JAMA Network Open

Original Investigation | Environmental Health

Association Between Maternal Exposure to Magnetic Field Nonionizing Radiation During Pregnancy and Risk of Attention-Deficit/Hyperactivity Disorder in Offspring in a Longitudinal Birth Cohort

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Abstract

IMPORTANCE An association between maternal exposure to magnetic field (MF) nonionizing radiation during pregnancy and the risk of attention-deficit/hyperactivity disorder (ADHD) has been reported in both animal and human studies.

OBJECTIVES To determine whether maternal exposure to high levels of MF nonionizing radiation is associated with an increased risk of ADHD in offspring by using more accurate measurements of MF nonionizing radiation levels and physician-diagnosed ADHD, rather than self-reports, and to determine whether the association differs for the subtypes of ADHD with or without immune-related comorbidities.

DESIGN, SETTING, AND PARTICIPANTS A longitudinal birth cohort study was conducted at Kaiser Permanente Northern California among 1482 mother-child pairs whose mothers were participants of an existing birth cohort and whose level of exposure to MF nonionizing radiation was captured during pregnancy in 2 studies conducted from October 1, 1996, to October 31, 1998, and from May 1, 2006, to February 29, 2012. The offspring were followed up from May 1, 1997, to December 31, 2017.

EXPOSURE All participating women wore a monitoring meter for 24 hours during pregnancy to capture the level of exposure to MF nonionizing radiation from any sources.

MAIN OUTCOMES AND MEASURES Physician-diagnosed ADHD and immune-related comorbidities of asthma or atopic dermatitis up to 20 years of age in offspring captured in the Kaiser Permanente Northern California electronic medical record from May 1, 1997, to December 31, 2017. Confounders were ascertained during in-person interviews during pregnancy. Cox proportional hazards regression was used to account for follow-up time and confounders, and analyses were conducted on continuous scales and with categorial exposure levels. No corrections were made for multiple comparisons.

RESULTS Among the 1454 mother-child pairs (548 white [37.7%], 110 African American [7.6%], 325 Hispanic [22.4%], 376 Asian or Pacific Islander [25.9%], and 95 other or unknown [6.5%]; mean [SD] maternal age, 31.4 [5.4] years]), 61 children (4.2%) had physician-diagnosed ADHD. For adjusted continuous scale analyses, children whose mothers were exposed to high levels of MF nonionizing radiation were not associated with higher risk of ADHD (HR, 1.1; 95% CI, 0.8-1.5). Similar results were observed for children with ADHD that persisted into adolescence (HR, 1.3; 95% CI, 0.9-1.9). In categorical analyses of the children with ADHD, among 8 levels of exposures, 2 levels of exposure were associated with risk for ADHD, but 6 levels were not. In categorical analyses of children with persistent ADHD, associations were observed for 4 of 8 levels of exposure. For children with ADHD and immune-related comorbidities (asthma or atopic dermatitis), there were no associations with

(continued)

Key Points

Question Could human exposure to magnetic field nonionizing radiation be associated with increased risk of attention-deficit/hyperactivity disorder in children?

Findings This birth cohort study found that some, but not all, high levels of maternal exposure to magnetic field nonionizing radiation, as captured with a monitoring meter, during pregnancy may have been associated with a higher risk of attention-deficit/hyperactivity disorder in offspring. The associations were not consistent or linear and were primarily for children with attention-deficit/hyperactivity disorder and immune-related comorbidities.

Meaning The findings may spur more research to examine the biological association of in utero magnetic field exposure with risk of attention-deficit/hyperactivity disorder in offspring.

This article was retracted and replaced on February 18, 2021. See supplemental content for versions that show errors and corrections.

+ Supplemental content

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Abstract (continued)

maternal exposure to MF nonionizing radiation in continuous scale analyses (HR, 1.2; 95% CI, 0.8-1.7), but there were associations in categorical analyses at all levels of exposure. However, the associations observed were not linear and CIs around the effect sizes were wide.

CONCLUSIONS AND RELEVANCE In this study, in utero exposure to some, but not all, high levels of MF nonionizing radiation was associated with a higher risk of ADHD. However, the associations observed were inconsistent and nonlinear. The findings may spur more research to examine the biological association of in utero MF exposure with potential risk of ADHD in at-risk offspring.

