ONLINE FIRST

Maternal Exposure to Magnetic Fields During Pregnancy in Relation to the Risk of Asthma in Offspring

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Objective: To determine whether maternal exposure to high levels of magnetic fields (MFs) during pregnancy is associated with the risk of asthma in offspring.

Design: A prospective cohort study.

Setting: Kaiser Permanente Northern California.

Participants: Pregnant Kaiser Permanente Northern California members in the San Francisco area.

Main Outcome Measures: Asthma was clinically diagnosed among 626 children who were followed up for as long as 13 years. All participants carried a meter to measure their MF levels during pregnancy.

Results: After adjustment for potential confounders, a statistically significant linear dose-response relationship was observed between increasing maternal median daily MF exposure level in pregnancy and an increased risk of asthma in offspring: every 1-mG increase of maternal MF level during pregnancy was associated with a 15% increased rate of asthma in offspring (adjusted hazard ratio [aHR], 1.15; 95% confidence interval [CI], 1.04-1.27). Using the categorical MF level, the results showed a similar dose-response relationship: compared with the children whose mothers had a low MF level (median 24-hour MF level, ≤0.3 mG) during pregnancy, children whose mothers had a high MF level (>2.0 mG) had more than a 3.5-fold increased rate of asthma (aHR, 3.52; 95% CI, 1.68-7.35), while children whose mothers had a medium MF level (>0.3-2.0 mG) had a 74% increased rate of asthma (aHR, 1.74; 95% CI, 0.93-3.25). A statistically significant synergistic interaction was observed between the MF effect and a maternal history of asthma and birth order (firstborn).

Conclusion: Our findings provide new epidemiological evidence that high maternal MF levels in pregnancy may increase the risk of asthma in offspring.

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ASTHMA IS THE MOST COMMON chronic condition among children. Approximately 13% of children younger than 18 years (9.4 million children in the United States) have asthma.[1] Based on reports from the Centers for Disease Control and Prevention, asthma is a leading cause of hospitalization and emergency department visits for children younger than 18 years in the United States, with staggering annual costs of more than $30 billion (http://www.cdc.gov/HealthyYouth/asthma).[1] The prevalence of asthma has been steadily rising during the last several decades, with an increase of about 74% from 1980 to 1996. While not ruling out genetic susceptibility, such a secular increase indicates the presence of important environmental risk factors that remain elusive.

Environmental exposures during pregnancy could affect fetal development of the immune system and lungs and thus have an impact on the risk of asthma in offspring.[2-5] Among the limited research, chemical exposures have represented much of the focus, while the potential of environmental physical exposures has rarely been examined. One such physical exposure is increasing man-made electromagnetic fields (EMFs). In addition to traditional low-frequency EMFs from power lines and appliances, the buildup of increasingly stronger wireless networks both inside and outside living and work spaces

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and the proliferation of cell phones and other wireless devices have led to human populations being surrounded by EMFs of increasing intensity. This parallel increase in both EMF exposure and asthma prevalence in the past several decades warrants examination.

Studies have shown that EMFs could adversely affect reproductive outcomes and the immune system.[6-15] A recent study also

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showed an EMF effect on brain cell activities.[16,17] Therefore, it is conceivable that exposure to high EMFs, especially during pregnancy (the period of fetal development), may have an impact on the risk of asthma in offspring. To examine this hypothesis, we conducted a prospective study based on a cohort of pregnant women whose daily exposure to magnetic fields (MFs) was captured objectively by a meter during their pregnancy and whose offspring from the index pregnancy were followed up for as long as 13 years for their asthma diagnosis.

METHODS

A prospective cohort study was conducted to examine the effect of EMF exposure on the risk of miscarriage among pregnant members of Kaiser Permanente Northern California (KPNC) in the San Francisco area who were recruited from 1996 to 1998.[6] The members of KPNC are representative of the racially/ethnically diverse underlying population. All pregnant women who submitted a pregnancy test in the KPNC facilities of the San Francisco area were informed of the study, and those with a positive pregnancy test result were recruited for their possible participation. The study was approved by the KPNC institutional review board, and all participants signed an informed consent form.

