268 (SR3B). A full protocol for the reviews was also published (Kenny et al., 2022).

3.1. Eligibility criteria

The PECO criteria (Morgan et al., 2018) are described below.

For those records deemed eligible for inclusion, the methods of exposure and outcome assessment used were recorded during data extraction, evaluated during the risk of bias assessment. There was no deviation from the eligibility criteria listed in full within the protocol (Kenny et al., 2022).

3.1.1. Populations

We considered for inclusion studies reporting on the influence of RF-EMF exposure in periconceptual adults (paternal and maternal) or pregnant adults on adverse pregnancy outcomes. As such, we also considered for inclusion studies including exposed post-partum females and their offspring.

3.1.2. Exposures

Specific information on exposure measurement for these reviews has been reported extensively in the protocol (Kenny et al., 2022). Specific absorption rate (SAR), expressed in watts per kilogram (W/kg) was the ideal exposure measurement of interest for both reviews. However, as it was unlikely that SAR at the reproductive organs would be readily provided, we also included epidemiological studies using surrogate RF-EMF exposure measures that rely on measured or modelled levels of electric or magnetic fields or power density (e.g. at the participants' residence) or on exposure proxies, as mentioned below.

Studies of mobile phone use were included when exposure assessments could be based on self-reporting of proxy measures of exposure such as hours of use. We included studies with both objective phone use measurement and self-reported phone use because these measurements are known to be well correlated, although this varies depending on the study design, outcome measure and age (Vanden Abeele et al., 2013, Samkange-Zeeb et al., 2004).

For studies assessing base stations, we only included studies utilising objectively measured distance to source assessments (e.g. derived from geocodes) (Martens et al., 2017). Studies utilising self-reported distance to source assessments were excluded, as self-report measures are not well correlated with actual measures (Martens et al., 2017).

If identified, studies utilising spot measurements, personal exposimeters and prediction models would have been included.

Occupational RF-EMF exposure occurs from a multitude of sources, such as 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). Occupational exposure information can be based upon measurements, observations, expert assessment or combinations of these (Bondo Petersen et al., 2018). We included studies that measured exposure to RF-EMF at work using any of the aforementioned methods, or when an exposure level was modelled based on job-exposure matrices (JEMs), but not when this was done based on job title alone.

We did not include studies where exposure assessment was reported as a dichotomous answer to a question indicating exposure to a source vs none (e.g. '*have you ever owned a mobile phone?*' yes/no), due to the high level of imprecision in this approach.

We also excluded studies of exposure from medical technologies if the population of interest was patients, rather than staff using the technology and exposed occupationally. 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.

When evaluating the outcomes of interest (see section 3.1.4), paternal exposure of the testes during the three months prior to pregnancy was of most interest. When evaluating the effect of maternal exposure on the outcome pre-term birth, exposure during the whole pregnancy was considered first, then during the first and second trimesters. When evaluating the outcome small for gestational age (SGA) and congenital anomalies, we considered exposure across the whole pregnancy. Had data allowed, we would have considered each trimester individually.

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 that compared RF-EMF exposure in a low exposure or non-exposure group to a "high" exposure group (i.e. using categorical data). 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

The outcomes of interest were pre-term birth, SGA (including low birth weight at term as indicators of intrauterine growth restriction), miscarriage (sometimes synonymously termed spontaneous abortion in papers identified), stillbirth and congenital anomalies.

Pre-term birth was defined as being born before 37 completed weeks of gestation. The following categories of pre-term birth were used: very pre-term being born before week 32 and after week 28; and extreme pre-term birth as being born before week 28, as diagnosed by any measure (e.g. date of last menstrual period, ultra-sound assessment by a health care professional such as a midwife or a physician, or extracted from medical records or data registers).

Low birth weight was identified using WHO reference ranges for normal values in specific settings (Schlaudecker et al., 2017, World Health Organization, 2004).

Miscarriage was defined as pregnancy loss before 24 weeks not associated with medical or surgical intervention to terminate the pregnancy, based on assessment by a health care professional or extracted from medical records or data registers.

We defined, stillbirth as non-live birth after 24 completed weeks of pregnancy (World Health Organization, 2020). Stillbirth based on assessment by a health care professional or extracted from medical records or data registers was also considered.

As definitions of pre-term birth, miscarriage and stillbirth can vary depending on geographic setting, we collected information on the outcomes, the geographic location of definition use and the definition according to the study authors.

Had data allowed, congenital anomalies, defined as structural or functional abnormalities that are present from birth (e.g. neural tube defects) (World Health Organization, 2010), would have been subdivided according to organ system. Studies measuring congenital anomalies based on an assessment by a health care professional or extracted from medical records or data registers were considered.

Studies using self-reported records of pre-term birth, SGA (including low birth weight at term), miscarriage, stillbirth and congenital anomalies were excluded.

3.1.5. Types of studies

3.1.5.1. Inclusion criteria. We included cross-sectional, cohort, and case-control study designs. We considered studies where the analysis was conducted using dose–response methods. We included retrospective studies on post-partum women where exposure during pre-conception or during pregnancy was provided.

3.1.5.2. Exclusion criteria. Case reports and studies with self-selection of participants from an unidentified study population, e.g. through advertisement, were excluded. Pre-clinical and in vitro studies were also excluded.

3.1.5.3. Years considered. We did not place any restrictions 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 consulted. The search strategy was developed iteratively based upon concepts integral to each review question and incorporated up to date 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 October 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 October 202, updated in December 2021 and then in January 2023, 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. An internet search using advanced search functionality in Google, and other search engines if appropriate, was also conducted.

These searches were supplemented by checks of the reference lists of previous systematic reviews and narrative reviews, as far as such reviews were available. Screening of references and citations of included studies was also completed. Papers highlighted by topic experts were also evaluated for inclusion. The updated search yielded no further studies in this review and we therefore believe the current trajectory of the research would not require further literature searching updates.

3.3. Selection process

De-duplicated search results were exported from EndNote to Rayyan for screening (Ouzzani et al., 2016). Pairs of reviewers (from RPWK, EEJ, AMA, CC, LBM) independently checked the relevance of the identified papers based on titles and abstracts. We excluded irrelevant records that did not fulfil at least one of the inclusion criteria. Full texts of records included at this stage were 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 process for grey literature searches.

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

3.4. Data extraction

A standard set of details were extracted from the relevant publication (s). The relevant data extracted are reported in the full protocol (Kenny et al., 2022).

Based on mutually agreed piloted Excel forms for data extraction, one reviewer (of RPWK, EEJ and AMA) extracted and recorded the relevant features of each eligible study. A second reviewer (of RPWK, EEJ and AMA as appropriate) checked the extracted study information against the accompanying article(s) for completeness and accuracy and using the excel comments feature. The reviewers resolved any possible disagreements by discussion; a third reviewer was involved to resolve conflicts (FP). We contacted study authors for missing information or data as required.

If findings from a study were reported in more than one record, we considered them together for data extraction. We used the earliest publication or report as the dominant record and only extracted findings reported in subsequent publications or reports when not already available from the original record or as relevant.

3.5. Risk of bias assessment

Risk of bias assessment was 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 but was considered in risk of bias assessments. Any further confounders reported by study authors and highlighted during data extraction were considered.

All OHAT risk of bias assessments were undertaken by two independent reviewers with ratings agreed as needed through opinion from a third independent reviewer. As outlined in the protocol risk of bias assessments were concerned with the accuracy of measurements used rather than directness which has been considered during OHAT GRADE assessment (Kenny et al., 2022).

3.6. Assessment of reporting biases

Selective outcome reporting bias was considered in risk of bias assessment, which is then considered in OHAT methodology (Office of Health Assessment and Translation (OHAT), 2019), based on the GRADE guidelines for evidence assessment, to evaluate the certainty in evidence of a health effect (Guyatt et al., 2011, Rooney et al., 2014).

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

3.7. Synthesis of results

A random-effects pairwise *meta*-analysis was conducted using the metafor package in RStudio (Viechtbauer, 2010). Tau (τ) was estimated using the restricted maximum likelihood (REML) method. The Hartung-Knapp-Sidik-Jonkman correction, using the t-distribution, for calculation of the 95 % confidence intervals (CIs) was utilised. The unadjusted risk ratios (RR) were calculated for outcomes reporting enough data to be combined. Heterogeneity was assessed using the I2 and τ2 statistics. Prediction intervals (PI) are also provided.

Where at least two studies reported results per increase in exposure, we performed a dose–response *meta*-analysis using RStudio (R Core Team, 2020; v4.0.4). The package *dosresmeta* was used to perform a *meta*-analysis of possible dose–response (Crippa and Orsini, 2016). All analyses were conducted using a linear and a non-linear quadratic model. It is important to assess whether a mathematical model provides the 'best' answer to a question. Often, non-linear models possibly reflect the exposure under study better than linear models. As this was potentially the case for RF-EMF we performed both a linear and a quadratic dose response analysis. We then assessed which model was providing the best answer to our question as denoted by fit (Shim and Lee, 2019). The model with the best fit, as assessed by the χ^2 test for goodness-of-fit, log likelihood, Akaike information criterion and Bayesian information criterion, was utilised. When the authors reported risk per category of exposure (odds ratio; OR), a single exposure dose was assigned to each category: for closed categories, the midrange score was used; and 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).

Between-study heterogeneity (τ) was calculated using the restricted maximum likelihood (REML) method. Additionally, we also calculated 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).

3.8. Certainty assessment

We examined the certainty of evidence for outcomes where *meta*-analysis was possible 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. After extensive discussion with the OHAT and GRADE experts, Dr Rooney and Dr Morgan, we decided that the use of the extra domain is 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 for each outcome based on each domain of OHAT GRADE. 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) Group consensus on ratings made were achieved across the authorship group. Where narrative synthesis was undertaken, we considered the risk of bias across studies reporting on an outcome.

3.9. Deviations from protocol

We had originally planned to divide analyses into subgroups by trimester but this was not possible due to lack of data. Additionally, we had planned for congenital anomalies, to be subdivided according to organ system but this was not possible due to limitations in the data.

Reporting biases, 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).

Due to the limited number of studies in both the dose–response and pairwise analyses, we could not perform any subgroup or sensitivity analyses.

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

Overall, database searching led to 20,329 records (after deduplication) being screened at the title and abstract stage. Of these, 278 were sought for full text assessment, nine were not retrievable. Citation chaining and expert identification led to a further 43 records being assessed. Eighteen studies were included in this review. Eight were related to general public exposure to RF-EMF, while the remaining 10 studies assessed exposure in occupational settings. Three studies reported on an overlapping population of male Norwegian Royal Navy personnel (Baste et al., 2012, Mageroy et al., 2006, Mollerlokken and Moen, 2008). Baste et al. (2012), being the largest and most recent study, was the only one included in the synthesis due to the high possibility of records including the same participants multiple times. 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 female fertility outcomes are presented in Table 1.

Eight studies were identified in which the general public were the population of interest (Baste et al., 2015, Boileau et al., 2020, Brizzi and Marinelli, 2018, Karuserci et al., 2019, Lu et al., 2017, Mahmoudabadi et al., 2015, Tsarna et al., 2019, Zhao et al., 2021), while 10 studies were identified in which the population of interest was an occupational group (Allam, 2016, Baste et al., 2012, Cromie et al., 2002, Källén et al., 1982, Khan et al., 2018, Kolmodin-Hedman et al., 1988, Lerman et al., 2001, Ouellet-Hellstrom and Stewart, 1993, Taskinen et al., 1990).