JAMA Network Open. 2020;3(3):e201417.
Retracted and Replaced on February 18, 2021. doi:10.1001/jamanetworkopen.2020.1417

Introduction

Approximately 11% of all children aged 4 to 17 years (>6.4 million children) in the United States receive a diagnosis of, or treatment for, attention-deficit/hyperactivity disorder (ADHD).[1] Attention-deficit/hyperactivity disorder has been associated with poor school performance during childhood and with lifelong disabilities.[2] According to the Centers for Disease Control and Prevention, the annual costs associated with ADHD treatment and care are estimated at $42 billion[1,3,4] (and as high as $124 billion when burden to the family is included).[5,6] The most troubling aspect of pediatric ADHD is that its prevalence has been steadily increasing during the last few decades, with acceleration since 2000.[7] Without ruling out genetic susceptibility, such a secular increase points to the presence of important environmental risk factors.

One of the most relevant time windows for environmental risk factors to be associated with brain development is during pregnancy, when fetal brain development is susceptible to external insults that could have a long-lasting effect on brain function and neurobehavior. Among the limited research into the causes of ADHD associated with in utero environmental exposures, to our knowledge, the focus has thus far been on chemicals.[8] One nonchemical factor that has not been examined is the ever-present nonionizing radiation, also known as magnetic fields (MFs), emitted from electric appliances, power lines, and wireless devices and networks including cell phone towers. Emerging human studies have begun to report that maternal exposure to MF nonionizing radiation during pregnancy is associated with an increased risk of several childhood illnesses, including immune-related conditions (such as asthma),[9] obesity,[10] and neurologic conditions (such as ADHD).[11,12] An experimental study[13] provided further evidence of (1) the direct link between in utero exposure to MF nonionizing radiation and ADHD in offspring and (2) a potential mechanism linking in utero exposure of MF nonionizing radiation with ADHD through altered neuronal developmental programming. Additional evidence from experimental animal studies has also recently been reported.[14] Finally, a *JAMA* report showed that MF nonionizing radiation could affect human brain cell functions.[15,16] The emerging evidence indicates that (1) there is a potentially adverse biological association between in utero exposure to MF nonionizing radiation and the health of offspring and (2) fetal brain development and programming is likely one of the vulnerable targets associated with in utero exposure to MF nonionizing radiation.

If research evidence shows that in utero MF nonionizing radiation exposure is a risk factor for ADHD, then this exposure would be a modifiable risk factor. Although almost everyone today is exposed to MF nonionizing radiation to some degree, prevention measures can be implemented to reduce the level of maternal MF nonionizing radiation exposure during pregnancy. Thus, understanding the association between in utero exposure to MF nonionizing radiation and the risk of ADHD would be an important first step. To further examine the association and improve on weaknesses in previous studies, we conducted a prospective birth cohort study with focuses on (1) an objective measurement of maternal exposure to MF nonionizing radiation during pregnancy and

(2) a more accurate determination of ADHD cases through a physician's diagnosis as opposed to maternal self-reporting.

Methods

Study Design and Participants

This study was based on the participants of an existing birth cohort of the Kaiser Permanente Northern California (KPNC) health care delivery system whose members have repeatedly been shown to be representative of the underlying community population.[17,18] The mothers were pregnant women who participated in 2 previous studies (one conducted from October 1, 1996, to October 31, 1998, and the other from May 1, 2006, to February 29, 2012) that followed the same study protocol. The level of MF nonionizing radiation exposure was measured by asking participants to wear a monitoring meter throughout a 24-hour monitoring period during pregnancy. Their offspring were followed up from May 1, 1997, to December 31, 2017. The study was approved by the KPNC Institutional Review Board, and all participants provided written informed consent. This study followed the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) reporting guidelines.

Recruitment of Pregnant Women

All pregnant KPNC members aged 18 years or older who resided in the San Francisco Bay Area counties were identified through KPNC electronic medical record data. Those who intended to carry the pregnancy to term at the time of recruitment were eligible for participation in the study. All participants were asked to wear a meter that captured the level of MF nonionizing radiation exposure during a 24-hour monitoring period. An in-person interview was also conducted to ascertain risk factors and potential confounders at the same time. Of 2060 participating pregnant women who had valid measurements for MF nonionizing radiation levels during pregnancy, 1568 delivered live-born offspring, while the rest of the pregnancies ended mostly owing to miscarriage. After excluding those whose offspring did not receive pediatric care at KPNC after delivery, 1482 mother-child dyads were eligible for the present study (eFigure 1 in Supplement 1).