RECRUITMENT

Women who spoke English and intended to carry the pregnancy to term at the time of recruitment were eligible for participation in the study. We recruited pregnant women early in gestation (5-13 weeks) because miscarriage usually occurs during the first trimester.[6] All participants were interviewed in person during pregnancy to ascertain risk factors for adverse pregnancy outcomes and potential confounders. Of the original 1063 recruited women, 829 delivered a live birth. Of these offspring, 28 did not have medical records in our KPNC system, which means that they likely received their pediatric care outside the KPNC system and therefore were not included in the study.

EXPOSURE MEASUREMENT: MFs

Electromagnetic field refers to both electric fields and MFs. In this study, because the instrument we used (EMDEX-II meter; Enertech Consultants, Campbell, California) measures only MFs, hereafter we will refer to our exposure as *MFs*. All participants were asked to wear an EMDEX-II meter for 24 hours during the first or second trimester so that their actual MF exposure level throughout the day from all sources could be measured objectively. The EMDEX-II meter collected MF measurements in the frequency range of 40 to 800 Hz every 10 seconds. The MF level was measured in milligauss. The meter was programmed to show only the time of day, without displaying any MF exposure level, so that participants were not aware of their MF exposure during the measurement period. This design was implemented to avoid changes of any routine daily activities due to the MF level displayed. At the end of the measurement period, the women were asked to rate their activity patterns during the measurement period as either similar to or quite different from those during a typical day of their pregnancy. Of 801 participants whose children had pediatric care at KPNC, 67 did not have complete 24-hour MF measurements. These mother-child pairs were excluded from the study.

OUTCOME MEASUREMENT: ASTHMA IN OFFSPRING

The children of the remaining 734 pairs with complete maternal 24-hour MF measurements during pregnancy were followed up until (1) they received a diagnosis of asthma, (2) they left the KPNC system (no longer a KPNC member), or (3) the end of the study period (August 31, 2010). To be considered as having a case of asthma, a child had to have received a clinical diagnosis of asthma (*International Classification of Diseases, Ninth Revision,* codes 493.00-493.99) on at least 2 occasions within a 1-year period during follow-up. We excluded those who had either only 1 diagnosis (n=67) or 2 diagnoses that were more than 1 year apart (n=17) or those who used antiasthmatic medications without a clinical diagnosis of asthma (n=24). These children were considered to have suspected asthma and formed a separate outcome group. They were not included in the main analyses but were analyzed separately for comparison. The final analyses included 626 mother-child pairs with both maternal MF measurements and a known asthma status.

POTENTIAL CONFOUNDERS

Although the number of known potential confounders are likely limited because of (1) a lack of association between MF exposure and many commonly known social, demographic, and behavioral factors and (2) the small number of known risk factors for asthma,[2,4] we evaluated many common sociodemographic characteristics and known prenatal and postnatal risk factors for asthma to ensure that they truly did not confound the association between maternal MF exposure during pregnancy and the risk of asthma in offspring. Because most variables evaluated were not confounders, we included the common sociodemographic variables such as maternal age, education, and race/ethnicity as well as the main risk factors for asthma such as a maternal history of asthma and smoking during pregnancy in the final model.

DATA ANALYSIS

We used the Cox proportional hazard regression model to examine the relationship between in utero MF exposure and the risk of asthma in offspring after controlling for potential confounders. Survival analysis has the advantage of taking into account different follow-up times for the offspring with regard to asthma diagnosis. All children were followed up starting from birth until (1) they received diagnoses of asthma (failed), (2) they left the KPNC system (censored), or (3) the end of the study (censored).

To quantify a woman's overall daily MF exposure burden, we used median 24-hour MF exposure to reflect her overall MF exposure during pregnancy to reduce the impact of outliers. Because everyone is exposed to MF at some level, we examined whether an increasing MF exposure during pregnancy is associated with an increased risk of asthma in offspring, a dose-response relationship rather than a dichotomized variable of yes/no. We first examined the dose-response relationship using the median MF level as a continuous variable. To present the association as categorical MF exposure for an easier interpretation, we divided the median MF level into 3 categories: low (≤10th percentile [≤0.3 mG]), medium (>10th-90th percentile [>0.3-2.0 mG]), and high (>90th percentile [>2.0 mG]).