For the occupational studies, participants were recruited from:

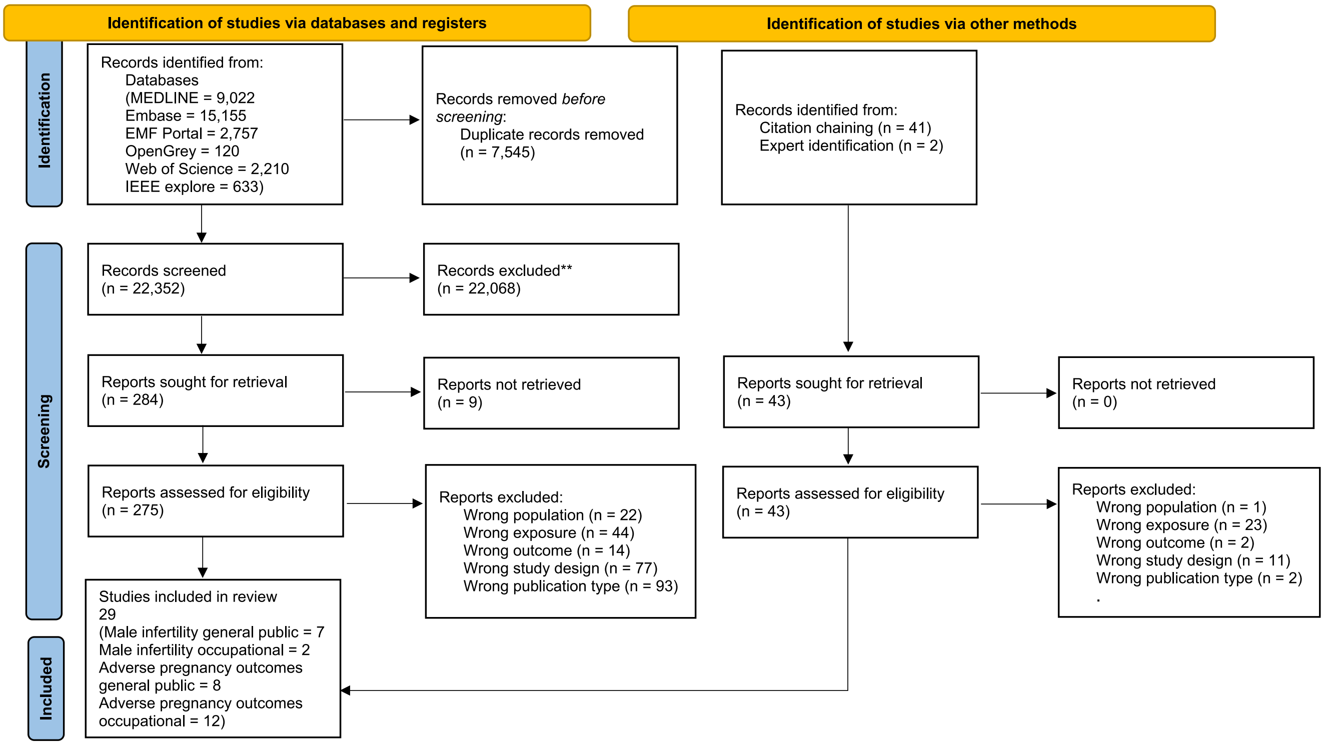

Fig. 1. PRISMA flow diagram which includes the screening process for both the male and female reviews.

hospitals or outpatient clinics (Allam, 2016); naval settings (Baste et al., 2012); registries of physiotherapists (Cromie et al., 2002, Källén et al., 1982, Lerman et al., 2001, Ouellet-Hellstrom and Stewart, 1993); a register of a retail company or a birth register (Khan et al., 2018); factories (Kolmodin-Hedman et al., 1988, Xu et al., 2016); or a register of congenital anomalies and hospital discharge register (Taskinen et al., 1990).

In total, five studies were cohort studies (Allam, 2016, Baste et al., 2012, Baste et al., 2015, Boileau et al., 2020, Lu et al., 2017, Zhao et al., 2021), five studies were case-control (Khan et al., 2018, Mahmoudabadi et al., 2015, Lerman et al., 2001, Taskinen et al., 1990), and four studies were cross-sectional (Brizzi and Marinelli, 2018, Cromie et al., 2002, Karuserci et al., 2019, Xu et al., 2016). Tsarna et al. (2019) presented an analysis of four separate cohort studies. Källén et al. (1982) reported on a cohort with an embedded case-control study, while the authors of Ouellet-Hellstrom and Stewart (1993) described the study as questionnaire with an embedded case-control study. The study authors of Kolmodin-Hedman et al. (1988) described the study as case-control, but the fertility outcomes were reported as if from a cohort study.

The smallest study recruited 85 women (Kolmodin-Hedman et al., 1988), while the largest included 55,507 across its analysis of four cohort studies (Tsarna et al., 2019).

The studies were conducted in: Norway (Baste et al., 2012, Baste et al., 2015); Sweden (Källén et al., 1982, Kolmodin-Hedman et al., 1988); Finland (Khan et al., 2018, Taskinen et al., 1990); Turkey (Karuserci et al., 2019); China (Xu et al., 2016, Zhao et al., 2021); Egypt (Allam, 2016); France (Boileau et al., 2020); Italy (Brizzi and Marinelli, 2018); Australia (Cromie et al., 2002); Israel (Lerman et al., 2001); the USA (Ouellet-Hellstrom and Stewart, 1993); Japan (Lu et al., 2017); Iran (Mahmoudabadi et al., 2015); and the Netherlands, Denmark, Spain and South Korea (Tsarna et al., 2019).

In general, the age of mothers was between 20 and 29 in four studies (Baste et al., 2012, Khan et al., 2018, Mahmoudabadi et al., 2015, Xu et al., 2016), between 30 and 39 in three studies (Boileau et al., 2020, Karuserci et al., 2019, Ouellet-Hellstrom and Stewart, 1993), and was not reported in four (Brizzi and Marinelli, 2018, Cromie et al., 2002, Lerman et al., 2001, Taskinen et al., 1990). A wider range of mothers' average ages was reported in six studies (Allam, 2016, Baste et al., 2015, Källén et al., 1982, Kolmodin-Hedman et al., 1988, Lu et al., 2017, Zhao et al., 2021). In Tsarna et al. (2019) the mean age of women across the cohorts ranged between approximately 29 and 34 years. Only two studies reported the age of fathers (Baste et al., 2012, Mahmoudabadi et al., 2015). One study contained groups analysing paternal characteristics but did not report the fathers' ages (Baste et al., 2015). And, additionally, Karuserci et al. (2019) reported on the age of children.

The education level, alcohol intake, smoking status and parity of women were either not reported or reported heterogeneously across the studies; see Table 1.

4.4. Exposure characteristics

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

In the general public studies, the sources of RF-EMF exposure were: mobile phones in five studies (Baste et al., 2015, Boileau et al., 2020, Lu et al., 2017, Mahmoudabadi et al., 2015, Tsarna et al., 2019); and antennas, radars and/or telecommunications devices in two studies (Baste et al., 2012, Brizzi and Marinelli, 2018).

In the occupational studies, the sources of RF-EMF exposure were: devices used by physiotherapists in five studies (Allam, 2016, Källén et al., 1982, Lerman et al., 2001, Ouellet-Hellstrom and Stewart, 1993, Cromie et al., 2002); machines used by plastic welders in two studies (Kolmodin-Hedman et al., 1988, Xu et al., 2016); mobile phones, Wi-Fi and base stations in one study (Karuserci et al., 2019); electronic article surveillance systems in one study (Khan et al., 2018); and various electrical appliances in one study (Zhao et al., 2021).

The exposure metric used to assess RF-EMF in the general population studies was: minutes or hours of equipment usage per day (Boileau et al., 2020, Karuserci et al., 2019, Zhao et al., 2021), calls per day (Tsarna et al., 2019), groups of exposures (e.g. high/excessive use vs no/low use) based on mobile phone calls (duration/number) (Baste et al., 2015) and usage time (Lu et al., 2017), effective SAR (Mahmoudabadi et al., 2015)

Table 1
Participant characteristics of studies focusing on female fertility.

Study ID	Groups	Number per group	Age	Occupation(s)	Education	Alcohol intake	Smoking	Parity
Allam, 2016	Pregnant, exposed	50	30.3 ± 3.2	Physiotherapists	NR	NR	NR	2.6 ± 0.6
	Pregnant, controls	75	31.2 ± 2.1					2.5 ± 0.7
	Not pregnant, exposed	70	23.5 ± 3.9					1.3 ± 0.3
	Not pregnant, controls	85	24.2 ± 4.2					1.4 ± 0.4
Baste 2012	Acute	660	Father's age Vessel: 27.3 ± 4.1 Fast patrol boat: 26.4 ± 3.4 Mother's age Vessel: 25.9 ± 4.1 Fast patrol boat: 25.3 ± 3.7	Royal Norwegian Navy personnel	NR	NR	NR	NR
	Non-acute	4456	Father's age Vessel: 31.7 ± 5.5 Fast patrol boat: 31.6 ± 5.1 Mother's age Vessel: 28.9 ± 4.8 Fast patrol boat: 29.0 ± 4.6					
Baste 2015	Maternal low cell phone exposure	24,171	31.2 ± 4.2	NR	NR	NR	Not smoking: 90 % Sometimes: 3 % Daily: 5 %	First versus second or later pregnancy: 28 % vs 72 %
	Maternal medium cell phone exposure	60,921	30 ± 4.6				Not smoking: 90 % Sometimes: 3 % Daily: 5 %	First versus second or later pregnancy: 47 % vs 53 %
	Maternal high cell phone exposure	15,139	29.4 ± 4.8				Not smoking: 89 % Sometimes: 3 % Daily: 6 %	First versus second or later pregnancy: 61 % vs 39 %
	Paternal low cell phone exposure	19,619	NR				Not smoking: 78 % Sometimes: 8 % Daily: 1 %	First versus second or later pregnancy: 43 % vs 57 %
	Paternal medium cell phone exposure	38,598	NR				Not smoking: 75 % Sometimes: 10 % Daily: 1 %	First versus second or later pregnancy: 49 % vs 51 %
	Paternal high cell phone exposure	15,250	NR				Not smoking: 73 % Sometimes: 11 % Daily: 1 %	First versus second or later pregnancy: 48 % vs 52 %
	No paternal exposure of head or testis	8878	NR				Not smoking: 82 % Sometimes: 9 % Daily: 8 %	First versus second or later pregnancy: 47 % vs 53 %
	Paternal head exposure	21,360	NR				Not smoking: 77 % Sometimes: 10 % Daily: 12 %	First versus second or later pregnancy: 51 % vs 49 %
	Paternal testis exposure	1864	NR				Not smoking: 78 % Sometimes: 9 % Daily: 12 %	First versus second or later pregnancy: 48 % vs 52 %

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Table 1 (*continued*)

Study ID	Groups	Number per group	Age	Occupation(s)	Education	Alcohol intake	Smoking	Parity
Boileau 2020	0 to < 5 mins per day 5 to < 15 mins per day 15 to < 30 mins per day ≥ 30 mins per day	428 264 179 507	30.9 ± 4.6 30.1 ± 5.0 30.1 ± 4.6 30.0 ± 5.0	NR	NR	Drank alcohol during pregnancy: 59	Used tobacco during pregnancy: 220	NR
Brizzi 2018	Not exposed Partially exposed Fully exposed	4712 856 1310	NR	NR	NR	NR	NR	NR
Cromie 2002	NR	NR	NR	Physiotherapists	NR	NR	NR	Never had a pregnancy: 221
Kallen 1982	Cases in case-control study Controls in case-control study	37 74	Maternal age of cohort study Up to 19: 0 20–24: 178 25–29: 1076 30–34: 666 35–39: 107 40+: 14 Unknown: 2	Physiotherapists	NR	NR	NR	Parity distribution in cohort study 1: 925 2: 793 3: 260 4: 64 Unknown: 1
Karusecri 2019	TV Mobile use Multiple mobile phone Computer Wi-Fi Base station near home	371 365 46 197 208 112	Mothers: 30.9 ± 6 Children: 2.2 ± 1.6	Mother's employment status Housewife: 240/397 (60.5 %) Working: 157/397 (39.5 %)	Mother's education status Illiterate: 11/394 (2.8 %) Literate: 24/394 (6.1 %) Primary school graduate: 89/394 (22.6 %) Secondary school graduate: 37/394 (9.4 %) High school graduate: 84/394 (21.3 %) University graduate: 149/394 (37.8 %) Father's education status Illiterate: 5/385 (1.3 %) Literate: 15/385 (3.9 %) Primary school graduate: 56/385 (14.5 %) Secondary school graduate: 36/385 (9.4 %) High school graduate: 102/385 (26.5 %) University graduate: 171/385 (44.4 %)	NR	Smokers: 9.8 % Average number of cigarettes actively smoked per day during pregnancy: 6.4 ± 5.7 (range 1–20)	Mean total number of children: 2.0 ± 1.1 (range 1–7)
Khan 2018	Exposed	309	Singleton birth mothers: 27.8 ± 4.8	Supermarket workers	NR	NR	Smoking status No smoking: 225 (72.8 %) No smoking after 1st trimester: 30	Prior deliveries No previous: 143 (46.3 %) 1: 111 (35.9 %)

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Table 1 (*continued*)