Measuring Levels of Exposure to MF Nonionizing Radiation During Pregnancy

Once a pregnant woman had given consent to participate in the study, she was asked to wear an EMDEX meter (Enertech Inc)[9,10,19,20] to capture the level of MF nonionizing radiation exposure. During the 24-hour monitoring period, which occurred during the first or second trimester, the meters (EMDEX II and EMDEX Lite) captured levels of 40 to 800 Hz of MF nonionizing radiation encountered by the participating woman throughout her daily life. The MF nonionizing radiation level was measured in milligauss. To avoid potential measurement biases, the meters were calibrated before each use and programmed to show only the time of day, without displaying any MF nonionizing radiation exposure level, so that participants were not aware of their MF nonionizing radiation levels during the measurement period. This design was implemented to avoid changes in any routine daily activities owing to the MF nonionizing radiation level being displayed.

The level of MF exposure has been reported to be relatively stable when measured repeatedly over 12 to 26 months, and the study concluded that the measurement of the MF nonionizing radiation level on a single visit is a good indicator of personal exposure levels during a period of up to 26 months.[21] In our study, we also conducted repeated measurements among a subset of 94 participants, and the correlation coefficient was 0.6 between 2 repeated measurements of MF nonionizing radiation, indicating a relatively stable exposure level during pregnancy.

To examine the association of high levels of MF nonionizing radiation with risk of ADHD, we used the 90th percentile of the 24-hour measurements as the MF index, which reflects the MF nonionizing radiation level at or above which a participant was exposed to for 10% of the time during the day.

Outcome Measurement: ADHD Diagnosis and Immune-Related Comorbidities

All eligible participating children included in the study were followed up to 20 years of age until (1) they received a diagnosis of ADHD, (2) they left the KPNC system, or (3) the study period ended (at the end of 2017). Unlike many previous studies based on self-report, the determination of ADHD in this study was based on a physician's diagnosis recorded in the KPNC electronic medical records. A diagnosis of ADHD was identified through *International Classification of Diseases, Ninth Revision* (*ICD-9*) code 314.x or *International Statistical Classification of Diseases and Related Health Problems, Tenth Revision* (*ICD-10*) code F90.x. To avoid ambiguous cases that might have had temporary symptoms similar to ADHD, a child was considered to have had ADHD if there were 2 or more ADHD diagnoses that were at least 1 year apart. We excluded 28 children who had only 1 diagnosis. Thus, the final analyses included 1454 mother-child dyads. To enhance the accuracy of our ADHD case definition, we further identified children who had an ADHD diagnosis that persisted into adolescence (≥12 years of age; persistent cases). The persistent cases were more likely to be true and more severe cases of ADHD. If the exposure of MF nonionizing radiation during pregnancy was associated with ADHD and not with other factors (eg, confounders), one would expect to observe a stronger association with persistent (true) ADHD cases. Thus, confirmation of a stronger association with persistent cases of ADHD than with cases of children with ADHD who did not receive the diagnosis in adolescence could strengthen the observed association.

In addition, emerging literature has shown that some individuals with ADHD have a higher concurrence of immune-related comorbidities, such as asthma and atopic dermatitis (AD); thus, an immune-related cause for ADHD has been proposed.[22-28] At the same time, MF nonionizing radiation exposure has been reported to have an association with the immune system.[9,29-33] Thus, it is conceivable that in utero exposure to MF nonionizing radiation may specifically increase the risk of ADHD with an underlying immune cause. To examine this potential causal pathway, we divided children with ADHD into those with immune-related comorbidities (asthma or AD), as reported in the literature,[23-27] and those without these comorbidities. Both asthma and AD were identified based on physicians' diagnoses: *ICD-9* codes of 493.x or *ICD-10* codes of J45.x for asthma and *ICD-9* codes of 691.8x or *ICD-10* codes of L20.x for AD (excluding diaper or skin rash). A stronger association with ADHD cases with immune-related comorbidity, combined with a lack of association with ADHD cases without immune-related comorbidity, would strengthen the biological basis for the association between in utero exposure to MF nonionizing radiation and risk of ADHD because it would be consistent with the underlying mechanistic pathway.

Potential Confounders

In-person interviews were conducted with all participants during their pregnancy to ascertain information on many potential confounders. We evaluated several risk factors for ADHD as potential confounders, including maternal age, race/ethnicity, educational level, prenatal smoking and alcohol use, prepregnancy body mass index, sex of offspring, and sociodemographic characteristics.

