



Residential Magnetic Field Exposure and Breast Cancer Risk: A Nested Case-Control Study from a Multiethnic Cohort in Los Angeles County, California

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Some experimental and epidemiologic evidence suggests that residential exposure to power-frequency magnetic fields can increase breast cancer risk. This association was investigated in a nested case-control study of female breast cancer within a cohort of African Americans, Latinas, and Caucasians in Los Angeles County, California. Incident breast cancer was ascertained from 1993 to 1999 by linkage to county and state tumor registries. Controls were selected from a random sample of cohort members without breast cancer at baseline. Exposure was assessed in 1995–2001 by means of wiring configuration coding (an indirect measure of magnetic field exposure that has been associated with increased risk of childhood leukemia in Los Angeles and elsewhere in North America) in all homes occupied over the previous 10 years for 743 cases and 699 controls and by measurement of magnetic fields in the bedroom over a 7-day period for 347 cases and 286 controls. The estimated risk of breast cancer was not higher among women with wiring configuration codes associated with the highest magnetic fields (for a very high current configuration relative to very low, the adjusted odds ratio was 0.76 (95% confidence interval: 0.49, 1.18)). Stronger measured fields were not significantly associated with increased risk. These data suggest that residential magnetic field exposures commonly experienced by US women do not influence risk of breast cancer.

breast neoplasms; electricity; electromagnetic fields; environmental exposure

Abbreviations: CI, confidence interval; SEER, Surveillance, Epidemiology, and End Results.

The hypothesis that power-frequency magnetic fields might be related to breast cancer risk has been suggested on the basis of several types of evidence. Exposure to power-frequency magnetic fields has been shown to enhance breast carcinogenesis in rats after induction with 7,12-dimethylbenz(a)anthracene (1). Recent experiments indicate that magnetic fields also act directly on breast tissue to increase proliferation in rats not treated with a carcinogen (2). In humans, there are some data suggesting that power-frequency magnetic fields can suppress melatonin production (3, 4), and it has been proposed that suppression of melatonin might lead to increased risk of breast cancer (5).

The epidemiologic data on the relation between residential exposure to magnetic fields and female breast cancer are limited and inconclusive (6). Several studies had only self-reported data on one source of exposure, electric blanket use (7–10)—a measure that is subject to recall bias. Eight studies (11–18) used an objective but indirect measure of exposure based on distance to power distribution and/or transmission lines. Among these studies, two included fewer than 32 cases (11, 13), and two large studies (14, 16) were conducted in Scandinavian countries, where population exposure is likely to be lower than in the United States because primary and secondary distribution lines are buried. The only published

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study with direct measurements was a case-control study from Seattle, Washington, in which no effect was seen (18).

To address the possible association between breast cancer incidence and residential magnetic field exposure, we conducted a nested case-control study of breast cancer within a multiethnic cohort of African Americans, Latinas, and Caucasians in Los Angeles County, California. Because the case-control study was nested within the cohort study, we were able to evaluate the potential distortion of effects due to selection bias. Selection bias is difficult to assess in case-control studies when the base population is not well defined, as occurs with the use of random digit dialing for control selection. We assessed magnetic field exposure by means of two objective methods—direct measurement of magnetic fields in the bedroom over a period of 7 days and an indirect measure of exposure known as wiring configuration coding, which has previously been shown to correlate with measured magnetic fields as well as with childhood leukemia risk in Los Angeles County and elsewhere in North America (19–24).

MATERIALS AND METHODS

Subjects

We conducted a nested case-control study among female participants of African-American, Latina, and Caucasian ethnicity in the Los Angeles County component of the Hawaii-Los Angeles Multiethnic Cohort Study, a large population-based cohort study of men and women aged 45–74 years at enrollment between 1993 and 1996 (25). The primary sampling frame for the cohort in Los Angeles County was the file of licensed drivers. A cohort of 52,112 female residents of Los Angeles County was enrolled through the use of selective sampling by Latino surname, the choice of census tracts with a majority of African Americans, and the use of Health Care Financing Administration files, which contain ethnic identifiers. Among these 52,112 women, self-described ethnicity was 19,132 African American, 23,760 Latina, and 9,220 Caucasian. Subjects were recruited into the study by mail and entered the cohort by completing a self-administered questionnaire. The 26-page questionnaire included information on height and weight, menstrual and reproductive history, use of oral contraceptives and menopausal hormone replacement therapy, and diet and physical activity.