RESULTS

Table 1 presents the characteristics of the study population according to their MF exposure level during pregnancy. We examined maternal, prenatal, genetic, and

Table 1. Characteristics of the Study Population

Characteristic	Median Magnetic Field (MF) Level, %			χ^2 Test (*P* Value)
	Low,[a] (n=81)[d]	Medium,[b] (n=482)[d]	High,[c] (n=63)[d]	
Sociodemographic factors				
Maternal age, y				.91
≤25	19.7	18.3	19.1	
26-30	32.1	31.5	31.7	
31-35	30.9	32.8	38.1	
>35	17.3	17.4	11.1	
Maternal education				.93
<College	51.8	55.8	57.1	
College	32.1	27.8	28.6	
Postgraduate	16.1	16.4	14.3	
Maternal race/ethnicity				.66
White	40.7	38.4	47.5	
Black	4.9	8.3	4.8	
Hispanic	21.0	19.5	17.5	
Asian/Pacific Islander	24.7	29.1	25.4	
Other	8.6	4.7	4.8	
Maternal prepregnancy BMI				.97
≤25	71.6	71.6	73.0	
>25	28.4	28.4	27.0	
Family income, $				.004
<30 000	24.4	18.4	13.3	
≥30 000	26.9	44.7	60.0	
≥60 000	48.7	36.8	26.7	
Prenatal factors				
Smoke during pregnancy				.90
Yes	8.6	9.5	7.9	
No	91.4	90.5	92.1	
Infection in pregnancy				.66
Yes	34.6	32.6	38.1	
No	65.4	67.4	61.9	
Antibiotic use in pregnancy				.48
Yes	34.6	41.3	42.9	
No	65.4	58.7	57.1	
Mode of delivery				.66
Vaginal birth	77.3	79.7	83.6	
Cesarean section	22.7	20.3	16.4	
Genetic factor				
Maternal history of asthma				.85
Yes	8.6	7.1	6.3	
No	91.4	92.9	93.7	
Infant factors				
Breastfed				.89
Yes	88.9	91.7	90.5	
No	11.1	8.3	9.5	
Sex				.66
Female	44.4	49.4	46.1	
Male	55.6	50.6	53.9	
Parity				.48
First child	51.9	45.6	50.8	
Not first child	48.1	54.4	49.2	
Low birthweight, <2500 g				.07
Yes	9.9	4.1	3.2	
No	90.1	95.9	96.8	
Preterm, <37 wk				.95
Yes	7.4	7.5	6.3	
No	92.6	92.5	93.7	
KPNC member at the end of follow-up				.92
Yes	58.0	60.4	60.3	
No	42.0	39.6	39.7	
NICU admission				.34
Yes	11.8	7.9	5.1	
No	88.2	92.1	94.9	
Use of antibiotics before the first diagnosis of asthma				.10
Yes	84.8	87.3	77.4	
No	15.2	12.7	22.6	
Other factors				
MF level measured on a typical day				.99
Yes	64.2	63.9	63.5	
No	35.8	36.1	36.5	

Abbreviations: BMI, body mass index (calculated as weight in kilograms divided by height in meters squared); NICU, neonatal intensive care unit; KPNC, Kaiser Permanente Northern California.

[a] Less than or equal to the 10th percentile (≤0.3 mG).

[b] Greater than the 10th percentile to the 90th percentile (>0.3-2.0 mG).

[c] Greater than the 90th percentile (>2.0 mG).

[d] The following 3 variables had missing data: family income (n=32), maternal mode of delivery (n=22), and NICU admission (n=24).

