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Exposures to radio-frequency electromagnetic fields and their impacts on children's health – What the science knows?

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Abstract

The possible health effects of radiofrequency electromagnetic radiation on children have become a public concern due to biological vulnerability of developing children. To evaluate the evidence for possible adverse health effects on children, we systematically reviewed epidemiological studies, and briefly reviewed the experimental animal or mechanistic studies. Using a search strategy and risk-of-bias assessment, we summarized the existing data on cancer, birth outcome, neurocognitive development, and behavioral problems. There was no sufficient evidence to determine the adverse effects. Recent large-scale animal studies have shown carcinogenic findings, but the biological mechanism has not yet been elucidated. A well-designed future study is needed to produce high-quality scientific evidence of the possible harmful effects of radiofrequency electromagnetic radiation exposure in children.

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Keywords

Radiofrequency-electromagnetic field, Cancer, Birth outcome, Neurocognitive development, Neurobehavioral problems, Children.

Introduction

Electromagnetic radiation in the frequency range of 100 kHz–300 GHz has been classified as radio frequency electromagnetic field (RF-EMF) by the World Health Organization; it is used in various types of telecommunication applications and the sources of exposure are becoming more diversified. According to the rapid ongoing development of mobile communication services and increasing number of children using the services, the possible adverse health effects of RF-EMF exposure on children become the public concern due to vulnerability of children, such as exposure for a longer lifetime, being a developmental stage of body, and having a higher specific absorption rate of RE-EMF energy than adult [1].

One of the most important non-thermal effects of RF-EMF is the carcinogenic effects. RF-EMF exposure to the head during mobile phone use has been classified as group 2B by the International Agency for Research on Cancer in 2010 [2], mainly based on the results of two studies: the INTERPHONE study on glioma and a large Swedish case-control study on acoustic neuroma [3,4]. However, this classification did not consider data on children due to the lack of relevant studies at that time. In addition to cancer, other possible effects on children, including birth outcomes, neurocognitive development, and behavioral problems, have been proposed. Over the past 10 years, some qualified epidemiological studies have been conducted on children. Therefore, a comprehensive evaluation of the current evidence and finding the research gaps are needed.

We aimed to assess the scientific evidence of the RF-EMF exposure effects on children's health by systematically reviewing epidemiological studies and briefly reviewing animal and mechanistic studies, then suggest a necessity of higher quality epidemiological study in the RF-EMF field.

Methods

For the systematic review of epidemiologic studies, we applied the literature search strategy, selection process, and risk-of-bias (RoB) assessment, according to the PRISMA guidelines [5] and RoB tool of Office of Health Assessment and Translation (OHAT) [6].

We set the epidemiological literature selection criteria as follows.

(1) Include only human observational studies,
(2) Include studies conducted on infants, children, and adolescents
(3) Any previous (prenatal and postnatal) and concurrent RF-EMF exposure or its proxy assessment

(4) Any health outcome assessment for cancer, birth outcome, neurocognitive development, and behavioral problems
(5) Published English-written articles in peer-review journals, with no restriction on publishing year

The search terms were determined by discussion with all authors (Table S1). Each author was assigned to one of the four outcomes (cancer, birth outcomes, neurocognitive development, and behavioral problems). We retrieved studies in November 2022 from the title and abstract reviews using two databases: PubMed and SCOPUS. The final review list was discussed and agreed upon by all authors.

Evidence from epidemiological studies

A flowchart of the process for retrieving articles showed in Figure S1. We summarized the main points and indicated the RoB tier for each study (13 cancer, 8 birth outcome, 19 neurocognitive development, and 11 behavioral problems studies,Tables S2 & S3). Table 1 shows the number of studies and their RoB tiers (first, second, and third) for each exposure source (near- or far-field), exposure window (prenatal or postnatal), and whether an adverse health effect was suggested (yes/no) according to each health outcome and study design.

Cancer

There were four ecological [7−10], one cross-sectional [11], seven case-control [12−18], and one cohort study [19]. The reported endpoints were all cancers [14,16], leukemia (all, lymphocytic, and myelocytic) [7−10,12−14,16,19], malignant lymphoma [10,14], and brain tumors (all, neuroepithelial, non-neuroepithelial) [7,10,12,14−19]. The exposure assessments were the distance [7−10,12,13] or estimated power or density [12,13,19] from radio or TV transmitters, the distance and estimated dose from phone base stations [14,16], and mobile phone usage assessed by questionnaire [15,17,18].