For the nested case-control study of magnetic field exposure in relation to breast cancer risk, we ascertained incident cases of breast cancer by computer linkage of the cohort with the Surveillance, Epidemiology, and End Results (SEER) cancer registry in Los Angeles County and with the state-wide cancer registry for California. A total of 751 case women without prior breast cancer were identified through August 1999. These cases were diagnosed from June 1993 to January 1999. From cohort members without a history of breast cancer at baseline, we randomly sampled 702 controls, using approximate frequency matching on self-reported ethnicity in three categories—African American, Latina, and Caucasian. Data on estrogen receptor and progesterone receptor status at breast cancer diagnosis were

obtained through linkage to the SEER registry and were available for 403 cases. The study was approved by the Institutional Review Board at the Keck School of Medicine of the University of Southern California. Subjects provided written informed consent.

Data collection

Data collection for the nested case-control study began in June 1995 and concluded in January 2001. We obtained data on traditional risk factors for breast cancer from the baseline cohort questionnaire completed by all potential subjects. Our assessment of magnetic field exposure included an indirect assessment known as wiring configuration coding, measurement of magnetic fields in the subject's bedroom over a 7-day period, and questionnaire data. We invited each eligible subject to undergo an in-home interview on factors relevant to magnetic field exposure. The reference date for the interview was the date of diagnosis for cases. For controls, at the beginning of each 6-month period, we set a reference date that was the average of the diagnosis dates for cases that had most recently been identified via linkage to the SEER registry. In this manner, we ensured that cases and controls interviewed at any point during the study had comparable reference dates. The reference period was the 10 years prior to the reference date. The questionnaire included sections on residential history, usual time of sleep, occupation, and use of appliances over the reference period. Measurements were made in the residence currently occupied by the subject if this residence had also been occupied on the reference date. Subjects who refused an in-home visit were offered a telephone questionnaire. Subjects who could not be reached or who refused both in-person and telephone interviews were mailed an abbreviated questionnaire with questions on residential history. The median time from diagnosis to interview was 17 months for cases (interquartile range, 14–25 months).

For more than 99 percent of subjects, we were able to assess magnetic fields by means of a surrogate measure known as wiring configuration coding (26), henceforth referred to as wire coding. We showed previously that wire code was associated with measured magnetic fields in Los Angeles (20, 23). Wire code has also been shown to be a useful surrogate measure for magnetic fields elsewhere in North America (27, 28). We attempted to perform wire coding on all homes that the subject had inhabited in Los Angeles County during the 10 years prior to the reference date. For subjects we could not contact, we used the address from the baseline cohort questionnaire.

To determine the wire code for a subject's home, field technicians first created a drawing of the house and all overhead electric power wiring within 150 feet (46 m) of any of its exterior walls. The technician then recorded, on a coding sheet, the distances to the nearest transmission lines, thick and thin three-phase primary distribution lines, and spun, open, and first-span secondary distribution lines. The technician also recorded whether there was electric power wiring of any type, including single-phase, two-phase, and "end-pole" primary lines, located within 150 feet of the home. These data were entered into a computer and were assigned wire codes using the Wertheimer-Leeper system (26, 29), as

TABLE 1. Completeness of data collection among subjects in a case-control study of breast cancer nested within a multiethnic cohort study, Los Angeles County, California, 1993–2001

	Cases		Controls	
	No.	%	No.	%
Eligible subjects with complete baseline questionnaire	751		702	
Current residential wire code	743	98.9	699	99.6
Magnetic field questionnaire	602	80.2	497	70.8
Complete interview	561	74.7	419	59.7
In person	366	48.7	310	44.2
By telephone	187	24.9	106	15.1
By proxy	8	1.1	3	0.4
Short questionnaire by mail	41	5.5	78	11.1
Wire codes for all residences inhabited during reference period	572	76.2	468	66.7
7-day bedroom magnetic field measurements	347	46.2	286	40.7

modified by Savitz et al. (21) and Kleinerman et al. (30). Homes were thus classified into the following five categories: very low current configuration, underground wiring (defined as having no overhead electric power wiring within 150 feet), ordinary low current configuration, ordinary high current configuration, and very high current configuration. A total of 872 case addresses and 803 control addresses for the 743 cases and 699 controls were wire-coded. Prior to assignment of final codes, each map and its coding sheet were reviewed by one of the investigators (W. T. K.), who had developed the wire coding protocol and instructed the field technicians in its use.