Study ID	Groups	Number per group	Age	Occupation(s)	Education	Alcohol intake	Smoking	Parity
							(9.7 %) Smoking after 1st trimester: 50 (16.2 %) No information: 4 (1.3 %)	2: 34 (11 %) 3+: 21 (6.8 %)
	Unexposed	217	Singleton birth mothers: 26.9 ± 4.5	Grocery store workers			Smoking status No smoking: 159 (73.3 %) No smoking after 1st trimester: 17 (7.8 %) Smoking after 1st trimester: 37 (17.1 %) No information: 4 (1.8 %)	Prior deliveries No previous: 107 (49.3 %) 1: 76 (35 %) 2: 20 (9.2 %) 3+: 14 (6.5 %)
Kolmodin-Hedman 1988	Exposed	62	39 ± 9	Plastic welding Mean employment: 13 ± 7	NR	NR	Smokers: 45 % Ex-smokers: 15 % Non-smokers: 40 %	NR
	Unexposed	23	40 ± 13	Sewing machine workers/ assembly workers Mean employment: 11 ± 8			Smokers: 52 % Ex-smokers: 4 % Non-smokers: 44 %	
Lerman 2001	Spontaneous abortion group Congenital malformation group Prematurity group Low birth weight group Controls	175 45 47 33 633	NR	Physiotherapists registered as members of the Union of Israeli Physiotherapists	NR	NR	NR	NR
Lu 2017	Excessive mobile phone user	46	25.09 ± 5.7	Full time job: 15 (32.6 %) Part time job: 17 (37 %) Housewife: 10 (21.7 %) Independent business: 2 (4.3 %) No answer: 2 (4.3 %)	High school degree: 37 (80.4 %) College degree: 9 (19.6 %) Otherwise: 0	NR	Smoker: 5 (10.9 %) Not smoker: 41 (89.1 %)	Primiparity: 26 (56.5 %) No primiparity: 20 (43.5 %)
	Normal mobile phone user	415	30.03 ± 5.08	Full time job: 96 (23.1 %) Part time job: 125 (32.5 %) Housewife: 152 (36.6 %) Independent business: 16 (3.9 %) No answer: 16 (3.9 %)	High school degree: 216 (52 %) College degree: 197 (47.5 %) Otherwise: 2 (0.5 %)		Smoker: 24 (5.8 %) Not smoker: 391 (94.2 %)	Primiparity: 281 (52 %) No primiparity: 134 (32.3 %)
Mahmoudabadi 2015	Cases	226	Maternal age: 27.81 ± 5.2 Paternal age: 32.62 ± 5.46	Housewife: 195 Employee: 31	Primary: 88 Secondary: 94 University: 44	NR	NR	Years since last delivery: 6.61 ± 3.93
	Controls	246	Maternal age: 27.34 ± 4.3 Paternal age: 31.9 ± 5.49	Housewife: 225 Employee: 21	Primary: 98 Secondary: 100 University: 48			Years since last delivery: 6.57 ± 3.46
Oullet-Hellstrom 1993	Total respondents	19,114	20–29: 23.7 % 30–39: 46.1 % 40–49: 16.7 % 50–59: 6.7 %	Physiotherapists-female members of the American Physical Therapy Association	NR	NR	NR	NR

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Table 1 (*continued*)

Study ID	Groups	Number per group	Age	Occupation(s)	Education	Alcohol intake	Smoking	Parity
			≥ 60: 5 % Missing: 1.7 %					
	Eligible respondents	11,596	20–29: 12.9 % 30–39: 53.1 % 40–49: 20.1 % 50–59: 7.9 % ≥ 60: 4.6 % Missing: 1.5 %					
		Ever-exposed eligible respondents 20–29: 5.5 % 30–39: 49.5 % 40–49: 27.9 % 50–59: 10.7 % ≥ 60: 5.5 % Missing: 0.9 %	6684					
		Cases	1753					
NR	Controls	1753						
Taskinen 1990	Spontaneous abortion cases	204	NR	Hospital: 52 (30.6 %) Health care centre: 36 (21.2 %) Rehabilitation institute: 4 (2.4 %) Occupational health care: 5 (2.9 %) Private enterprise: 32 (18.8 %) Self-employed: 17 (10.0 %) Other job: 24 (14.1 %	NR	Less than 4–5 drinks: 113 Alcohol − 4–5 + drinks per week: 8	Smoking: 10	1 previous delivery: 74 2 + previous deliveries: 33
	Spontaneous abortion controls	483		Hospital: 105 (27.7 %) Health care centre: 72 (19.0 %) Rehabilitation institute: 17 (4.5 %) Occupational health care: 13 (3.4 %) Private enterprise: 106 (28.0 %) Self-employed: 43 (11.3 %) Other job: 23 (6.1 %)		Less than 4–5 drinks: 263 4–5 + drinks per week: 22	Smoking: 43	1 previous delivery: 177 2 + previous deliveries: 54
	Congenital malformation cases	46		NR		NR	NR	NR
	Congenital malformation controls	187		NR		NR	NR	NR
Tsarna 2019 A (DNBC)	No exposure	30,185 mother–child pairs	31 ± 0.024	NR	Primary: 4 Secondary: 8845 University: 21,336	Consumption during pregnancy: 11,572	Smoking: 6972 Second hand smoke: 14,469	Before index pregnancy 0: 12,952 1: 11,936 2: 5297
	Low exposure	10,860 mother–child pairs	30.27 ± 0.047		Primary: 0 Secondary: 3206 University: 7653	Consumption during pregnancy: 3833	Smoking: 2657 Second hand smoke: 5084	Before index pregnancy 0: 5774 1: 3687 2: 1400
	Intermediate exposure	6172 mother–child pairs	29.66 ± 0.059		Primary: 1 Secondary: 2361 University: 3810	Consumption during pregnancy: 2286	Smoking: 2021 Second hand smoke: 3103	Before index pregnancy 0: 3469 1: 1927 2: 776
	High exposure	2451 mother–child pairs	30.2 ± 0.088		Primary: 2 Secondary: 939 University: 1511	Consumption during pregnancy: 1035	Smoking: 879 Second hand smoke: 1253	Before index pregnancy 0: 1333 1: 800 2: 319

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Table 1 (*continued*)

Study ID	Groups	Number per group	Age	Occupation(s)	Education	Alcohol intake	Smoking	Parity
Tsarna 2019B (ABCD)	No exposure	180 mother–child pairs	33.78 ± 0.318	NR	≤ 5 years after primary: 41 6–9 years after primary: 36 ≥ 10 years after primary: 103	Consumption during pregnancy: 25	Smoking: 4 Second hand smoke: 63	Before index pregnancy 0: 68 1: 75 2: 37
	Low exposure	1125 mother–child pairs	33.36 ± 0.345		≤ 5 years after primary: 125 6–9 years after primary: 258 ≥ 10 years after primary: 742	Consumption during pregnancy: 262	Smoking: 70 Second hand smoke: 538	Before index pregnancy 0: 605 1: 415 2: 105
	Intermediate exposure	703 mother–child pairs	32.54 ± 0.357		≤ 5 years after primary: 40 6–9 years after primary: 168 ≥ 10 years after primary: 495	Consumption during pregnancy: 231	Smoking: 60 Second hand smoke: 434	Before index pregnancy 0: 476 1: 188 2: 39
	High exposure	589 mother–child pairs	33.17 ± 0.364		≤ 5 years after primary: 39 6–9 years after primary: 109 ≥ 10 years after primary: 441	Consumption during pregnancy: 224	Smoking: 64 Second hand smoke: 372	Before index pregnancy 0: 372 1: 167 2: 50
Tsarna 2019C (INMA)	No exposure	53 mother–child pairs	32.33 ± 0.587	NR	Primary: 17 Secondary: 21 University: 15	Consumption during pregnancy: 3	Smoking: 14 Second hand smoke: 31	Before index pregnancy 0: 20 1: 31 2: 2
	Low exposure	703 mother–child pairs	32.2 ± 0.609		Primary: 188 Secondary: 294 University: 221	Consumption during pregnancy: 66	Smoking: 198 Second hand smoke: 417	Before index pregnancy 0: 384 1: 254 2: 65
	Intermediate exposure	753 mother–child pairs	31.57 ± 0.607		Primary: 207 Secondary: 305 University: 241	Consumption during pregnancy: 79	Smoking: 262 Second hand smoke: 516	Before index pregnancy 0: 427 1: 284 2: 42
	High exposure	425 mother–child pairs	31.24 ± 0.622		Primary: 87 Secondary: 168 University: 170	Consumption during pregnancy: 36	Smoking: 155 Second hand smoke: 308	Before index pregnancy 0: 241 1: 157 2: 27
Tsarna 2019 D (MOCEH)	No exposure	15 mother–child pairs	30.9 ± 0.954	NR	Primary: 1 Secondary: 6 University: 8	Consumption during pregnancy: 2	Smoking: 0 Second hand smoke: 8	Before index pregnancy 0: 7 1: 5 2: 3
	Low exposure	242 mother–child pairs	31.22 ± 0.983		Primary: 1 Secondary: 62 University: 179	Consumption during pregnancy: 13	Smoking: 2 Second hand smoke: 143	Before index pregnancy 0: 96 1: 125 2: 22
	Intermediate exposure	642 mother–child pairs	30.67 ± 0.965		Primary: 0 Secondary: 177 University: 465	Consumption during pregnancy: 37	Smoking: 1 Second hand smoke: 404	Before index pregnancy 0: 332 1: 251 2: 59
	High exposure	409 mother–child pairs	30.78 ± 0.971		Primary: 3 Secondary: 101	Consumption during pregnancy: 28	Smoking: 6 Second hand smoke: 250	Before index pregnancy 0: 219

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Table 1 (*continued*)

Study ID	Groups	Number per group	Age	Occupation(s)	Education	Alcohol intake	Smoking	Parity
					University: 305			1: 150 2: 40
Xu 2016	High exposure	71	27.3 ± 5.85	Worked in shoe factories Years of work: 2.9 ± 1.82	Years of education: 7.9 ± 2.81	NR	NR	NR
	Low exposure	109	27.83 ± 6.05	Worked in shoe factories Years of work: 3.29 ± 2.07	Years of education: 7.66 ± 3.25			
	Control	349	26.96 ± 5.94	Worked in nearby supermarkets Years of work: 3.92 ± 3.91	Years of education: 8.38 ± 4.74			
Zhao 2021	Cases	585	< 30: 390 (66.7 % 30+: 195 (33.3 %)	Farmer: 52 (8.9 %) Other: 533 (91.1 %)	Low: 409 (69.9 %) High: 176 (30.1 %)	Drinks alcohol: 22 (3.8 %) Does not drink alcohol: 563 (96.2 %)	Passive smoking: 162 (27.7 %) No passive smoking: 423 (72.3 %)	1: 348 (59.5 %) 2+: 237 (40.5 %)
	Controls	1754	< 30: 1027 (58.6 %) 30+: 727 (41.4 %)	Farmer: 28 (1.6 %) Other: 1726 (98.4 %)	Low: 434 (24.7 %) High: 1320 (75.3 %)	Drinks alcohol: 12 (0.7 %) Does not drink alcohol: 1742 (99.3 %)	Passive smoking: 171 (9.7 %) No passive smoking: 1583 (90.3 %)	1: 1313 (74.9 %) 2+: 441 (25.1 %)

or altitude and distance from radar (Brizzi and Marinelli, 2018).

In the occupational studies, this was: hours of equipment usage per week (e.g. shortwave diathermy) (Cromie et al., 2002, Lerman et al., 2001, Taskinen et al., 1990), how often equipment was used (Källén et al., 1982, Ouellet-Hellstrom and Stewart, 1993), hours per week and distance from exposure source (Allam, 2016) or individual exposure either estimated (Baste et al., 2012) or measured at the person using the equipment (Khan et al., 2018, Kolmodin-Hedman et al., 1988, Xu et al., 2016).

It is worth noting that in the study reported by Khan et al., 2018 the exposed and non-exposed groups had exposure at cashier seats measured and it was assumed that the exposed group had a higher exposure based on measurements 1.8 to 2.7 m from electronic article surveillance (EAS) gates. However, EMF exposure only increased (8.2 MHz) when passing by the gates at short distance (Khan et al., 2018). Additionally, in Xu et al., 2016, low and high categorisation of RF-EMF exposure was based on electric field measurements. The mean of both low (51.3 ± 16.2 V/m) and high (86.5 ± 22.4 V/m) exposures both exceeded the Chinese National Standard (25 V/m) at the abdomen, which suggests that the characterisation of the RF-EMF exposure in this study may be flawed. However, it is unclear whether the reported values were averaged over six minutes, as per ICNIRP guidelines.

Exposure location across the body, distribution, background exposures, exposure strength and co-exposures considered by studies were either not reported or reported heterogeneously; see Table 1.

4.5. Risk of bias in studies

Table 3 shows the risk of bias for all studies reporting on female fertility outcomes, ranked from the study with the most assessments of "definitely low" to the most "definitely high" assessments. Concerns were spread across all domains of the OHAT tool, with no single domain being mostly free from risk of bias except for use of statistics.

Although three studies were assessed as being at definitely low risk with regards to the characterisation of the exposure (Khan et al., 2018, Mahmoudabadi et al., 2015, Brizzi and Marinelli, 2018, Xu et al., 2016), there were still concerns about this domain in three studies judged to be at probably low risk (Baste et al., 2015, Boileau et al., 2020, Kolmodin-Hedman et al., 1988), seven at probably high risk (Allam, 2016, Karuserci et al., 2019, Cromie et al., 2002, Källén et al., 1982, Lu et al., 2017, Taskinen et al., 1990, Zhao et al., 2021), and two at definitely high risk (Tsarna et al., 2019, Baste et al., 2012) of bias. This was mainly due to the studies not taking critical confounders into account (see Section 3.5.1 for the list of critical confounders of relevance to this review). Two studies were deemed to have used inappropriate or insufficient statistical methods because they did not perform any adjustments in their analyses (Karuserci et al., 2019, Källén et al., 1982).