Although the first ecological study conducted in the United Kingdom (UK) investigating population residing within the vicinity of radio stations or TV transmitters did not find an elevated standardized incidence ratio

Table 1

The number and risk-of-bias tier of reviewed epidemiological studies grouped by the characteristics of exposure, outcome, study design, and reported association of adverse health effects.

Outcome (no. Of studies) / Study design	Exposure sources RF-EMF exposure time Suggesting adverse health effects									
	Near field source				Far field source				Near + Far field	
	Prenatal		Postnatal		Prenatal		Postnatal		Postnatal	
	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
Neoplasm (13)										
Ecological design							②②	②②		
Cross-sectional								③		
Case-Control				②②②				①①①①		
Cohort								①		
Birth outcome (8)										
Cross-sectional	③	③			③					
Case-Control	②	②								
Cohort	②②	②								
Neurocognitive development (19)										
Cross-sectional			②	②②			①	②	②	②
Case-Control			②							
Cohort	②	②②②②②	①①②②	①②						
Behavioral problems (11)										
Cross-sectional			②	②			①②②			
Cohort	②②②②	②	②②②②							①

RF-EMF: radiofrequency electromagnetic field. Near-field source included exposure by mobile phone use and far-field source included exposure from radio/TV transmitters, mobile phone base stations.
According to OHAT(Office of Health Assessment and Translation, Division of the National Toxicology Program, U.S. National Institute of Environmental Health Sciences) risk-of-bias rating tool, grade was noted that the first tier (low risk of bias) as ①, the second tier (medium risk of bias) as ②, and the third tier (high risk of bias) as ③.
The number of circles in each cell denoted the number of studies that are not always consistent with the number of papers in the parentheses because some papers fall into multiple groups.

(SIR) of leukemia or brain tumors [7], two ecological studies conducted in the UK and Italy in the early 2000s reported that the SIR of leukemia decreased as the distance between the residence and a TV transmitter or radio station increased [8,9]. A case-control study in the Republic of Korea [12] showed that children living within 2 km of an AM radio transmitter had a higher leukemia risk than those living at least 20 km of transmitter, but there was no significant increase in the leukemia risk according to the estimated RF power density in the residence. Likewise, a case-control study in Germany showed no increase in leukemia risk according to the distance metrics or quantitatively-estimated RF-EMF power in the residence [13]. Moreover, two case-control studies with estimated power density from mobile phone base stations in the UK [14] and Taiwan [16] and one census-based cohort study with estimated power density from broadcast transmitters in Switzerland [19] did not find a significant increase in the risk of developing brain cancer, CNS cancer, leukemia, or non-Hodgkin's lymphoma.

Two large multi-country case-control studies on near-field exposure have been conducted [15,18]. One was a multicenter case-control study (CEFALO) conducted in Denmark, Sweden, Norway, and Switzerland that recruited children and adolescents aged 7–19 years, including 352 patients with brain tumors and 646 controls. The results showed that the risks in regular mobile phone users were not higher than those in non-users (OR = 1.36, 95% CI: 0.92–2.02), suggesting the need to examine the populations with prolonged use of mobile phones [15]. The MOBI-Kids, a recently published study with 14 participating countries, included 899 patients with brain tumors and 1910 controls, aged 10–24 years. The findings from this study were contrary to the a priori hypothesis; as the time since the start of mobile phone use, cumulative number of calls, or cumulative call time increased, the neuroepithelial tumor risk tended to decrease. Moreover, the analysis using the estimated cumulative RF-specific energy also showed a decrease in neuroepithelial tumor risk. The authors suggested the possibility of a recall bias and the effect of residual confounding [18].

Half of the far-field studies were assessed as the first tier, and all of them showed no association between environmental RF exposure and cancer in childhood (Table 1), which suggests no evidence for carcinogenic effect on children.

Birth outcomes

Eight studies on birth outcomes were reviewed, including three cross-sectional [20–22], two case-control [23,24], and three cohort studies [25–27]. Studied outcomes were fetal growth or birth weight, gestational age at birth, preterm delivery, spontaneous abortion, and craniosynostosis. Most of the studies measured exposure using a questionnaire on maternal mobile phone use during pregnancy.