Table 2. Maternal Exposure to Magnetic Fields (MFs) During Pregnancy and the Risk of Asthma in Offspring

Maternal Daily Median MF Level	Asthma in Children: Yes	Asthma in Children: No	cHR (95% CI)	aHR[a] (95% CI)
Continuous MF level, mean[b] (SD), mG	1.22 (1.22)	0.98 (1.09)	1.12 (1.02-1.23)	1.15 (1.04-1.27)
MF level in category, No. (%)				
Low, ≤10th percentile	11 (13.6)	70 (86.4)	1 [Reference]	1 [Reference]
Medium, >10th-90th percentile	98 (20.3)	384 (79.7)	1.65 (0.88-3.08)	1.74 (0.93-3.25)
High, >90th percentile	21 (33.3)	42 (66.7)	3.16 (1.52-6.57)	3.52 (1.68-7.35)

Abbreviations: aHR, adjusted hazard ratio (adjusted for maternal age, race, education, smoking during pregnancy, and a history of asthma; further adjustment for the remaining variables in Table 1 did not materially change the results); cHR, crude hazard ratio; CI, confidence interval.
[a] Trend test, $P<.001$.
[b] Mean of median.

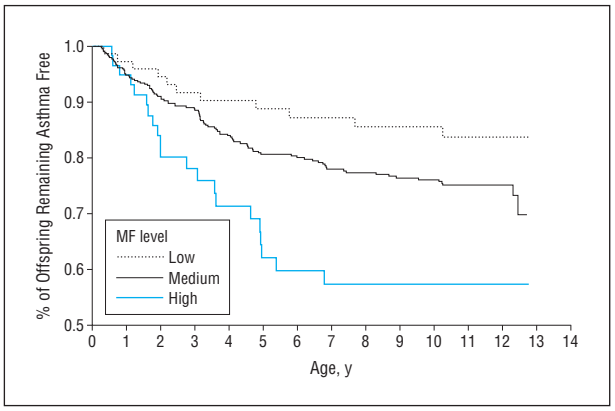

Figure. Kaplan-Meier estimates of asthma risk by maternal magnetic field (MF) exposure level during pregnancy.

infant factors that may be related to MF exposure, the risk of asthma, or both (ie, potential confounders). Of the 19 factors examined, none was related to MF exposure level except family income, which did not show a clear pattern of a relationship (Table 1). The percentages of children who were unavailable for follow-up at the end of the study because of their exiting KPNC membership and those whose MF exposure was measured on a typical day during pregnancy were quite similar among all MF exposure levels (Table 1).

Overall, 130 children (20.8%) of the study participants developed asthma during 13 years of follow-up, with most cases (>80%) diagnosed by 5 years of age. **Table 2** presents the results examining the dose-response relationship between increasing maternal MF exposure level in pregnancy and the risk of asthma in offspring using MF exposure level as both a continuous and a categorical variable. After adjustment for maternal age, race, education, smoking during pregnancy, and a history of asthma, a statistically significant linear dose-response relationship was observed between increasing maternal median daily MF exposure level in pregnancy and an increased risk of asthma in offspring (adjusted hazard ratio [aHR], 1.15; 95% confidence interval [CI], 1.04-1.27). In other words, 1 unit (1 mG) of increase in the maternal median MF exposure level during pregnancy was associated with a 15% increased rate of asthma in offspring (Table 2). Using the categorical MF level (low, medium, and high) as dummy variables, the results confirmed the linear dose-response relationship: compared with children whose mothers had a low MF level (<0.3 mG) during pregnancy, children whose mothers had a medium MF level (>0.3-2.0 mG) had a 74% increased rate of developing asthma (aHR, 1.74; 95% CI, 0.93-3.25). Furthermore, children whose mothers had a high MF level (>2.0 mG) during pregnancy had more than a 3.5-fold increased rate of developing asthma (aHR, 3.52; 95% CI, 1.68-7.35). Further adjustment for the remaining 14 factors, including family income, listed in Table 1 did not materially change the results. Finally, a similar association was also observed using suspected asthma cases, although the association was weaker, perhaps because of the misclassification of asthma cases. The aHRs were 1.24 and 1.41 for medium and high maternal MF exposure levels, respectively.

The **Figure** shows the Kaplan-Meier survival curves for the percentages of offspring who remained free of asthma during the 13-year follow-up period for 3 different maternal MF exposure levels in pregnancy. The cumulative asthma risks (1−cumulative survival rate) in offspring were 0.16, 0.30, and 0.43 for low, medium, and high maternal MF exposure levels, respectively.