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 particular 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

4.7.1.1. Miscarriage. Two studies in the general public reported on miscarriage, but were not suitable for *meta*-analysis as the exposures were too heterogeneous to combine (Brizzi and Marinelli, 2018, Mahmoudabadi et al., 2015). Brizzi and Marinelli (2018) reported that there was little difference in risk of miscarriage when comparing those unexposed to radar base stations with three different levels of exposure groups combined (RR 1.038, 95 % CI: 0.515–1.561). The same study suggested that those who were exposed to the highest level of RF-EMF (altitude and orientation 120–60 m) may have a greater risk of miscarriage than unexposed participants (RR 1.308, 95 % CI: 0.736–1.887). Mahmoudabadi et al. (2015) reported that those exposed to a greater level of effective SAR from mobile phones were at a slightly greater risk of miscarriage compared to those whose effective SAR level was lower (OR 1.11, 95 % CI: 1.07–1.16). However, both studies were at

Table 2
Exposure characteristics of studies focusing on female fertility.

Study ID	Case definition	Control definition	Exposure location	Exposure distribution	Exposure strength	Background exposure levels	Listed co-exposures	Metric
Allam, 2016	Physiotherapist using equipment	recruited from the outpatient clinics with no history of work at anyplace which could expose them to nonionizing radiation	Distance from the devices in meters: 2.6 ± 1.1	NR	NR	NR	Alcohol, coffee, tobacco	Exposure to radiofrequency, shortwave diathermy and microwave diathermy (provides average hours per week and distance from exposure source)
Baste 2012	Acute exposure = any conception 3 months or less from the father's exposure Non-acute exposure = more than 3 months from exposure to conception	Land based personnel	NR	NR	RF dose (unitless, see metric), Fast Patrol Boat: Acute exposure: Mean = 3 Non-acute: 16 (radar frequencies: 2.1 MHz – 9.4 GHz)	NR	Year of birth, maternal age, paternal age	Individual exposure dose, based on average exposure level by the number of days of service, time period and fast patrol boat class in question
Baste 2015	Pregnant women: low, medium and high exposure to mobile phone use Men: low, medium and high exposure to mobile phone use	Low exposure set as the reference	Head, testis, "Other places on the body"	NR	NR	NR	Parity, maternal and paternal age, smoking	Low, medium and high exposure based on questionnaire regarding usage habits
Boileau 2020	Minutes of exposure to mobile phone, assessed via questionnaire	NR	NR	NR	NR	NR	Maternal education, tobacco use, maternal age, gestational arterial hyper tension, history of arterial hyper tension, gestational diabetes, and history of diabetes	Minutes of mobile phone use per day
Brizzi 2018	Slightly exposed: living < 4.5 km from the radar, altitude < 80 m or > 200 m) Markedly exposed: living < 4.5 km from the radar and facing it, altitude 80–120 m or 160–200 m) Fully exposed: altitude and orientation 120–160 m from radar	Unexposed to radar	Full body exposure based on home location from radar station	"Since the altitude of the radar is 140 m a.s.l., the vertical amplitude of the signal is 2°38' (at −3 dB), and the distance from the town centre is 4 km, the sector which receives the radar emission corresponds to the range of altitude from 80 to 200 m a. s.l."	NR (frequency 1000—2000 MHz, 20 MW, 40 dB gain)	NR	NR	Range of altitude (distance from radar)
Cromie 2002	NR	NR	NR	NR	NR	NR	Maternal age	NR
Hatch 2021	Mobile phone use in male partner	0 h of mobile phone use	Pants pocket exposure	NR	NR (frequencies: 800–900 MHz for Danish cohort 800–2600 MHz	NR	Male consumption of sugar sweetened drinks	hours of use

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Table 2 (*continued*)

Study ID	Case definition	Control definition	Exposure location	Exposure distribution	Exposure strength	Background exposure levels	Listed co-exposures	Metric
					for American cohort)			
Kallen 1982	Working as a physiotherapist and had given birth to a baby with a major malformation or whose infant died perinatally without malformation	Working as a physiotherapist and had not given birth to a baby with a major malformation or an infant who died perinatally without malformation	NR	NR	NR	NR	NR	NR
Karusecri 2019	Exposed to TV, mobile phone, multiple mobile phone, computer, wi-fi and base station near the home	Not watching TV (unclear for other exposures)	NR	NR	NR	NR	NR	Hours or minutes of use depending on exposure
Khan 2018	Cashiers working near electronic article surveillance (EAS) systems	Six grocery stores where EAS was not in use	NR	NR	Case group exposure at cashier desk varied between 0.005 μT and 0.025 μT (broadband measurement, 0.3 – 30 MHz). At 10 cm from gates, exposure was found to vary between 0.11 μT and 1.38 μT	Control group exposure at cashier desk varied between 0.005 μT and 0.053 μT (broadband measurement, 0.3 – 30 MHz)	NR	Exposure to IF MF
Kolmodin-Hedman 1988	Working as a plastic welder	Sewing machine operators/ assembly workers	Standardised according to right and left hands, abdomen, inguinal region, right and left knees, right and left feet	NR	50 % of the welding machines exceeded 250 W/m^2 at (25 – 30) MHz	NR	NR	Power density
Lerman 2001	Physiotherapists (male and female) registered as members of the Union of Israeli Physiotherapists who had ever been pregnant who had a spontaneous abortion, congenital malformation, prematurity or low birth weight – more than one pregnancy could be a case	Pregnancies of mothers who reported no adverse reproductive outcomes in any pregnancy. Normal pregnancies from mothers who had other pregnancies ending in abnormal delivery were excluded	NR	NR	Shortwaves measured on a scale 0 = no exposure 1 = less than 10 h/week 2 = more than 10 h/week	NR	Heavy lifting, measured on a scale 0 = no exposure 1 = 5–25 times/week 2 = more than 25 times/week	Hours exposed per week
Lu 2017	Excessive mobile phone use (assessed by short version of the Self-Perception of Text-Message Dependency Scale (STDS))	Non-excessive users	Bag, trouser pocket, shirt pocket, coat pocket, other	NR	NR	NR	NR	Excessive mobile phone use (defined as > 15 points on the Self-Perception of Text-Message Dependency Scale (STDS))
Mahmoudabadi 2015	An unexplained spontaneous abortion at < 14	Pregnant women at 14 weeks	Use of hands free, use of other apps	NR	Effective SAR Case: 7.02 ± 13.92 Control: 2.28 ±	NR	NR	Effective SAR

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Table 2 (*continued*)

Study ID	Case definition	Control definition	Exposure location	Exposure distribution	Exposure strength	Background exposure levels	Listed co-exposures	Metric
	weeks (early abortion)		When not in use: on tables, handbags, in pocket, or 60–70 cm away from body		3.2 (NB: units are not specified)			
Oullet-Hellstrom 1993	Recognised miscarriages that were reported by physical therapists (occurring before 28 weeks gestation), were working at time of pregnancy and exposed to microwave or shortwave diathermy	Any pregnancy, except ectopic pregnancy, if the therapist was not working 6 months prior to or during the first trimester, this was classes as “unexposed”.	NR	NR	NR	NR	NR	Number of times exposed to microwave (shortwave) diathermy
Taskinen 1990	Spontaneous abortion: any physiotherapist treated in hospital or clinic for spontaneous abortion between 1973 and 1983 (ICD-8 codes 143 and 645) Congenital malformations: any physiotherapist who had given birth to a “malformed” child between years 1973 and 1982	Not having a spontaneous abortion or child with a congenital malformation	Ultrasounds noted to be used in hands; others NR	NR	NR Exposure to deep heat therapy: shortwaves (27.12 MHz), Microwaves	NR	NR	Hours per week
Tsarna 2019	Intermediate/ high exposure to mobile phone	No/Low exposure to mobile phone group used as reference	NR	NR	NR	NR	Smoking during pregnancy, alcohol use during pregnancy	Mobile phone calls per day
Xu 2016	NR	Supermarket workers	Head, chest, abdomen	NR	Plastic welding machines: High exposure (V/m) Head: 241.9 ± 58.6 Chest: 368.9 ± 54.5 Abdomen: 86.5 ± 22.4 Low exposure (V/m) Head: 84 ± 26.7 Chest: 117.5 ± 31.4 Abdomen: 51.3 ± 16.2 frequencies: (25 – 30) MHz	Control group exposure < 1 V/m	NR	High or low exposure based on electric field measurements
Zhao 2021	Due dates from January 2014 to December 2016, from 28 weeks after pregnancy to 7 after birth, included single	Selected new-borns without birth defects from the same hospitals, randomly matched with	Standing beside induction cooker; standing within 1 m of microwave	NR	Using the appliance (e.g., mobile phone, television, or computer) at least 1 day per	NR	maternal age, education, residence, ethnicity, job, household income, maternal	Hours of usage first 3 months prior to pregnancy and first trimester

(*continued on next page*)

Table 2 (*continued*)

Study ID	Case definition	Control definition	Exposure location	Exposure distribution	Exposure strength	Background exposure levels	Listed co-exposures	Metric
	live births and stillbirths, diagnosed with congenital heart disease (CHD) according to ICD-10 classification criteria	cases at rate of 1:3 by birth date	oven while it was in operation		week and at least 0.5 h per day		passive smoking, drinking, folic acid supplement, fever or cold, medicine history, gravidity and parity history, radiation protection suits wearing, and the other four types of electrical appliance exposure	

Table 3
Risk of bias assessments across female studies.

Study ID	Selection bias	Confounding bias	Attrition bias	Exposure characterisation bias	Outcome assessment bias	Selective reporting bias	Appropriate statistics
Khan 2018	DL	PL	PL	DL	DL	DL	Y
Boileau 2020	PL	DL	DL	PL	PL	PL	Y
Taskinen 1990	PL	PL	PL	PH	PL	DL	Y
Lu 2017	PL	PL	PL	PH	PH	DL	Y
Baste 2015	DL	PH	PH	PL	DL	DL	Y
Xu 2016	PL	PH	PL	DL	PH	PL	Y
Allam, 2016	PL	DH	PL	PH	DL	DL	Y
Mahmoudabadi 2015	DL	PH	PH	DL	PH	PL	Y
Brizzi 2018	PL	PH	PH	PH	PL	PL	Y
Tsarna 2019	PH	PL	DL	DH	PH	DL	Y
Zhao 2021	DH	DL	PL	PH	PH	DL	Y
Oullet-Hellstrom 1993	PH	PL	PH	PH	PH	DL	Y
Lerman 2001	PH	PL	PH	PH	PH	DL	Y
Karusecri 2019	PL	DH	PL	PH	PH	DL	N
Kolmodin-Hedman 1988	PH	PH	PH	PL	DL	DH	Y
Baste 2012	PH	PH	PL	DH	PH	DL	Y
Kallen 1982	PL	DH	PL	PH	PH	PH	N
Cromie 2002	PL	DH	PH	PH	DH	PH	Y

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

some risk of confounding and attrition bias.

4.7.1.2. Congenital anomalies. Four studies reported on congenital anomalies but were unable to be pooled as the types of anomalies reported were too heterogeneous to combine (Baste et al., 2015, Boileau et al., 2020, Brizzi and Marinelli, 2018, Zhao et al., 2021).

In Baste et al. (2015), all congenital anomalies were included in their analyses; they did not consider subtypes. Risk of all congenital anomalies from maternal exposure was measured from weeks 15 to 30 of gestation, with the study reporting that there may be little to no difference between those with medium (RR 0.99, 95 % CI: 0.92–1.06) and high exposure to mobile phones (RR 1.01, 95 % CI: 0.92–1.11) compared with those with low exposure. These analyses were adjusted for parity, maternal age and smoking status (Baste et al., (2015). Similarly, Zhao et al. (2021) examined the risk of children being born with congenital heart disease (CHD) if the mother was exposed to RF-EMF three months before pregnancy and during the first trimester in adjusted analyses. The study reported that, three months before pregnancy and compared to unexposed participants, the risk of CHD in children may increase steadily with greater exposure to RF-EMF from < 180 min of mobile phone usage per day (OR 1.17, 95 % CI: 0.75–1.84), to 180–300 min per day (OR 1.35, 95 % CI: 0.83–2.19) and finally > 300 min per day (OR 2.7, 95 % CI: 1.69–4.3). There was a similar pattern in the first trimester of pregnancy, with risk of CHD in children compared with unexposed women also potentially increasing steadily with greater exposure to RF-EMF from < 180 min of mobile phone usage per day (OR 1.23, 95 % CI: 0.8–1.89), to 180–300 min per day (OR 1.25, 95 % CI: 0.78–1.99) and finally > 300 min per day (OR 1.8, 95 % CI: 1.14–2.83) (Zhao et al., 2021).