The association between shortened pregnancy duration or preterm delivery and maternal mobile phone usage was reported in a cross-sectional study conducted in the Republic of Türkiye [20] and in a pooled analysis of four birth cohorts with 55,507 pregnant mothers from Denmark, the Netherlands, Spain, and the Republic of Korea, which showed significant exposure-response relationships [25].

The risk of having an AUDIPOG score below the 10th percentile, which represents growth restriction at birth, was significantly higher in mothers who used mobile phones in a French birth cohort [26], while no association was found between maternal mobile phone use and birth weight, or small or large for gestational age in the Norwegian Mother and child cohort Study (MoBa) [27], or in the pooled analysis of four birth cohorts [25].

Although two studies on spontaneous abortion showed positive associations, a case-control study in Iran was not free from recall bias [23], and a large Chinese cross-sectional study used the distance from the mobile phone base station as an exposure proxy [21].

The number of studies showing an adverse effect and no effect was 3 and 2, respectively, and the quality of these studies was moderate. This suggests a lack of sufficient evidence of an association between prenatal RF exposure from maternal mobile phone use and birth outcomes (Table 1).

Neurocognitive development

Nineteen studies on neurocognitive development were reported, including seven cross-sectional [28–34], one case-control [35], and eleven cohort studies [36–46]. Most studies were on near-field exposure.

Exposure was assessed using self-reported questionnaires and operators' records of mobile phone use [38,43,45], estimation of the RF-EMF exposure dose to the brain and whole body [34,38,43,45], estimation of the residential dose from base stations [29,32], and direct exposure measurement on the pregnant mothers [39] or adolescents [43]. The children's neurocognitive development was assessed by the Bayley Scales of Infant Development [36,39]; CogHealth^{TM} test battery and Stroop color-word test [28,31,33,40,41]; a computerized cognitive test battery [38]; Amsterdam Neuropsychological Tasks [29]; developmental milestone delay [37]; IQ by Wechsler Preschool and Primary Scale of Intelligence, Revised, and McCarthy Scales of Children's Abilities [42,46]; and a comprehensive test battery [30].

For prenatal maternal mobile phone use, a Spanish birth cohort, INMA, reported higher mental and lower psychomotor development scores in children aged 14 months [36]. However, this result could not be replicated in the 6- and 18-month-old children of the Danish National Birth Cohort (DNBC) [37] or in the 6- to 36-month-old children of the Mothers and Children's Environmental Health Study (MOCEH), a Korean birth cohort [39]. In 5-year-old children, a pooled analysis of the above three birth cohorts did not find a significant association between prenatal maternal mobile phone use and IQ [46].

In the Amsterdam Born Children and their Development (ABCD) cohort, a cross-sectional analysis between various RF-EMF exposure sources (mobile phone base stations, indoor sources, and children's mobile phone and cordless phone calls) and the cognitive function of 5–6-year-old children did not show a consistent association [29].

However, in schoolchildren and adolescents aged 9–17 years, concurrent exposure to mobile phones or exposure to mobile phones a year before the diagnosis was associated with a reduction in memory performance or reaction time [28,38,41], changes in task performance or problem-solving capacity [40]. Decreased IQ, verbal expression/comprehension, and non-verbal intelligence were associated with increased RF-EMF levels in the surroundings of children's dwellings, although definitive conclusions could not be drawn [30,34].

Most studies on prenatal exposure from maternal mobile phone use showed no association and the second-tier quality, while those on postnatal exposure from children's own mobile phone use (or mother use) showed more weight of evidence of negative neurocognitive development in children (Table 1,Table S2 & S3).

Behavioral problems

We reviewed four cross-sectional [30,47–49] and seven cohort studies [43,50–55] on behavioral problems. RF-EMF exposure was assessed by conducting a questionnaire-based survey on prenatal maternal mobile phone use [50,51,53–55] and children's mobile phone use [43,47–49,52], reviewing the operator's records of phone use [43], using a personal dosimeter [43,49], performing a direct spot measurement near the dwelling [30], estimating the dose emitted from base stations [47], or calculating the cumulative dose of exposure to the brain and whole body [43]. To assess behavioral problems, the Strength and Difficulties Questionnaire and the Child Behavior Checklist were used.