To determine whether other factors would modify the observed association, we examined the association stratified by 2 known risk factors for asthma: maternal history of asthma (a possible genetic risk factor) and firstborn child (a possible environmental risk factor, the hygiene hypothesis).[2-5] **Table 3** shows that the observed association was noticeably stronger among the children whose mothers had a history of asthma (aHR, 6.06; a more than 6-fold increased rate of asthma for 1 unit [1 mG] of increase in MF level in the maternal median MF exposure level during pregnancy) than among those whose mothers did not have a history of asthma (aHR, 1.12). Similarly, the association between increasing maternal MF exposure levels in pregnancy and the risk of asthma in offspring was stronger among firstborn children (aHR, 1.40; a 40% increased rate of asthma for every 1 unit [1 mG] of increase in MF level) than among later-born children (aHR, 1.07) (Table 3). The presence of these 2 risk factors (ie, history of maternal asthma [$P<.005$] and being a firstborn child [$P<.05$]) significantly exacerbated the adverse effect of maternal MF exposure in pregnancy on the risk of asthma in offspring.

Table 3. Maternal Exposure to Magnetic Fields During Pregnancy and the Risk of Asthma in Offspring in Relation to Other Risk Factors for Asthma

Other Risk Factor for Asthma	Total No.	Asthma in Children, Mean (SD)		aHR (95% CI)	*P* Value
		Yes	No		
Maternal history of asthma					*P*<.005
Yes	45	1.17 (0.87)	0.65 (0.49)	6.06 (2.20-16.72)	
No	581	1.22 (1.25)	1.01 (1.11)	1.12 (1.01-1.25)	
Birth order					*P*<.05
First child	294	1.33 (1.31)	0.96 (0.88)	1.40 (1.16-1.70)	
Not first child	332	1.13 (1.14)	1.01 (1.25)	1.07 (0.92-1.25)	

Abbreviations: CI, confidence interval; aHR, adjusted hazard ratio (adjusted for maternal age, race, education, smoking during pregnancy, and a history of asthma; further adjustment for the remaining variables in Table 1 did not materially change the results).

Table 4. The Strengths of the Association in Relation to the Measurement Accuracy of Magnetic Fields (MFs)

Maternal Daily Median MF Level	Asthma in Children, No. (%)		aHR (95% CI)
	Yes	No	
Measured on a typical day			
Low, ≤10th percentile	5 (9.6)	47 (90.4)	1 [Reference]
Medium/high, >10th percentile	73 (21.0)	275 (79.0)	2.52 (1.01-6.30)
Measured on a nontypical day			
Low, ≤10th percentile	6 (20.7)	23 (79.3)	1 [Reference]
Medium/high, >10th percentile	46 (23.3)	151 (76.7)	1.31 (0.55-3.13)

Abbreviations: CI, confidence interval; aHR, hazard ratio (adjusted for maternal age, race, education, smoking during pregnancy, and a history of asthma).

COMMENT

In this prospective cohort study, we found that a high maternal MF exposure level in pregnancy is associated with a significantly increased risk of asthma in offspring. The observed association showed a dose-response relationship. Given the lack of understanding of the causes of asthma, our findings could open up a new research area to elucidate risk factors of asthma that are unknown and have not been examined before. Also, our study provides new findings for the potential adverse health effect of MF exposure on an end point (asthma) that, to our knowledge, has not been previously studied. While the public has been increasingly aware of EMF exposure owing to the increasing presence of infrastructure of wireless networks and the pervasive use of wireless devices, studies on EMF health effects remain limited. Because EMF exposure is ubiquitous and exposure to it is involuntary, these new findings have important public health implications. Nevertheless, they need to be replicated by other studies.

While prenatal risk factors for asthma are not well understood, pregnancy is one of the most influential periods when allergic sensitization (atopy) is developed in the fetus.[2,18,19] The underlying pathogenesis of asthma is likely structural and due to functional defects in epithelium and an impaired innate immune system.[3] Prenatal exposure to high MF levels could interfere with the development of both epithelial cells and normal immune systems. Research by multidisciplinary collaborative studies is needed to understand these mechanisms.