Baste et al. (2015), also measured the risk of congenital anomalies from paternal exposure was six months before conception, with the study again suggesting that there may be little difference between those with medium (RR 1.05, 95 % CI: 0.98–1.14) and high exposure to mobile phones (RR 0.97, 95 % CI: 0.97–1.17) compared with those with low exposure. These analyses were adjusted for parity, maternal and paternal age, and maternal and paternal smoking status (Baste et al., (2015).

Brizzi and Marinelli (2018) reported a slightly increased risk of what the study authors term "birth defects" for those who had been exposed to base station radar compared to unexposed participants (RR 1.244, 95 %

Table 4
GRADE Evidence profile.

Certainty assessment								Summary of findings			Certainty	Comments
								Participants	Effect			
No of studies	Starting level[1]	Risk of bias	Inconsistency	Indirectness	Imprecision	Publication bias	Upgrading Domains	No of participants	Relative (95 % CI)	Absolute		
Effects of maternal RF-EMF exposure on pre-term birth in the general public												
4	3 cohort, 1 cross-sectional	Downgrade[2]	Downgrade twice[3]	Downgrade[4]	No downgrade	No downgrade	No upgrades	153,929	RR 1.14 (95 % CI 0.97 to 1.34)	N/A	Very low-certainty	Tsarna 2019 reported on data from four separate cohorts, meaning seven cohorts were included in the *meta*-analysis.
Effects of maternal RF-EMF exposure on small for gestational age (SGA) in the general public												
2	Cohort	Downgrade[2]	Downgrade twice[3]	Downgrade[3]	No downgrade	No downgrade	No upgrades	153,027	RR 1.13 (95 % CI 1.02 to 1.24)	N/A	Very low-certainty	Tsarna 2019 reported on data from four separate cohorts, meaning five cohorts were included in the *meta*-analysis.
Effects of maternal RF-EMF exposure on low birth weight in the general public												
4	Cohort	Downgrade[2]	Downgrade[5]	Downgrade[7]	No downgrade	No downgrade	No upgrades	153,929	RR 1.14 (95 % CI 0.96 to 1.36)	N/A	Very low-certainty	Tsarna 2019 reported on data from four separate cohorts, meaning seven cohorts were included in the *meta*-analysis.
Effects of RF-EMF exposure on miscarriage in occupational studies (dose–response *meta*-analysis)												
2	Case-control	Downgrade[6]	Downgrade[5]	Downgrade[7]	No downgrade	No downgrade	No upgrades	952	Exponentiated OR 1.02 (95 % CI 0.94 to 1.1)	N/A	Very low-certainty	Dose-response *meta*-analysis based on exposure of physiotherapists to shortwave diathermy (SWD)
Effects of RF-EMF exposure on miscarriage in occupational studies (pairwise *meta*-analysis)												
5	1 cohort, 2 cross-sectional, 1 case-control, 1 questionnaire + nested case-control	Downgrade[2]	No downgrade	Downgrade[8]	No downgrade	No downgrade	No upgrades	4932	RR 1.06 (95 % CI 0.96 to 1.18)	N/A	Very low-certainty	Varying exposure to equipment (see Fig. 6 for details)
Effects of female RF-EMF exposure on congenital anomalies in occupational studies (dose–response *meta*-analysis)												
2	Case-control	Downgrade[6]	Downgrade[5]	Downgrade twice[9]	Downgrade[10]	No downgrade	No upgrades	834	Exponentiated OR 1.4 (95 % CI −0.85 to 2.32)	N/A	Very low-certainty	Dose-response *meta*-analysis based on exposure of physiotherapists to shortwave diathermy (SWD)
Effects of maternal RF-EMF exposure on pre-term birth in occupational studies												
3	1 cohort, 1 case-control, 1 cross-sectional	Downgrade[2]	No downgrade	Downgrade[11]	Downgrade[10]	No downgrade	No upgrades	1093	RR 1.19 (95 % CI 0.33 to 4.28)	N/A	Very low-certainty	One study based on exposure to shortwave diathermy (SWD) alone; one study based on exposure to radiofrequency, SWD and microwave diathermy; one study based on exposure to exposure to plastic welding machines in factory workers

(*continued on next page*)

Table 4 (*continued*)

Certainty assessment								Summary of findings			Certainty	Comments
								Participants	Effect			
No of studies	**Starting level**[1]	**Risk of bias**	**Inconsistency**	**Indirectness**	**Imprecision**	**Publication bias**	**Upgrading Domains**	**No of participants**	**Relative (95 % CI)**	**Absolute**		
Effects of maternal RF-EMF exposure on low birth weight in occupational studies												
3	1 cohort, 1 case-control, 1 cross-sectional	Downgrade[2]	Downgrade[5]	Downgrade[11]	Downgrade[12]	No downgrade	No upgrades	1081	RR 2.83 (95 % CI 0.77 to 10.46)	N/A		One study based on exposure to shortwave diathermy (SWD) alone; one study based on exposure to radiofrequency, SWD and microwave diathermy; one study based on exposure to exposure to plastic welding machines in factory workers

[1] Cohort studies start at moderate certainty level.
[2] High risk of bias across included studies.
[3] Substantial statistical heterogeneity on I^2.
[4] Majority of studies are based on call time.
[5] Moderate statistical heterogeneity on I^2.
[6] Concerns about risk of bias in one included study.
[7] Hours of usage per day are used as a proxy for dose.
[8] Exposure based on different uses of shortwave diathermy, EAS and plastic welding machines;
[9] Hours of usage per day is a proxy for dosage; compiles all congenital malformations instead of specific congenital malformations.
[10] 95% CIs suggest a moderate variation in risk.
[11] Based on exposure to shortwave diathermy and plastic welding machines.
[12] 95% CIs suggest a very wide variation in risk.

CI: 0.649–1.805). The same study also compared unexposed participants to those with the highest exposure to base station radar (altitude and orientation 120–60 m), and reported that the risk of "birth defects" was higher for the exposed group (RR 1.461, 95 % CI: 0.818–2.113) (Brizzi and Marinelli, 2018). The nature of "birth defects" in this study was not described, and there were also concerns surrounding characterisation of the exposure, confounding and attrition bias (Brizzi and Marinelli, 2018).

Finally, Boileau et al. (2020) reported that 16 anomalies were detected across the whole cohort of 1353 participants but did not state which groups these belonged to (Boileau et al., 2020).

4.7.1.3. Pre-term birth. Four studies were included in the *meta*-analysis (Karuserci et al., 2019, Lu et al., 2017, Tsarna et al., 2019, Baste et al., 2015). Tsarna et al. (2019) provided data for four separate cohorts, which are analysed separately, meaning a total of seven cohorts were included in the *meta*-analysis. The evidence is very uncertain about the effects of maternal mobile phone exposure on pre-term birth risk (RR 1.14, 95 % CI: 0.97–1.34, 95 % PI: 0.83–1.57; very low-certainty evidence; see Fig. 2).

4.7.1.4. Stillbirth. No studies in the general population reported on stillbirth.

4.7.1.5. Small for gestational age (SGA). Two studies were included in the *meta*-analysis (Baste et al., 2015, Tsarna et al., 2019). Tsarna et al. (2019) provided data for four separate cohorts, which are analysed separately, meaning five cohorts were included in the *meta*-analysis. The evidence is very uncertain about the effects of maternal mobile phone exposure on SGA (RR 1.13, 95 % CI 1.02–1.24, 95 % PI: 0.99–1.28; very low-certainty evidence; see Fig. 3). This equates to a potential increase in risk of SGA of 13 % but the evidence is very uncertain and the PIs suggest a possibly non-significant risk.

Baste et al. (2015) also presented risk ratios adjusted for parity, maternal age and maternal smoking status, which showed no statistically significant association between SGA and mobile phone exposure for medium or high exposure compared to low exposure (RR 1.02, 95 % CI 0.96–1.09 and 1.01, 95 % CI 0.95–1.11, respectively). In addition, they report the effects of paternal mobile phone exposure on LBW. They observed no statistically significant risk of medium or high exposure, compared to low exposure (RR 0.99, 95 % CI 0.93–1.06 and 1.05, 95 % CI 0.97–1.14, respectively). Tsarna et al. (2019) presented adjusted odds ratios (maternal age, parity, active/passing smoking, alcohol consumption, pre-pregnancy body mass index, educational level, socioeconomic position, marital status, and maternal height), showing no statistically significant differences between low exposure and no exposure (OR 0.94, 95 % CI 0.89–1.07), intermediate exposure (OR 1.03, 95 % CI 0.88–1.21), or high exposure (OR 0.98, 95 % CI 0.83–1.16).

4.7.1.6. Low birth weight. Four studies were included in the analysis (Karuserci et al., 2019, Lu et al., 2017, Tsarna et al., 2019, Baste et al., 2015). Tsarna et al. (2019) provided data for four separate cohorts, which were analysed separately, meaning seven cohorts were analysed in the *meta*-analysis. of the evidence is very uncertain about the effects of maternal mobile phone exposure on LBW (RR 1.14, 95 % CI 0.96–1.36, 95 % PI 0.84–1.57; very low-certainty evidence; see Fig. 4). Baste and colleagues (2015) also presented RRs adjusted for parity, maternal age and maternal smoking status, which showed no statistically significant association between LBW and mobile phone exposure for medium or high exposure compared to low exposure (RR 0.99, 95 % CI 0.92–1.06 and 1.01, 95 % CI 0.93–1.11, respectively). In addition, they report the effects of paternal mobile phone exposure on LBW. They observed no statistically significant risk of medium or high exposure, compared to low exposure (RR 0.95, 95 % CI 0.86–1.05 and 0.97, 95 % CI 0.86–1.09, respectively). Tsarna et al. (2019) presented adjusted odds ratios (maternal age, parity, active/passing smoking, alcohol consumption, pre-pregnancy body mass index, educational level, socioeconomic position, marital status, and maternal height), showing no statistically significant differences between low exposure and no exposure (OR 0.87, 95 % CI 0.76–1), intermediate exposure (OR 0.95, 95 % CI 0.81–1.13), or high exposure (OR 1.13, 95 % CI 0.92–1.4).

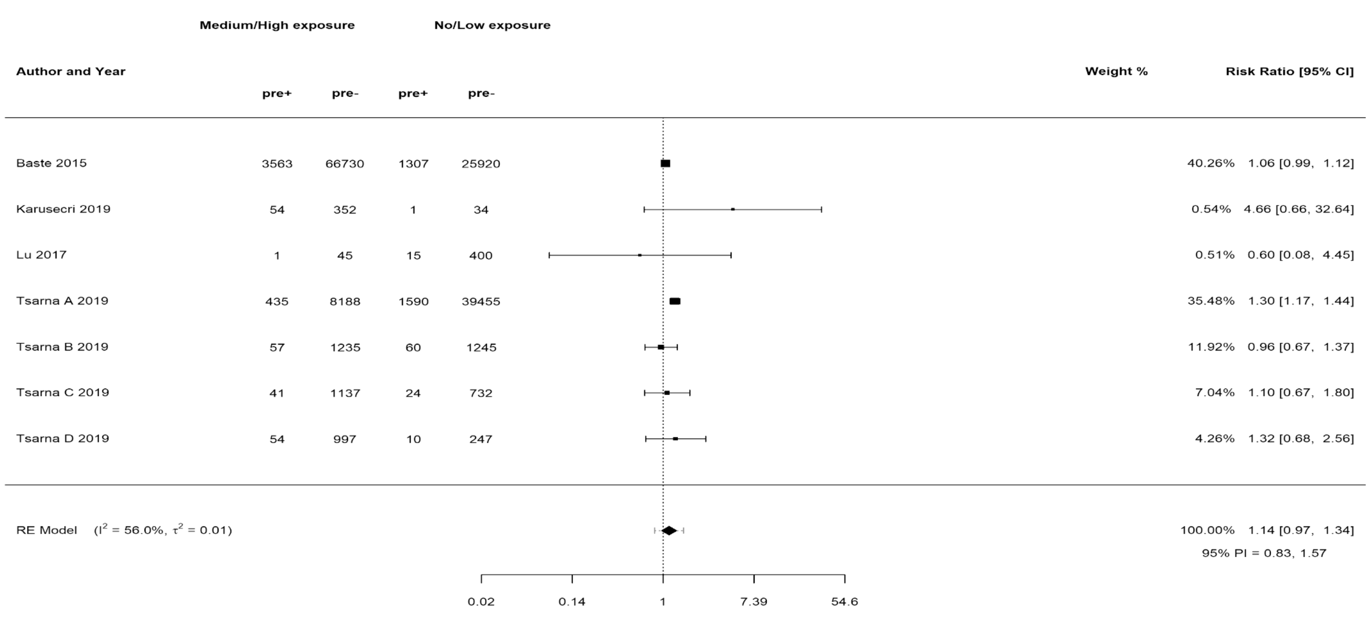

Fig. 2. Pairwise *meta*-analysis for risk of pre-term birth between medium/high exposure and no/low exposure for mobile phone use in the general popualtion. A risk ratio above one indicates greater risk of higher exposure, whereas a risk ratio below one represents a reduce risk for no/low exposure. The black diamond represents the combined effect estimate and 95 % CI, the dotted lines are the 95 % PI. Tsarna 2019 A = Danish National Birth Cohort (DNBC), B = Amsterdam Born Children and Their Development Study (INMA), C = Spanish Environment and Childhood Study (ABCD), D = Korean Mothers and Children's Environment Health Study (MOCEH); pre+ = pre-term birth; pre- = normal birth time.