The behavioral problems of 5-year-old children in the ABCD cohort were not associated with prenatal maternal mobile or cordless phone use, or children's phone use [47,53]. However, prenatal maternal mobile phone use increased the risk of behavioral problems at 7 and 11 years of age in the DNBC, and the risk was even higher for combined exposure to mobile phone use during the prenatal and postnatal periods; the exposure information was collected concurrently during the behavioral outcome assessment [50,51,54]. Prenatal maternal mobile phone use was significantly associated with hyperactivity/inattention problems in children aged 4–7 years old in the five pooled birth cohorts, with a similar result obtained in the analysis of three cohorts, whose mobile phone use data were collected prospectively [55]. In addition, the higher incidence of emotional symptoms among 5-year-old children from the ABCD cohort showed a significant relationship with higher estimated residential RF-EMF doses from the base station [47].

Among older children and adolescents, the risk of inattention or behavioral problems increased according to the duration of children's mobile phone use, which was assessed prospectively [52] or concurrently [30,48,49], although the exposure-response pattern appeared to be inconsistent within the 1-year follow-up analysis in Switzerland [43].

Both prenatal and postnatal near field RF exposure showed effects on children's behavioral problems with the second-tier quality (Table 1, Table S2 & S3).

Other related symptoms

The common symptoms related to mobile phone use in children and adolescents are headache, fatigue, and sleep disturbances [56,57]. Among these, sleep has been the most studied. A 1.39-fold increase in the prevalence of poor sleep quality was reported in adolescents who used mobile phones after 9:00 PM [58]. Mobile phone use increased risk of shorter sleep and insomnia for more than 5 h a day use and depression for social networks and chats more than 2 h a day [59]. Nighttime mobile phone use is associated with later increases in the prevalence of depressed mood, externalizing behavior, and low self-esteem and coping, which is mediated by poor sleep [60].

Carcinogenic evidence from animal experimental studies

Although most animal experimental studies have reported null findings on cancer occurrence [61–63], recent large-scale studies have suggested that RF-EMF exposure may cause the development of some cancers. The National Toxicology Program (NTP) under the US National Institutes of Health announced surprising results from long-term studies. In a previous study in which the B6C3F1/N mice were exposed to whole-body GSM- and CDMA-modulated cell phone RF-EMF at 1,900 MHz for 2 years, an equivocal finding was reported for skin, lung, and liver tumors and malignant lymphoma

[64]. However, in another study in which Sprague Dawley (SD) rats were exposed to whole-body GSM- and CDMA-modulated cell phone RF-EMF at 900 MHz for 2 years, a malignant schwannoma developed in the hearts of male rats in both GSM and CDMA exposure groups, which was determined to be clear evidence by the authors. Furthermore, the incidence of malignant brain glioma was found to be related to RF-EMF exposure [65].

In 2018, the Ramazzini Institute reported a result consistent with that of the NTP study in SD rats exposed to near-field RF-EMF from a 1.8-GHz GSM antenna of the radio base station for 19 h per day from gestational day 12 until natural death. Although the specific absorption rates (SARs) in this study were much lower than those in the NTP study, the incidence of heart schwannoma in male rats was significantly increased in the highest exposure group. The incidence of Schwann cell hyperplasia in male rats and brain malignant glial tumors in female rats also increased, but the difference was not significant [66].

Biological mechanisms

A meta-analysis of approximately 1,000 in vitro cell studies from 1990 to 2015 found that rapidly growing undifferentiated cells, human spermatozoa, and epithelial cells were more sensitive to RF-EMF exposure than well-differentiated cells (e.g., glial cells and lymphocytes). However, the response rates were not associated with exposure levels (SAR or cumulative SAR) [67].

A recent review of in vitro and in vivo studies suggested that reactive oxygen species and DNA damage were consistently observed, although evidence for a link between RF-EMF exposure and carcinogenicity remained inconclusive [68]. According to published animal and cell experimental studies, RF-EMF exposure below the reference level causes oxidative damage, especially in the brain and testis of rats and mice [69]. Nevertheless, no study has reported the mutagenic effects [70].