Statistical Analysis

The Cox proportional hazards regression model was used to control for potential confounders. The Cox survival analysis also has the advantage of accounting for differing durations of follow-up for offspring. All children were followed up starting from birth until (1) they received a diagnosis of ADHD or (2) they were censored (ie, either left the KPNC system or did not have an ADHD diagnosis at the end of the study). We first examined the association between maternal MF nonionizing radiation exposure and the risk of ADHD using a continuous measure of MF levels (log-transformed due to the skewed distribution). Second, we examined potential dose-response associations with multicategorical levels of maternal MF exposure and ADHD in offspring in quintiles of number of mother-child dyads. Exposure categories were formed with constant 0.1-mG increments until 2.0 mG or greater. These analyses were conducted first including all ADHD cases. We then examined the associations for ADHD that persisted into adolescence to assess the robustness of the association.

Finally, we examined the associations separately for ADHD cases with or without the immune-related comorbidities of asthma or AD.

We used the change-in-estimate criterion to identify confounders based on whether the ADHD hazard ratio for MF nonionizing radiation changed by 10% or more when the potential confounder was introduced into the model. A Kaplan-Meier survival curve was used to present the ADHD survival pattern separately for offspring across multiple categories of in utero exposure levels to MF nonionizing radiation. Consistent with previous studies examining the effect of MF nonionizing radiation,[9,10,19,20,34] we did not identify any factors that met the definition for being a confounder using the change-in-estimate criterion. Nevertheless, we included in the model common sociodemographic characteristics, such as maternal age, educational level, and race/ethnicity, as well as some known risk factors for ADHD, such as maternal smoking and alcohol use during pregnancy, prepregnancy body mass index, and sex of offspring. All *P* values were from 2-sided tests and results were deemed statistically significant at $P < .05$. No corrections were made for multiple comparisons.

Results

The mean (SD) maternal age of the study population was 31.4 (5.4) years; the racial/ethnic distribution was 548 White (37.7%), 110 African American (7.6%), 325 Hispanic (22.4%), 376 Asian or Pacific Islander (25.9%), and 95 other or unknown (6.5%); 137 (9.4%) reported smoking during pregnancy, and 620 (42.6%) reported alcohol use during pregnancy. **Table 1** presents the mean levels of MF nonionizing radiation exposure at the 90th percentile according to participants' characteristics. As similarly shown in previous studies,[9,10,19,20,34] the level of MF nonionizing radiation exposure was not associated with commonly known ADHD risk factors or socioeconomic characteristics, including race and ethnicity, maternal smoking and alcohol use during pregnancy, educational level, household income, preterm delivery status, sex of offspring, and breastfeeding history. Among all the factors examined in Table 1, maternal age, marital status, history of ADHD, and prepregnancy body mass index showed a statistically significant difference between the 2 groups.

A total of 61 children (4.2%) had physician-diagnosed ADHD. Of these, 49 had ADHD that persisted into adolescence, and 39 had ADHD and immune-related comorbidities.

eFigure 2 in Supplement 1 shows the association between maternal exposure level of MF nonionizing radiation and the rate of ADHD in offspring among 5 quintiles of mother-child dyads. eFigure 2 shows no linear or dose-response association and suggests a possible "threshold effect" of 1.3 mG (Supplement 1). The risk of ADHD appeared to increase for the third quintile (1.3-1.9 mG of exposure) and decrease for the fourth and fifth quintiles, but remained elevated.

After adjustment for known risk factors for ADHD, including maternal age, educational level, race and ethnicity, maternal smoking and alcohol use during pregnancy, prepregnancy body mass index, and sex of offspring, using continuous MF exposure levels, there was no statistical association between MF exposure and ADHD in offspring (HR, 1.1; 95% CI, 0.8-1.5) (**Table 2**). The results of the analysis using categorical MF exposure show that among 8 levels of maternal MF exposure level during pregnancy, 2 levels of exposure were associated with risk of ADHD (1.3 to <1.4 mG and 1.7 to <1.8 mG), but 6 other levels were not associated with risk of ADHD (Table 2).

Table 3 shows the results of the analysis for children with ADHD who had or had not received the diagnosis during adolescence. Using continuous MF exposure levels, there was no statistically significant association (HR, 1.3; 95% CI, 0.9-1.9). In multicategorical assessment, high levels of maternal MF exposure level during pregnancy were associated with a risk of ADHD in offspring at 4 levels of exposure. These associations were not linear and there were no statistically significant associations with other levels of exposure. In addition, there was no association for children who no longer had an ADHD diagnosis in adolescence (Table 3).