Over the course of the study, two technicians performed the wire coding blinded as to the case or control status of the resident of the home. For reinforcement of adherence to the protocol, every 6–9 months the two technicians were required to code 20–25 homes independently; they then compared their maps and coding sheets and reached a consensus code if there were any discrepancies. So that we could evaluate the degree of concordance between the two technicians, they independently mapped 56 homes without consultation. The weighted kappa statistic was 0.78 (95 percent confidence interval (CI): 0.65, 0.91). The disagreements in coding were minor—three homes varied from “ordinary low current configuration” to “ordinary high,” four homes varied from “underground” to “very low,” one home varied from “ordinary high” to “very high,” and two homes varied from “very low” to “ordinary low.”

Magnetic fields were measured in the subject’s bedroom using an Emdex II meter (Enertech Consultants, Campbell, California). Residential magnetic fields typically consist of 60-Hz fundamental field components along with smaller harmonic components at frequencies of 180 Hz, 300 Hz, 420 Hz, 600 Hz, etc. (31). The Emdex II meter uses filters to measure both the fundamental and harmonic components in a bandwidth extending from 40 Hz to 800 Hz and to separately measure only the harmonic components in a bandwidth extending from 100 Hz to 800 Hz. The former measurement is of the broadband field and the latter measurement is of the harmonic field. For our purposes, the

meter was programmed to take and retain in its memory a sample every 120 seconds during a 7-day period (total number of samples = 5,040). The meter was placed on a bedside stand, on the floor under the bed, or next to the bed at a location where the measurement was within 0.05 μ T of the field strength on the surface of the bed where the upper third of the subject’s body would normally lie.

We checked the proper operation and approximate calibration of our Emdex meters weekly by placing the meters in the known magnetic field produced by a simple rectangular coil (Electric Field Measurements Company, West Stockbridge, Massachusetts). The absolute calibration of each meter was performed by the manufacturer (Enertech Consultants) every 6–9 months throughout the data collection period.

The primary magnetic field measurement metric was the nighttime mean, because we knew that subjects would be in the bedroom during this period. Each subject’s questionnaire responses regarding the usual times of going to bed and rising were used to determine the nighttime period. We elicited separate responses for weekends and weekdays. Our metrics of nighttime magnetic field measurements were the overall mean for bedtime hours over the 7-day period for both the harmonic and broadband magnetic fields, the proportion of time above 0.4 μ T, and a rate-of-change metric proposed by Wilson et al. (32) for assessment of short-term variability in the magnetic field.

Statistical methods

We estimated odds ratios and their 95 percent confidence intervals using unconditional logistic regression (SAS, version 8.00; SAS Institute, Inc., Cary, North Carolina). In all models, results were adjusted for self-reported ethnicity (African American, Latina, or Caucasian) because of the frequency matching. Age was included as a continuous variable; inclusion of categorical age did not materially alter the odds ratio estimates given that the age distributions of cases and controls were so similar. We considered confounding by established risk factors for breast cancer, including age at

TABLE 2. Selected characteristics of subjects in a nested case-control study of breast cancer, according to current residential wiring configuration code and 7-day bedroom magnetic field measurements, Los Angeles County, California, 1993–2001

Characteristic	Wire code data				Magnetic field data			
	Cases (n = 743)		Controls (n = 699)		Cases (n = 347)		Controls (n = 286)	
	No.	%	No.	%	No.	%	No.	%
Mean age (years) at reference date	64.7 (8.3)*		63.1 (8.4)		63.9 (8.4)		62.5 (8.1)	
Ethnicity								
Caucasian	146	20	110	16	70	20	68	24
Latina	284	38	298	43	135	39	113	40
African American	313	42	291	42	142	41	105	37
Postmenopausal								
No	57	8	73	10	35	10	30	10
Yes	670	90	613	88	304	88	251	88
Unknown	16	2	13	2	8	2	5	2
Age (years) at menopause								
<40	114	15	124	18	55	16	49	17
40–44	114	15	98	14	54	16	38	13
45–49	170	23	174	25	75	22	75	26
50–54	175	24	143	20	85	24	55	19
>54	50	7	38	5	22	6	23	8
Premenopausal	57	8	73	10	35	10	30	10
Unknown	63	8	49	7	21	6	16	6
Hormone replacement therapy at reference date								
No	527	71	530	76	246	71	210	73
Yes	189	25	154	22	95	27	75	26
Missing data	27	4	15	2	6	2	1	0
Age (years) at menarche								
<13	380	51	327	47	190	55	135	47
13–14	265	36	262	37	119	34	111	39
>14	90	12	99	14	37	11	40	14
Missing data	8	1	11	2	1	0	0	