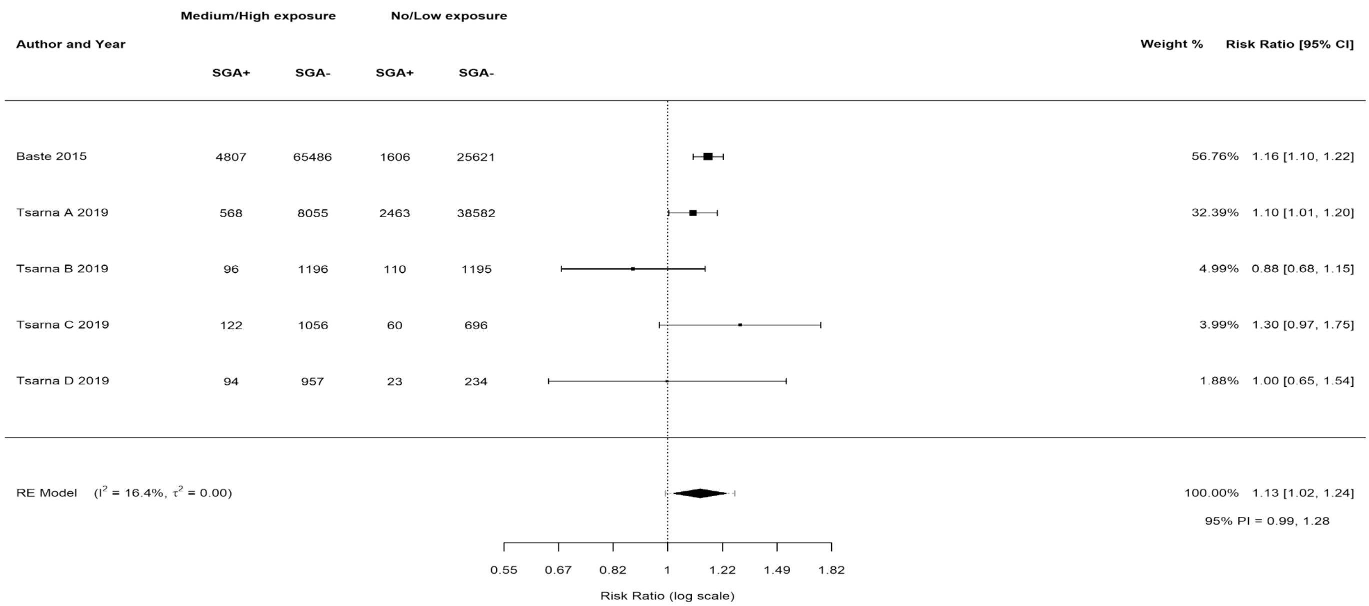

Fig. 3. Pairwise *meta*-analysis for risk of SGA between medium/high exposure and no/low exposure for mobile phone use in the general popualtion. A risk ratio above one indicates greater risk of higher exposure, whereas a risk ratio below one represents a reduce risk for no/low exposure. The black diamond represents the combined effect estimate and 95 % CI, the dotted lines are the 95 % PI. Tsarna 2019 A = Danish National Birth Cohort (DNBC), B = Amsterdam Born Children and Their Development Study (INMA), C = Spanish Environment and Childhood Study (ABCD), D = Korean Mothers and Children's Environment Health Study (MOCEH).

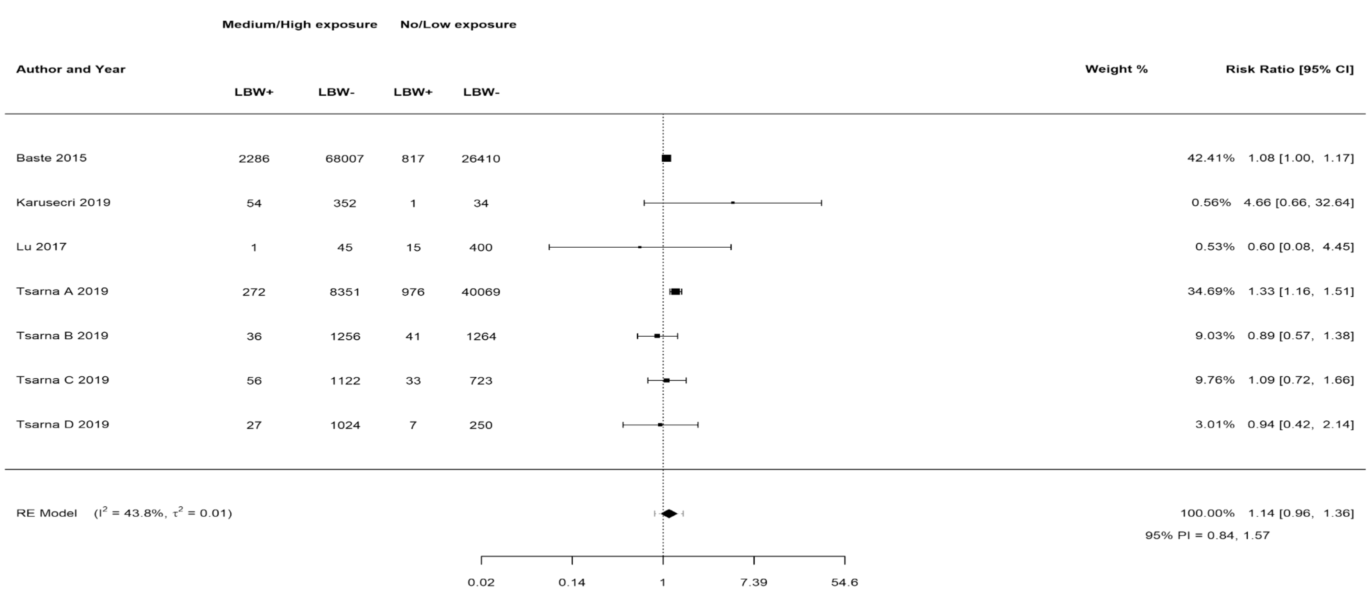

Fig. 4. Pairwise *meta*-analysis for risk of LBW between medium/high exposure and no/low exposure for mobile phone use in the general popualtion. A risk ratio above one indicates greater risk of higher exposure, whereas a risk ratio below one represents a reduce risk for no/low exposure. The black diamond represents the combined effect estimate and 95% CI, the dotted lines are the 95% PI. v.

4.7.2. Occupational studies

4.7.2.1. Miscarriage. Two studies were included in a dose–response *meta*-analysis (Lerman et al., 2001, Taskinen et al., 1990). Both reported exposure of physiotherapists to shortwave diathermy (SWD). At one hour of usage, the evidence is very uncertain about the effects of per hour exposure to shortwave diathermy in physiotherapists on miscarriage (OR 1.02, 95 % CI 0.94–1.1; I^2 = 72 %; τ = 0.017; very low-certainty evidence; see Fig. 5).

Five studies were included in a pairwise *meta*-analysis (Allam, 2016, Cromie et al., 2002, Ouellet-Hellstrom and Stewart, 1993, Khan et al., 2018, Xu et al., 2016) with varying equipment exposure (see Fig. 6 for details). The evidence is very uncertain about the effects of RF-EMF exposure compared to no exposure on risk of miscarriage (RR 1.06, 95 % CI 0.96 to 1.18; very low-certainty evidence).

4.7.2.2. Congenital anomalies. Two studies were included in a dose–response *meta*-analysis, both assessing the exposure of SWD in female physiotherapists on congenital anomalies (Lerman et al., 2001, Taskinen et al., 1990). The χ^2 test for non-linearity was violated (χ^2 = 7.47, df = 1, P = 0.006). We therefore calculated a quadratic model. The evidence is very uncertain about the effects of SWD exposure in physiotherapists and congenital abnormalities (OR 1.4, 95 % CI 0.85 to 2.32; I^2 = 68.1 %; τ = 0.31; very low-certainty evidence; see Fig. 7).

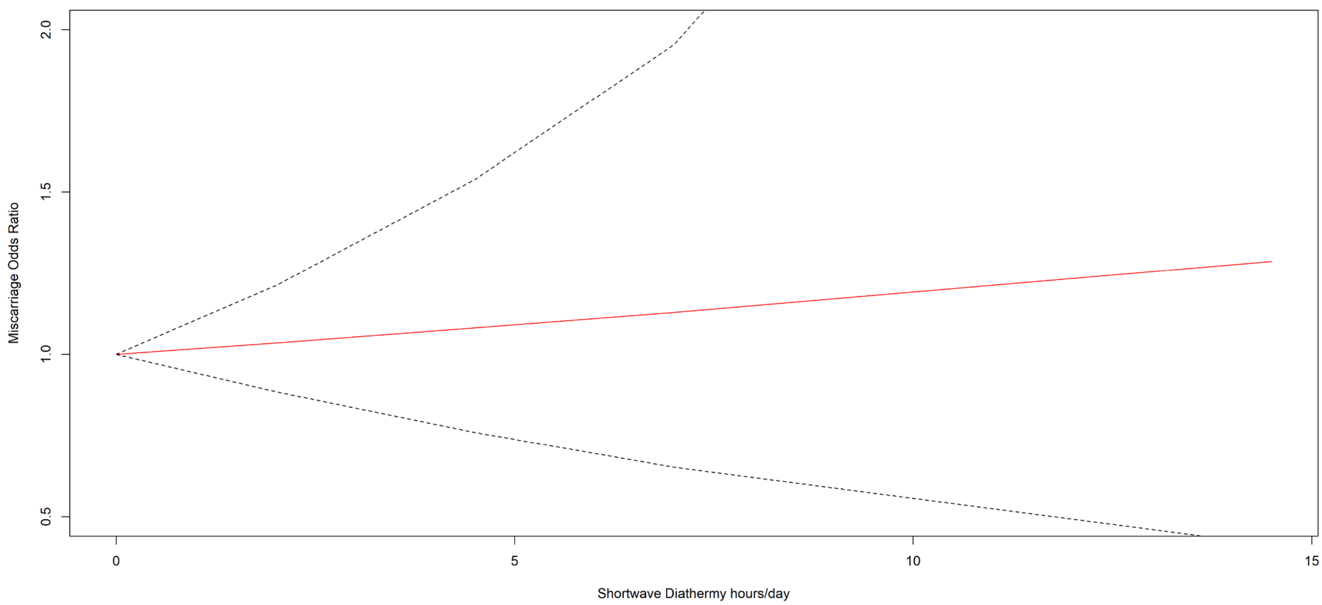

Fig. 5. Dose-response curve for the linear model of odds of miscarriage for hours of usage per day for shortwave diathermy. The red line represents the linear dose–response, while the black dotted lines represent the 95% confidence intervals. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

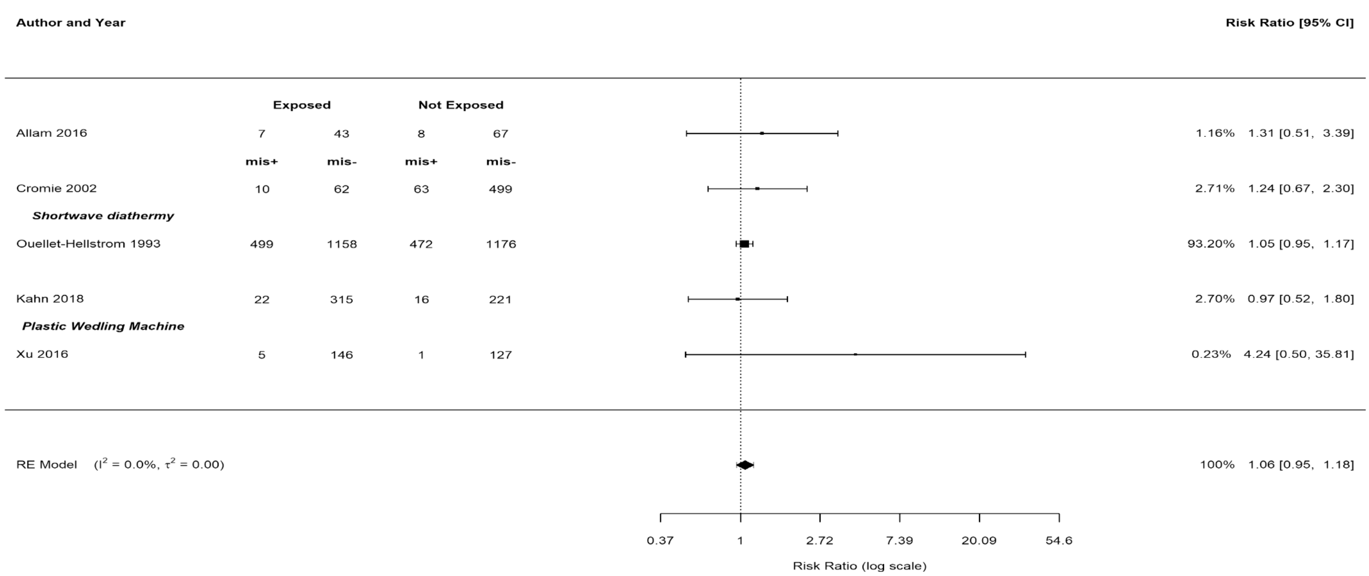

Fig. 6. Pairwise *meta*-analysis for risk of miscarriage between those exposed and not exposed in occuptaional studies. A risk ratio above one indicates greater risk for those exposure, whereas a risk ratio below one represents a reduce risk for no exposure. The black diamond represents the combined effect estimate and 95% CI.