Given the previously reported associations of MF nonionizing radiation exposure with immune-related diseases and the existence of potential ADHD immune-related causes, we further examined the association of in utero exposure to MF nonionizing radiation with the risk of ADHD separately for

Table 1. Characteristics of the Study Population by Daily MF Exposure Level Among Pregnant Women Participants

Characteristic	Total No.[a]	MF at 90th percentile, mean (SD), mG	*P* value[b]
Maternal age, y			
≤25	201	1.8 (2.3)	<.05
26-30	420	1.8 (2.3)	
31-35	472	1.6 (2.3)	
≥36	361	1.5 (2.2)	
Race/ethnicity			
White	548	1.7 (2.2)	.73
African American	110	1.6 (2.1)	
Hispanic	325	1.7 (2.3)	
Asian or Pacific Islander	376	1.7 (2.4)	
Others/unknown	95	1.5 (2.5)	
Education			
<College	762	1.7 (2.4)	.06
College	424	1.6 (2.2)	
Postgraduate	268	1.5 (2.2)	
Household income, $			
<20 000	101	1.8 (2.7)	.35
20 000-40 000	253	1.8 (2.2)	
≥40 000	1043	1.6 (2.3)	
Marital status			
Single	107	2.0 (2.3)	<.05
Partner	187	1.7 (2.4)	
Married	1157	1.6 (2.3)	
Smoked since LMP			
Yes	137	1.7 (2.2)	.68
No	1317	1.7 (2.3)	
Alcohol use since LMP			
Yes	620	1.7 (2.2)	.97
No	834	1.7 (2.4)	
Maternal ADHD history			
Yes	14	1.1 (1.9)	<.05
No	1440	1.7 (2.3)	
Maternal prepregnancy BMI			
<25	858	1.8 (2.2)	<.05
≥25	596	1.5 (2.4)	
Preterm delivery			
Yes	112	1.7 (2.3)	.97
No	1342	1.7 (2.3)	
Breastfeeding			
No	144	1.7 (2.3)	.78
Yes	1280	1.7 (2.3)	
Sex of offspring			
Male	755	1.7 (2.3)	.85
Female	699	1.7 (2.3)	
Offspring still enrolled in KPNC at end of the study			
Yes	995	1.6 (2.3)	<.05
No	459	1.8 (2.3)	

Abbreviations: ADHD, attention-deficit/hyperactivity disorder; BMI, body mass index (calculated as weight in kilograms divided by height in meters squared); KPNC, Kaiser Permanente Northern California; LMP, last menstrual period; MF, magnetic field.

[a] The number in individual categories may not match the total number owing to missing data.

[b] From analysis of variance test.

children with ADHD and immune-related comorbidities (asthma or AD diagnosis) (n = 39) and children with ADHD without such comorbidities (n = 22). **Table 4** shows the results for all children with ADHD and for children with persistent ADHD. For continuous maternal MF exposure levels, there was no statistically significant association between maternal MF exposure and offspring ADHD (HR, 1.2; 95% CI, 0.8-1.7). However, for multicategorical analyses, all categories showed a nonlinear statistically significant increased risk of ADHD in offspring compared with the reference category, ranging from an HR of 3.8 (95% CI, 1.3-11.2) for 2.0 mG or greater to an HR of 8.9 (95 % CI, 1.9-40.8) for 1.7 to less than 1.8 mG (Table 4). This nonlinear association was stronger for offspring with persistent ADHD and immune-related comorbidities, with associations ranging from an HR of 6.5

Table 2. Maternal Exposure to MF Nonionizing Radiation During Pregnancy and Risk of ADHD in Offspring

MF at 90th percentile	ADHD, No. (%)		
	Yes	No	aHR[a] (95% CI)
Continuous MF level, mean (SD), mG[b]	1.9 (2.2)	1.7 (2.3)	1.1 (0.8-1.5)
MF level in category, mG			
<1.3	12 (2.1)	560 (97.9)	1 [Reference]
1.3-<1.4	5 (8.1)	57 (91.9)	3.2 (1.1-9.3)
1.4-<1.5	2 (3.6)	53 (96.4)	1.8 (0.4-8.1)
1.5-<1.6	4 (7.5)	49 (92.5)	2.1 (0.7-6.8)
1.6-<1.7	1 (3.1)	31 (96.9)	1.4 (0.2-10.9)
1.7-<1.8	4 (10.3)	35 (89.7)	3.8 (1.2-12.0)
1.8-<1.9	4 (10.0)	36 (90.0)	2.0 (0.6-6.4)
1.9-<2.0	2 (5.0)	38 (95.0)	1.9 (0.4-8.6)
≥2.0	27 (4.8)	534 (95.2)	1.8 (0.9-3.6)

Abbreviations: ADHD, attention-deficit/hyperactivity disorder; aHR, adjusted hazard ratio; MF, magnetic field.