The current study has several methodological strengths that enhanced the validity of the new findings. First, it was a prospective cohort study in which MF exposure was measured in pregnancy, long before the diagnosis of asthma in offspring. This study design substantially reduces the likelihood of potential biases associated with participation influenced by the presence of outcomes. Second, both the exposure (MF levels) and the outcome (diagnosis of asthma) in this study were measured objectively without the knowledge of each other, thus reducing the concern of recall bias associated with the ascertainment of exposure and outcome variables that has existed in many epidemiological studies. Unlike many case-control studies of the MF health effect, in which MF exposure in the etiologically relevant period of the past was either reconstructed or surrogated by the current exposure measurement (eg, studies of childhood leukemia), MF exposure levels in this study were prospectively measured during the etiologically relevant period (eg, pregnancy). Also, while EMF exposure measurement in past studies was frequently based only on recalls, surrogate measures, and home spot measurements, the current study asked participants to carry an EMDEX-II meter that objectively captured their MF exposure from all sources during pregnancy. Furthermore, all diagnoses of asthma were based on clinical records, not on self-report by the participants, thereby reducing measurement errors of the outcome of interest. Finally, MF exposure is not related to most sociodemographic, behavioral, and commonly known risk factors (Table 1).[6,9] Given that confounders have to be associated with the exposure of interest, a lack of association between MF exposure and those factors limits the number of potential confounders, making the observed association robust against potential biases.

While, compared with previous studies, we improved the accuracy of measuring MF exposure by asking participants to wear an EMDEX II meter for 24 hours, it was not feasible to measure MF exposure throughout pregnancy. Therefore, the accuracy of the MF measurement in reflecting the MF exposure in pregnancy may still be questioned, although one study has reported that MF exposure levels were relatively stable within 12 to 36 months.[20] Assuming that there was some misclassification of MF exposure because of measurement errors, given that this was a cohort study and MF was measured long before the diagnosis of asthma, such misclassification would be nondifferential (ie, the same degree of misclassification to both mothers of children with and without asthma). Nondifferential misclassification generally leads to attenuation of observed associations. Without such misclassification, the observed association could have been stronger. In fact, our reanalysis of the association, stratified by whether the MF measurement was conducted on a typical day of pregnancy (more representative of MF exposure in pregnancy) or a nontypical day (less representative of MF exposure in pregnancy, thus more measurement errors) provided evidence supporting this argument. As shown in **Table 4**, we indeed observed that less measurement error (ie, measured on a typical day) led to a stronger observed association (>2.5 times risk of asthma associated with a higher maternal MF exposure level during pregnancy) compared with more measurement error (ie, measured on a nontypical day), a nonstatistically significant 31% increased risk of asthma. Therefore, had we been able to measure participants throughout pregnancy, the observed association between maternal MF exposure in pregnancy and the risk of asthma might have been stronger than that presented in Table 2.

In addition to observing an association between high maternal MF exposure during pregnancy and the risk of asthma in offspring with a dose-response relationship, we also observed a statistically significant interaction between the MF effect on asthma and the other 2 risk factors for asthma: maternal history of asthma and birth order (firstborn). A maternal history of asthma is a well-established risk factor for genetic susceptibility that has been supported by the results of both genome-wide association studies and candidate gene studies.[2,5] Such an interaction with known risk factors for asthma not only revealed possible synergistic adverse effects between prenatal MF exposure and these 2 risk factors on the risk of asthma but also provided further support for the underlying association between maternal MF exposure in pregnancy and the risk of asthma in offspring. Synergistic factors themselves are often independent risk factors.

In conclusion, the findings of the present study open up a new area in understanding the risk factors for asthma and the health effects of ubiquitous MF exposure, especially during pregnancy. As with any epidemiological study, these findings need to be replicated. If confirmed, they have the potential to inform new intervention strategies to reduce asthma, the most prevalent chronic disease among children.

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