Two studies provided data on congenital anomalies but were unable to be pooled due to heterogeneous populations (Baste et al., 2012, Kolmodin-Hedman et al., 1988). In the first study, male employees in the Royal Norwegian Navy exposed to high frequency antennas were split into two groups: acute RF-EMF exposure and non-acute RF-EMF exposure (where acute exposure was defined by the study authors as being any conception 3 months or less from the father's exposure) and compared with men serving on other vessels. For the men in the acute exposure group, those with low exposure were less likely to have a child with an anomaly (RR 0.2, 95 % CI 0.03–1.4), there was no difference with medium exposure compared with control (RR 0.92, 95 % CI 0.49–1.72) but those with high exposure had a greater risk of having a child with anomalies compared with controls (RR 2.14, 95 % CI 0.32–14.3) (Baste et al., 2012).

In the non-acute group, there was little difference in risk of anomalies between those with low (RR 1.08, 95 % CI 0.79–1.48) or medium exposure (RR 1.12, 95 % CI 0.83–1.5), though those with high exposure seemed less likely to have a child with anomalies than controls (RR 0.74, 95 % CI 0.52–1.07) (Baste et al., 2012).

The other study assessed female factory workers, compared with controls, stating that there were four minor anomalies (Kolmodin-Hedman et al., 1988). However, the study did not state in which group these anomalies occurred, or what type of congenital anomalies were recorded (Kolmodin-Hedman et al., 1988).

4.7.2.3. Pre-term birth. Maternal exposure to RF-EMF and its effect on pre-term births was presented in three studies (Allam, 2016, Lerman et al., 2001, Xu et al., 2016). Two of these studies assessed RF-EMF exposure in female physiotherapists (Allam, 2016, Lerman et al., 2001). Lerman et al. (2001) assessed SWD, while Allam (2016) analysed

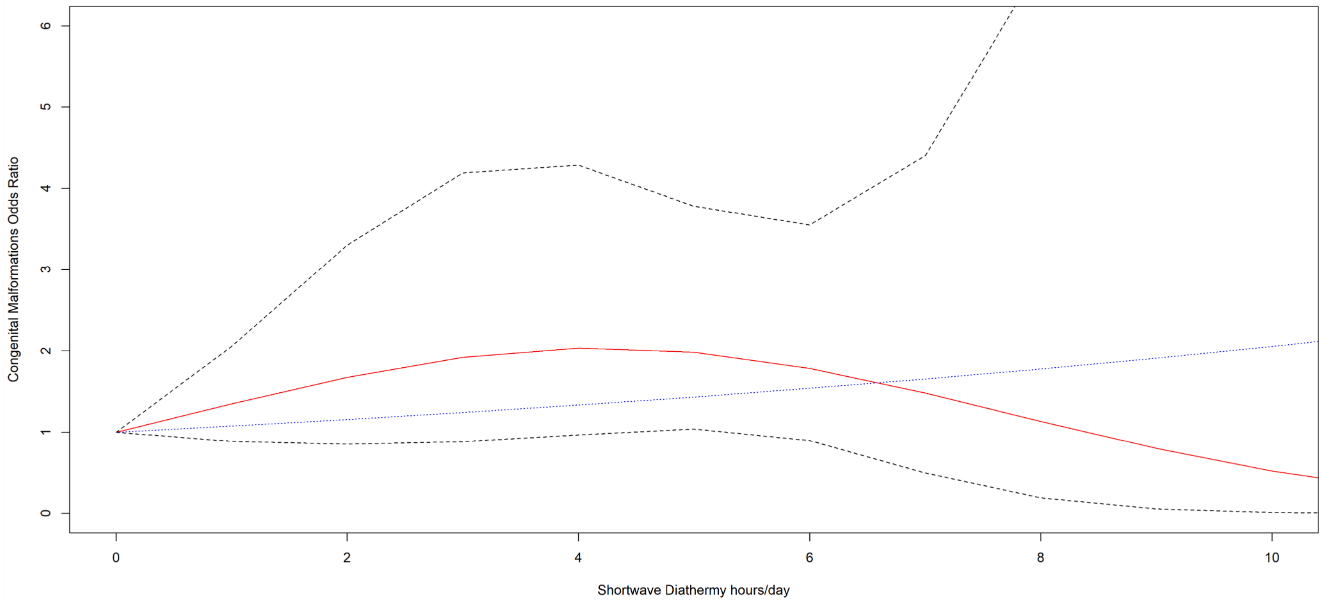

Fig. 7. Quadratic dose–response curve for odds of congenital malformations in female physiotherapists using shortwave diathermy. Red line represents the non-linear (quadratic) dose–response. Blue line represents the linear dose–response. Black dotted lines are the 95% confidence intervals for the non-linear dose response. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

a combination of radiofrequency, SWD and microwave diathermy. The other study assessed exposure in female factory workers exposed to RF-EMF from plastic welding machines (Xu et al., 2016). A pairwise *meta*-analysis was conducted on the unadjusted data (see Fig. 8). The evidence is very uncertain about the effects of exposure compared with no exposure on pre-term birth (RR 1.19, 95 % CI 0.32 to 4.37, 95 % PI 0.18–7.87; very low-certainty evidence).

One other study reported on pre-term births (Baste et al., 2012). In this study, male employees in the Royal Norwegian Navy exposed to high frequency antennas were split into two groups (acute RF-EMF and non-acute RF-EMF exposure) and compared with men serving on other vessels (Baste 2012). In the acute RF group, those with low exposure were reported to have a decreased risk of pre-term birth (RR 0.2, 95 % CI 0.03–1.4), there was little reported difference between those with medium exposure and control (RR 0.92, 95 % CI 0.49–1.72), while those with high exposure were more likely to lead to pre-term birth (RR 2.14, 95 % CI 0.32–14.3) (Baste 2012). In the non-acute group, there was little difference between men with low exposure (RR 1.08, 95 % CI 0.79–1.48) and medium exposure compared with control (RR 1.12, 95 % CI 0.83–1.5), though there was reported to be a reduced risk of pre-term birth in those with high exposure (RR 2.14, 95 % CI 0.32–14.3).

4.7.2.4. Stillbirth. Four studies reported on stillbirth but could not be pooled (Cromie 2002, Kallen 1982, Oullet-Hellstrom 1993, Xu 2016). In Cromie 2002, only one case of stillbirth (0.2 %) was reported, while in Kallen 1982 seven stillbirths were reported. Neither Cromie 2002 nor

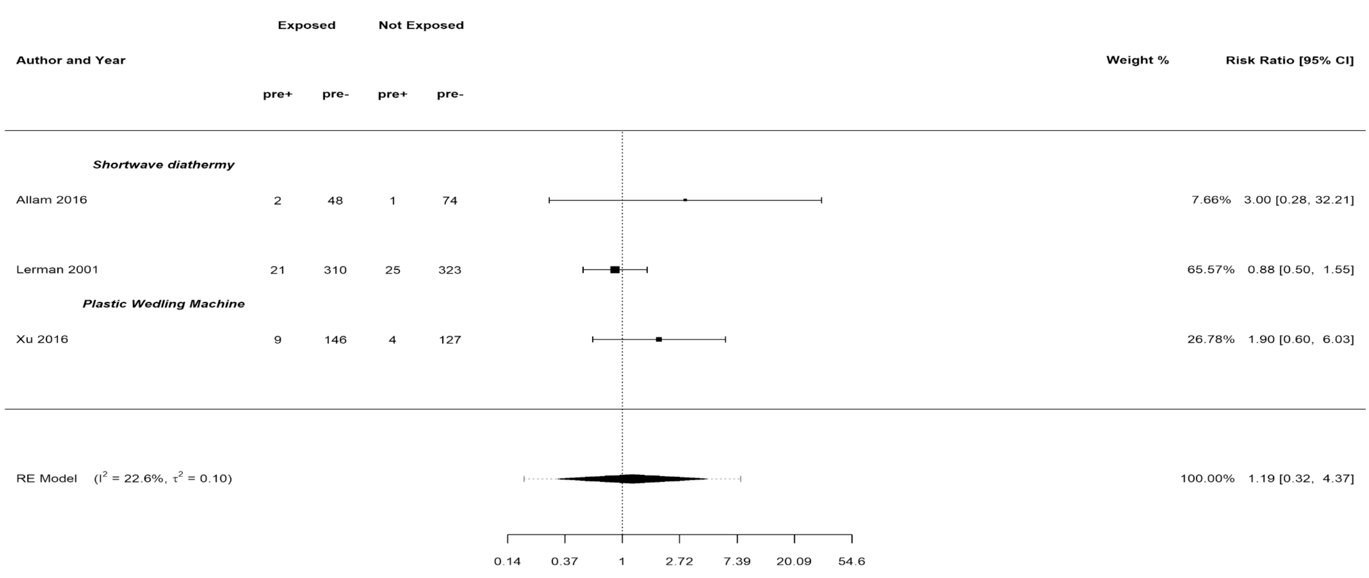

Fig. 8. Pairwise *meta*-analysis for risk of pre-term birth between those exposed and not exposed in occupational studies (maternal exposure). A risk ratio above one indicates greater risk for those exposure, whereas a risk ratio below zero a reduce risk for no exposure. The black diamond represents the combined effect estimate and 95% CI, the dotted lines are the 95% PI.

Kallen 1982 provided a definition of stillbirth. Oullet-Hellstrom 1993 reported that stillbirths, defined as miscarriages occurring after 27 weeks gestation, occurred in "three pregnancies" but did not report further details. Finally, Xu et al., 2016 defined stillbirths as the intra-uterine death of a foetus after 28 weeks gestation or the death of a foetus weighing at least 500 g. The study reported that stillbirths occurred in 1/49 (2.0 %) in the high exposure group and 1/95 (1.0 %) in the control group, with 0/85 in the low exposure group experiencing stillbirths.

4.7.2.5. Small for gestational age (SGA). Two occupational studies reported on SGA but could not be pooled (Baste 2012, Khan 2018). In Baste et al. (2012), those with low acute exposure were reported to have a decreased risk of SGA (RR 0.2, 95 % CI 0.02–1.4), there was little difference between those with medium acute exposure and control (RR 0.92, 95 % CI 0.49–1.72), while there was an increase in risk of SGA for the children of men with high acute exposure (RR 2.14, 95 % CI 0.32–14.3). In the non-acute subgroup, there was little reported difference in children SGA for men with low exposure (RR 1.08, 95 % CI 0.79–1.48) and medium exposure (RR 1.12, 95 % CI 0.83–1.5), though there was an apparent decrease in risk for men with high exposure (RR 0.74, 95 % CI 0.52–1.07) (Baste et al., 2012). In an adjusted analysis, another study noted that female cashiers exposed to electronic article surveillance may be less likely to give birth to a child with SGA compared to workers in smaller grocery stores (OR 0.49, 95 % CI 0.16–1.43) (Khan et al., 2018).

4.7.2.6. Low birth weight. The same three studies that assessed maternal exposure and its effect on pre-term birth rate also analysed risk of LBW (Allam, 2016, Lerman et al., 2001, Xu et al., 2016). The evidence is very uncertain about the effects of RF-EMF on miscarriage risk (RR 2.90, 95 % CI: 0.69 to 12.23; very low-certainty evidence; see Fig. 9).