[a] Adjusted for maternal age, race, education, prenatal smoking and alcohol use, prepregnancy body mass index, and sex of offspring.

[b] The natural log of the continuous MF level.

Table 3. Maternal Exposure to MF Nonionizing Radiation During Pregnancy and Risk of ADHD in Offspring With or Without Diagnosis Persisting into Adolescence

MF at 90th percentile	ADHD, No. (%)		
	Yes	No	aHR (95% CI)[a]
Persistent ADHD[b]			
Continuous MF level, mean (SD), mG[c]	2.1 (1.9)	1.7 (2.3)	1.3 (0.9-1.9)
MF level in category, mG			
<1.3	6 (1.1)	560 (98.9)	1 [Reference]
1.3-<1.4	4 (6.6)	57 (93.4)	5.0 (1.4-18.3)
1.4-<1.5	2 (3.6)	53 (96.4)	3.6 (0.7-18.2)
1.5-<1.6	4 (7.5)	49 (92.5)	4.3 (1.2-15.9)
1.6-<1.7	0	31 (100.0)	NA
1.7-<1.8	4 (10.3)	35 (89.7)	7.3 (2.0-26.3)
1.8-<1.9	3 (7.7)	36 (92.3)	3.2 (0.8-13.1)
1.9-<2.0	2 (5.0)	38 (95.0)	3.7 (0.7-18.6)
≥2.0	24 (4.3)	534 (95.7)	3.0 (1.2-7.4)
No ADHD diagnosis in adolescence			
Continuous MF level, mean (SD), mG[c]	1.0 (2.7)	1.7 (2.3)	0.4 (0.2-1.0)
MF level in category, mG			
<1.3	6 (1.1)	560 (98.9)	1 [Reference]
1.3-<1.4	1 (1.7)	57 (98.3)	1.7 (0.2-14.6)
1.4-<1.5	0	53 (100.0)	NA
1.5-<1.6	0	49 (100.0)	NA
1.6-<1.7	1 (3.1)	31 (96.9)	2.3 (0.2-21.9)
1.7-<1.8	0	35 (100.0)	NA
1.8-<1.9	1 (2.7)	36 (97.3)	1.0 (0.1-8.7)
1.9-<2.0	0	38 (100.0)	NA
≥2.0	3 (25.0)	534 (99.4)	0.5 (0.1-2.2)

Abbreviations: ADHD, attention-deficit/hyperactivity disorder; aHR, adjusted hazard ratio; MF, magnetic field, NA, not available.

[a] Adjusted for maternal age, race, education, prenatal smoking and alcohol use, prepregnancy body mass index, and sex of offspring.

[b] Persistent ADHD is defined as those who continued to have ADHD diagnoses at age 12 or older.

[c] The natural log of the continuous MF level.

Table 4. Maternal Exposure to MF Nonionizing Radiation During Pregnancy and Risk of ADHD With or Without Immune-Related Comorbidity[a]