RF-EMF exposure can affect the expression and function of voltage-gated ion channels [71]. The voltage-gated calcium channel expression in the hippocampus and hypothalamus decreased in mice exposed to 835 MHz of RF-EMF with an SAR of 4.0 W/kg [72,73], while the neuronal excitability of Purkinje cerebellar neurons at 4 weeks of age decreased in rats exposed to 900 MHz of pulse EMF during pregnancy [74]. Mechanistic studies on learning and memory have also reported decreased function and excitatory activity of hippocampal neurons; on the contrary, the memory and cognitive ability in triple transgenic mice were reported to have improved [75]. Effects on the permeability of the blood-brain barrier, myelin sheaths, and neuronal autophagic activities have been reported but not elucidated [75].

Discussion

We systematically reviewed 49 epidemiological studies and briefly reviewed an additional 5 epidemiological and 15 animal and mechanistic studies. There was less evidence for the prenatal exposure effects on neurocognitive development while more evidence was reported on behavioral problems. Postnatal exposure than prenatal showed more evidence for effects both on neurocognition or behavior. Fetal exposure did not show a definite effect on birth outcomes. Far- or near-field exposure to RF showed no evidence for carcinogenic effect on children.

However, the effect of postnatal exposure on the neurocognition and behavior of children should be cautiously interpreted due to the possibility of reverse causality. Behavioral characteristics may associate with the usage of mobile phones or any other IT devices. Furthermore, sleep deprivation and depressive moods by mobile phone usage in children may be another pathway to resulting behavioral problems.

Of several birth outcomes, shortened pregnancy duration was significantly associated with increased maternal mobile phone use. However, this finding should be interpreted with caution owing to the difficulties in disentangling the effects of RF-EMF exposure and maternal physical activity/behavioral factors, such as child-raising characteristics, caused by mobile phone usage. The same caution also should be applied to the results indicating an effect of prenatal exposure on the neurocognitive development and behavior of children.

We did not find clear evidence to determine whether RF-EMF exposure affects children's health outcomes. The quality of the epidemiological studies is mostly low to moderate, and the direction and size of effect estimates are inconsistent.

We found that few studies have been assessed as high quality (low RoB) (Table 1). This is mostly due to the exposure assessment (Table S4). RF-EMF exposure has been assessed using proxy exposure variables for the use of electronic devices, mainly mobile phone use, or distance from mobile communication base stations. This type of exposure assessment may cause a non-differential misclassification which leads the association toward the null.

Despite the remaining ambiguity of the biological mechanism, recent animal studies showing consistent carcinogenic findings have driven more epidemiological studies, repetition of animal studies, and mechanistic studies, with higher levels of quality.

Conclusion

The current studies examining the possible association between RF-EMF exposure and children's health do not

provide conclusive evidence. The results should be interpreted with caution due to the possibility of reverse causality, confounding or mediation of behavioral/environmental factors, and exposure misclassification.

Above all, in the epidemiological research, the accuracy of personal RF-EMF exposure assessment needs to be improved. A recent systematic review on the health effects of RF-EMF exposure in children and adolescents also recommended high-quality research [76]. Furthermore, advanced study design or analysis method that mimic a counter-factual model or randomization and strengthen causal inference, such as instrumental variable analysis, difference-in-differences analysis, and causal mediation analysis, are warranted.

Moreover, we suggest designing a census-based cohort that incorporates data from telecommunication operators. This would be relatively free from the recall and measurement biases of exposure, and exposure history can be profiled in detail. A sufficient statistical power with a large sample size would reveal the relatively small effect of RF-EMF from other competing risk factors, and be effective in the modeling to control confounding or modifying factors, such as restriction or stratified analysis.

With the ongoing development of next-generation mobile communication, RF-EMF exposure is expected to increase in the general population. A well-designed future study is needed to produce high-quality scientific evidence of the possible harmful effects of RF-EMF exposure in children.

Author contributions

Hyungryul Lim: Investigation, Resources, Writing – Original Draft, Writing – Review & Editing., **Jonghyuk Choi**: Investigation, Resources, Writing – Review & Editing. **Hyunjoo Joo**: Investigation, Resources, Writing – Review & Editing., **Mina Ha**: Supervision, Project administration, Funding acquisition, Investigation, Writing – Review & Editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.coesh.2023.100456.

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* of special interest
** of outstanding interest

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