Two occupational studies reported on low birth weight but could not be pooled. Baste et al. (2012) presented data for paternal exposure to radar on fast patrol boats and its effect on LBW. Men with acute low exposure were less likely to father a child with low birth weight (RR 0.2, 95 % CI 0.03–1.4), there was reportedly little difference in risk of low birth weight between men with acute medium exposure and controls (RR 0.92, 95 % CI 0.49–1.72), but an increase in risk of low birth weight in children fathered by men with high acute exposure (RR 2.14, 95 % CI 0.32–14.3). In the nonacute subgroup, it was reported that there may be little difference in low birth weight between children fathered by men with low exposure (RR 1.08, 95 % CI 0.79–1.48) and medium exposure (RR 1.12, 95 % CI 0.83–1.5), but that men with high exposure might be less likely to father a child with low birth weight (RR 0.74, 95 % CI 0.52–1.07) (Baste 2012). In Xu et al. (2016), two female factory workers with high RF-EMF exposure (4.1 %) and two with low exposure (3.5 %) had children with low birth weight, compared to three in the control group (3.2 %).

5. Discussion

5.1. Summary of the evidence and interpretation of the results

In total, 18 studies were identified for this review: in eight the general public was the population of interest and in 10 the populations of interest were occupational. Within the general population, the evidence is very uncertain about the effects of RF-EMF on pre-term birth, SGA and low birth weight. It was not possible to conduct *meta*-analyses for miscarriage and congenital anomalies due to significant heterogeneity between studies. Within the occupational studies, the evidence is very uncertain about the effects of RF-EMF on miscarriage and the effects of maternal RF-EMF exposure on pre-term birth, congenital anomalies and low birth weight.

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 on pre-term birth; SGA; miscarriage; still birth and, or, congenital anomalies compared to no or low level exposure in pre-conception or pregnant adults.

Risk of bias was often apparent in both general public and occupational studies; all but one of the included studies were rated as probably or definitely high risk for at least two domains on the OHAT risk of bias tool. Nine studies were at probably or definitely high risk of exposure characterisation bias (Allam, 2016, Baste et al., 2012, Cromie et al., 2002, Källén et al., 1982, Karuserci et al., 2019, Lu et al., 2017, Taskinen et al., 1990, Tsarna et al., 2019, Zhao et al., 2021), while another nine were at risk of outcome assessment bias (Baste et al., 2012, Cromie et al., 2002, Källén et al., 1982, Karuserci et al., 2019, Lu et al., 2017, Mahmoudabadi et al., 2015, Tsarna et al., 2019, Xu et al., 2016, Zhao et al., 2021). In 10 studies, issues surrounding the identification and handling

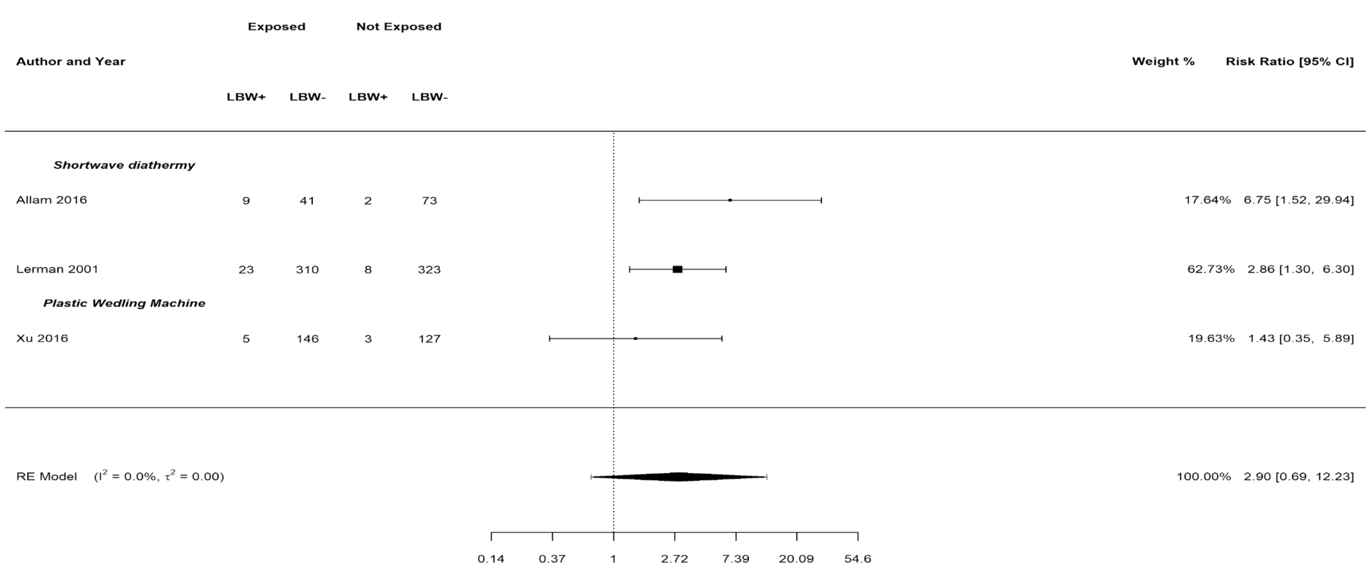

Fig. 9. Pairwise *meta*-analysis for risk of low body weight between those exposed and not exposed in occupational studies. A risk ratio above one indicates greater risk for those exposure, whereas a risk ratio below zero a reduce risk for no exposure. The black diamond represents the combined effect estimate and 95% CI.

of confounders was present (Allam, 2016, Baste et al., 2012, Baste et al., 2015, Brizzi and Marinelli, 2018, Cromie et al., 2002, Källén et al., 1982, Karuserci et al., 2019, Kolmodin-Hedman et al., 1988, Mahmoudabadi et al., 2015, Xu et al., 2016), while three were also at risk of selective reporting (Cromie et al., 2002, Källén et al., 1982, Kolmodin-Hedman et al., 1988).

More generally, reporting of exposures across studies was often inconsistent and lacking in detail (see Tables 1 and 2). Most studies in the general population used a proxy exposure, such as time spent on mobile phone or mobile phone usage, with heterogeneity between how these were measured.

One of the main issues of the evidence base is a lack of confounding assessment in studies (Baste et al., 2015, Allam, 2016, Brizzi and Marinelli, 2018, Karuserci et al., 2019, Kolmodin-Hedman et al., 1988, Baste et al., 2012, Källén et al., 1982, Cromie et al., 2002, Mahmoudabadi et al., 2015, Xu et al., 2016) and inconsistency regarding the method of exposure measurement. All analyses were downgraded to either low-certainty or very low-certainty evidence on OHAT GRADE, with risk of bias, indirectness and imprecision causing concerns. Indirectness was an issue for occupational studies measuring congenital anomalies. Many of the studies only stated that they were assessing the risk of any congenital anomalies rather than identifying and assessing the risk of specific congenital anomalies (e.g. the effect of RF-EMF could potentially affect different congenital anomalies in different ways). This limits our ability to assess the risk of different kinds of congenital anomalies following RF-EMF exposure.

5.3. Strengths and limitations in the review process

We conducted a comprehensive search for literature and conducted both forwards and backwards citation chaining and contacted RF-EMF 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 does means inconsistency in judgements made could be inherent within review screening. 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. OHAT risk of bias assessments were undertaken by two independent reviewers with ratings agreed as needed through opinion from a third independent reviewer to reduce subjectivity in decision making.

The pairwise *meta*-analyses were performed using either a combination of high/intermediate versus low/no exposure or exposed versus not exposed participants. Ideally, a pairwise *meta*-analysis at varying levels or a dose–response analysis for all studies would have been completed. However, this was not possible due to small study numbers and the varied reporting of RF-EMF exposure.

Where it was feasible to conduct OHAT GRADE assessment, following guidance, a single reviewer made initial assessments of the evidence level starting point for each outcome, which was then checked by another reviewer. Two reviewers then independently assessed the certainty of evidence based on each domain with disagreements resolved by discussion and where needed with input from a third reviewer. Final confidence ratings were assigned to each outcome after group consensus on ratings was achieved across the authorship group.

5.4. Implications for biological plausibility

Currently, the evidence base on the effects of RF-EMF on female reproductive outcomes is too uncertain to draw any implications for biological plausibility.

5.5. Implications for research

The dose–response analyses conducted in this systematic review are of very low-certainty. Meaning, due to the quality of the body of evidence being summarised, we have very little confidence in the presented RF-RMF dose response effect estimates. It is likely estimates differ substantially from the true effects. We cannot conclude what the impact of varying levels of RF-EMF exposure are on the female reproductive outcomes assessed in this systematic review.

The GRADE system allows for transparent assessment of the quality of a body of evidence on an individual outcome of interest and draws from information on within study risk of bias, inconsistency, indirectness, imprecision, publication bias, magnitude of effect, existence of a dose–response gradient and/or existence of plausible residual bias or confounding.

Our assessments demonstrate a need for rigorous prospective research that is appropriately powered to evaluate the effects of RF-EMF exposure in both general public and occupational settings on all prespecified outcomes of interest within this systematic review. We cannot conclude what the impact of varying levels of RF-EMF exposure are on female reproductive outcomes or if increased exposure leads to increased risk. The need for safe threshold guidance development and implementation at this point cannot be evidence led rather guided by expert opinion.

Future studies in a general public setting should provide the definitions of the outcomes consistently (e.g. by standardising the reporting of congenital anomalies so that these were reported separately). Congenital anomalies are a clinically heterogenous group of conditions that can be structural, functional or both with varying severity of implications for those effected. This umbrella term can include, as examples, heart defects, hernias and limb malformation. Often when the term is used there is a lack of transparency about the conditions being incorporated. Standardising reporting at a more granular level would allow for greater transparency and the assessment of risk for developing clinically homogenous congenital anomalies. We are currently not able to assess risk of developing individual anomalies or homogenous sub-groups of anomalies due to the way in which they are reported (i.e. multiple conditions and heterogenous sub-groups are analysed together).

Researchers should consider assessing a greater range of technologies with the potential to contribute to RF EMF exposure levels in general public settings. For example, far-field exposures (e.g. base stations) should be considered. Most of the evidence being generated is assessing the impact of mobile phone exposure. Researchers should also try to report more detailed exposure metrics and in occupational settings, greater effort should be made to complete studies by taking exposure measurements using appropriate equipment or, at the least, using a JEM. Additionally, the majority of the evidence was derived from physiotherapists exposed to SWD. Further information about this exposure and others in an occupational setting are needed to understand the impact of exposures in different job roles. In both general public and occupational settings, there is also a need for further assessment of the impact of paternal exposures to RF-EMF and the impact of this on pregnancy outcomes. Furthermore, all authors should collect and report all available demographic, exposure, and analysis data. This would greatly enhance the research area and the ability to further combine studies. Studies in both populations should also consider consistently reporting exposure to the RF-EMF by a measure that lends itself to a dose–response analysis, or that can be transformed for analysis, and provides a more direct correlation to adverse pregnancy outcomes (e.g. minutes/hours of use at the location of interest, in this case near the genitalia).

5.6. Conclusions

Overall, the majority of evidence suggest that there is little to no effect of RF-EF on female reproductive outcomes. The evidence was rated as low to very low certainty, was 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 body of research is indicating about the effect of RF-EMF on female reproductive outcomes. The *meta*-analyses that were possible suggest no increased relative risk for female reproductive outcomes due to RF-EMF exposure in the general public or occupational settings. This is further supported by the dose–response *meta*-analysis in female physiotherapists using SWD. For studies that were not *meta*-analysed, there was variation in effect. Most included studies were at risk of bias.

Overall, while we observe a lack of effect, further prospective studies conducted with greater rigour would build the existing evidence base and are required to have greater certainty in any potential effects of RF-EMF on female 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 SR3B).

6.2. Funding support

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CRediT authorship contribution statement

Eugenie Evelynne Johnson: Writing – review & editing, Writing – original draft, Validation, Investigation, Formal analysis. **Ryan P.W. Kenny:** 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, Funding acquisition, Conceptualization. **Carolina Calderon:** Writing – original draft, Validation. **Judith Rankin:** Validation. **Mark S. Pearce:** Validation. **Mireille Toledano:** Validation. **Dawn Craig:** Funding acquisition, Conceptualization. **Fiona Pearson:** Writing – review & editing, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: [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), and the COSMOS (cohort study of mobile phone use and health) a longitudinal cohort study which is completed (2019). Carolina Calderon has been involved in MOBI-Kids (risk of brain cancer from exposure to radiofrequency fields in childhood adolescence) and GERoNIMO, of which the Tsarna 2019 study was one of the outcomes. However, they were not directly involved in the Tsarna 2019 paper and was not involved in the selection, data extraction or risk of bias assessment for this study.].

Data availability

Data will be made available on request.

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Availability of other material

None.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2024.108816.

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