MF at 90th percentile	ADHD, No. (%)		aHR (95% CI)[b]
	Yes	No	
Case definition of ADHD[c]			
ADHD cases with asthma or AD			
Continuous MF level, mean (SD), mG[d]	2.0 (2.1)	1.7 (2.3)	1.2 (0.8-1.7)
MF level in category, mG			
<1.3	4 (0.7)	560 (99.3)	1 [Reference]
1.3-<1.4	3 (5.0)	57 (95.0)	6.8 (1.5-31.3)
1.4-<1.5	2 (3.6)	53 (96.4)	5.4 (1.0-29.9)
1.5-<1.6	3 (5.8)	49 (94.2)	5.3 (1.1-24.6)
1.6-<1.7	0	31 (100.0)	NA
1.7-<1.8	3 (7.9)	35 (92.1)	8.9 (1.9-40.8)
1.8-<1.9	4 (10.0)	36 (90.0)	6.5 (1.6-26.6)
1.9-<2.0	2 (5.0)	38 (95.0)	5.7 (1.0-31.6)
≥2.0	18 (3.3)	534 (96.7)	3.8 (1.3-11.2)
ADHD cases without asthma and AD			
Continuous MF level, mean (SD), mG[d]	1.7 (2.2)	1.7 (2.3)	0.9 (0.5-1.7)
MF level in category, mG			
<1.3	8 (1.4)	560 (98.6)	1 [Reference]
1.3-<1.4	2 (3.39)	57 (96.6)	1.6 (0.3-8.1)
1.4-<1.5	0	53 (100.0)	NA
1.5-<1.6	1 (2.0)	49 (98.0)	0.7 (0.1-5.8)
1.6-<1.7	1 (3.1)	31 (98.9)	1.6 (0.2-14.0)
1.7-<1.8	1 (2.8)	35 (97.2)	1.5 (0.2-12.5)
1.8-<1.9	0	36 (100.0)	NA
1.9-<2.0	0	38 (100.0)	NA
≥2.0	9 (1.7)	534 (98.3)	0.9 (0.3-2.4)
Persistent ADHD[e]			
ADHD cases with asthma or AD			
Continuous MF level, mean (SD), mG[d]	2.2 (1.8)	1.7 (2.3)	1.4 (0.9-2.1)
MF level in category, mG			
<1.3	2 (0.4)	560 (99.6)	1 [Reference]
1.3-<1.4	3 (5.0)	57 (95.0)	13.0 (2.1-79.7)
1.4-<1.5	2 (3.6)	53 (96.4)	10.5 (1.4-76.4)
1.5-<1.6	3 (5.8)	49 (94.2)	11.0 (1.8-68.6)
1.6-<1.7	0	31 (100.0)	NA
1.7-<1.8	3 (7.9)	35 (92.1)	17.3 (2.8-106.2)
1.8-<1.9	3 (7.7)	36 (92.3)	10.4 (1.7-64.3)
1.9-<2.0	2 (5.0)	38 (95.0)	10.9 (1.5-78.4)
≥2.0	16 (2.9)	534 (97.1)	6.5 (1.5-28.7)
ADHD cases without asthma and AD			
Continuous MF level, mean (SD), mG[d]	2.0 (2.2)	1.7 (2.3)	1.1 (0.5-2.4)
MF level in category, mG			
<1.3	4 (0.7)	560 (99.3)	1 [Reference]
1.3-<1.4	1 (1.7)	57 (98.3)	1.5 (0.2-14.1)
1.4-<1.5	0	53 (100.0)	NA
1.5-<1.6	1 (2.0)	49 (98.0)	1.1 (0.1-10.9)
1.6-<1.7	0	31 (100.0)	NA
1.7-<1.8	1 (2.8)	35 (97.2)	3.2 (0.3-31.7)
1.8-<1.9	0	36 (100.0)	NA
1.9-<2.0	0	38 (100.0)	NA
≥2.0	8 (1.5)	534 (98.5)	1.3 (0.4-4.5)

Abbreviations: AD, atopic dermatitis; ADHD, attention-deficit/hyperactivity disorder; aHR, adjusted hazard ratio; MF, magnetic field, NA, not available.

[a] Asthma or AD.

[b] Adjusted for maternal age, race, education, prenatal smoking and alcohol use, prepregnancy body mass index and sex of offspring.

[c] Case definition of ADHD is defined as those who had 2 ADHD diagnoses at least 1 year apart.

[d] The natural log of the continuous MF level.

[e] Persistent ADHD is defined as those who continued to have ADHD diagnoses at age 12 years or older.

(95% CI, 1.5-28.7) for a 2.0 mG or greater level of exposure to an HR of 17.3 (95% CI, 2.8-106.2) for a 1.7 to less than 1.8 mG level of exposure (Table 4). In contrast, no association was observed for children with ADHD without immune-related comorbidities. We also provided the results stratified by immune-related comorbidities in the eTable in Supplement 1. The results are consistent with those in Table 4, although the interpretation of the stratified results could be different.

The **Figure** provides the Kaplan-Meier survival curve showing the proportion of offspring who remained free of ADHD with immune-related comorbidity throughout childhood, from birth up to 20 years of age by multiple maternal MF exposure level categories. This graph shows that, starting at an early age when ADHD was normally diagnosed (around 5 years of age), there was a separation of the ADHD probability among the categories of maternal MF nonionizing radiation exposure levels. Offspring whose mothers were exposed to high levels of MF nonionizing radiation during pregnancy generally had a higher risk of ADHD (lower probability of remaining ADHD free) throughout childhood compared with offspring whose mothers were exposed to lower levels of MF nonionizing radiation during pregnancy.

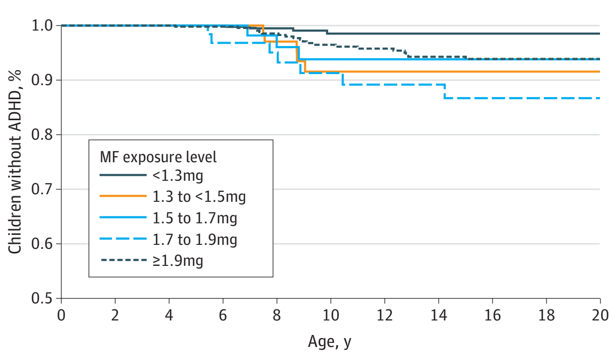
Discussion

In this large birth cohort study of 1454 mother-child dyads, we observed that in utero exposure to some, but not all, higher levels of MF nonionizing radiation appeared to be associated with risk of ADHD. However, there were no statistically significant associations when examined on a continuous scale. The observed association was mainly for children with ADHD and concurrent immune-related comorbidities (asthma and/or AD) (Table 4), which is consistent with reported biological plausibility.[9,29-32] However, the number of children with ADHD and concurrent immune-related comorbidities in this study was small.

Limitations and Strengths

This study has some limitations. Despite the significantly improved accuracy of our MF nonionizing radiation exposure measurements compared with previous studies, we were not able to ask women to carry the meter throughout pregnancy because it was not feasible. Thus, there may still be some inaccuracy in maternal MF nonionizing radiation exposure level. In addition, no corrections were made for multiple comparisons and for many of the significant associations observed among children with ADHD and concurrent immune-related comorbidities, the CIs were wide, indicating that these findings should be interpreted with caution.

Figure. Kaplan-Meier Survival Curve for Attention-Deficit/Hyperactivity Disorder (ADHD) With Immune-Related Comorbidities by Maternal Magnetic Field Nonionizing Radiation Exposure During Pregnancy



No. at risk											
<1.3mg	564	524	487	429	275	174	124	123	115	115	19
1.3 to <1.5mg	115	103	92	86	63	44	32	30	30	29	7
1.5 to 1.7mg	83	71	70	62	45	34	27	26	26	25	4
1.7 to 1.9mg	78	68	65	60	52	44	36	36	32	31	5
≥1.9mg	592	525	493	444	359	286	259	245	235	227	62

This study also has some strengths, including (1) a prospective design, thus reducing the likelihood of participation bias; (2) physician-diagnosed, rather than self-reported, ADHD, thus increasing the accuracy of outcome measurement; and (3) an objective measure of maternal MF nonionizing radiation level ascertained by a meter to reduce measurement error for the exposure.

These findings would need to be replicated in future studies, building on these strengths but also addressing the limitations in the statistical analyses.

Conclusions

The study found that in utero exposure to some, but not all, high levels of MF nonionizing radiation may be associated with a risk of ADHD in offspring. However, given that the associations were not linear and inconsistent, the results should be interpreted with caution.

ARTICLE INFORMATION

Accepted for Publication: January 30, 2020.

Published: March 24, 2020. doi:10.1001/jamanetworkopen.2020.1417

Retraction and Replacement: This article was retracted and replaced on February 18, 2021, to add an eFigure to Supplement 1 and fix errors in the Abstract, text, Tables, and Figure (see Supplement 2 for the retracted article with errors highlighted and Supplement 3 for the replacement article with corrections highlighted).

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Concept and design: Li.

Acquisition, analysis, or interpretation of data: All authors.

Drafting of the manuscript: Li.

Critical revision of the manuscript for important intellectual content: All authors.

Statistical analysis: Li, Chen, Ferber, Hirst.

Obtained funding: Li.

Administrative, technical, or material support: Li, Ferber, Odouli.

Supervision: Li.

Conflict of Interest Disclosures: None reported.

Funding/Support: This study was supported through funds provided by the National Institute of Environmental Health Sciences and the California Public Health Foundation.

Role of the Funder/Sponsor: The funding sources had no role in the design and conduct of the study; collection, management, analysis, and interpretation of the data; preparation, review, or approval of the manuscript; and decision to submit the manuscript for publication.

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SUPPLEMENT 1.

eFigure 1. Flow Chart for the Study Population
eFigure 2. Rate of Attention-Deficit/Hyperactivity Disorder (ADHD) by Maternal Magnetic Field Non-ionizing Radiation Exposure during Pregnancy (Quintiles)
eTable. Maternal Exposure to MF Nonionizing Radiation During Pregnancy and Risk of ADHD Stratified by the Presence or Absence of Immune-Related Comorbidity
Supplement 2. Retracted Article With Errors Highlighted
Supplement 3. Replacement Article With Corrections Highlighted