Table continues

menopause/menopausal status, use of hormone replacement therapy, age at first birth, parity, history of breast cancer in a mother or full sister, alcohol intake, body mass index, and vigorous physical activity. For a woman using hormone replacement therapy before her reported age at the last menstrual period, we set her age of menopause as the year in which she began hormone replacement therapy (excluding use of progestin alone), with the rationale that she started hormone replacement therapy because of menopausal symptoms (33). We also considered potential confounding by season of measurement. We included all factors that were associated with increased or decreased risk of breast cancer at the $p = 0.10$ level of significance. The following variables met this criterion: age at menarche, parity, age at first birth, age at menopause/menopausal status, current use of hormone replacement therapy, alcohol intake, and history of breast cancer in a mother or sister. Although there was minimal confounding by these factors, we present the multi-

variate-adjusted results along with the results from the age- and ethnicity-adjusted models.

For the wire coding, we conducted the analysis in two ways. We first considered the wire code for the house occupied at the end of the reference period. We ordered the five categories according to the mean broadband nighttime magnetic field values measured in the subjects' homes, as follows: very low current configuration (0.06 μT), underground wiring (0.07 μT), ordinary low current configuration (0.10 μT), ordinary high current configuration (0.11 μT), and very high current configuration (0.13 μT). Median fields by wire code category were 0.04 μT for a very low current configuration and for underground wiring, 0.05 μT for the ordinary low and ordinary high current configurations, and 0.10 μT for the very high current configuration. To quantify the risk associated with wire codes at multiple residences over a period of 10 years prior to the reference date, we also created variables that represented the number of years spent at each wire code level over the past 10 years. The parameter

TABLE 2. Continued

Characteristic	Wire code data				Magnetic field data			
	Cases (n = 743)		Controls (n = 699)		Cases (n = 347)		Controls (n = 286)	
	No.	%	No.	%	No.	%	No.	%
No. of children								
0	146	20	94	13	72	21	44	15
1	98	13	75	11	44	13	34	12
2–3	281	38	260	37	125	36	104	36
>3	210	28	260	37	103	30	99	35
Missing data	8	1	10	1	3	1	5	2
Age (years) at first birth								
No births	146	20	94	13	72	21	44	15
<21	223	30	239	34	108	31	89	31
21–30	315	42	306	44	145	42	134	47
>30	42	6	39	6	18	5	16	6
Missing data	17	2	21	3	4	1	3	1
Breast cancer in a mother or sister								
No	590	79	596	85	284	82	252	88
Yes	128	17	74	11	60	17	34	12
Unknown	25	3	29	4	3	1		
Estrogen receptor status								
Negative	106	14			46	13		
Positive	293	39			143	41		
Missing data	344	46			158	46		
Alcohol consumption (g/day)								
0	471	63	453	65	209	60	172	60
>0–11.7	87	12	82	12	42	12	44	15
11.7–47.6	90	12	92	13	40	12	39	14
>47.6	95	13	72	10	56	16	31	11

* Numbers in parentheses, standard deviation.

estimates associated with each of the variables are the odds ratios for someone who spent the entire 10 years with that wire code. Furthermore, the odds ratios for multiple residences are then the time-weighted combinations of the wire code odds ratios for each residence.

RESULTS

Table 1 summarizes the completeness of data collection. We obtained the additional questionnaire data on factors relevant to magnetic field exposure for 80.2 percent of cases and 70.8 percent of controls. We performed wire coding on the homes of 98.9 percent of cases and 99.6 percent of controls. The number of subjects with wire coding for all 10 years was reduced, because this analysis required a complete residential history from the magnetic field questionnaire (provided by 585 cases and 480 controls). We were able to wire code all residences occupied during the reference period for 99.1 percent of cases and 99.3 percent of controls who reported that they had lived in Los Angeles County continuously during this 10-year period. The number of subjects with magnetic field measurements was substantially

lower than the number with questionnaire or wire-code data, reflecting less willingness to participate in the 7-day in-home measurement phase of the study.

Characteristics of the study subjects are shown in table 2. We give data for subjects with wire code information as well as the smaller subset of subjects with magnetic field measurements. There were no notable or statistically significant differences between the group with wire code data (the entire study group) and the smaller subgroup with magnetic field measurements.

Breast cancer risk did not increase across wire code levels associated with higher fields (table 3). The adjusted odds ratio for the very high current configuration category relative to the very low category was 0.76 (95 percent CI: 0.49, 1.18). Likewise, we found no association between wiring configuration code and breast cancer risk in the analysis incorporating all residences occupied in Los Angeles County during the reference period (table 3).

The mean values for 7-day nighttime magnetic fields in the residence occupied on the reference date were similar between cases and controls (case mean = 0.097 μ T (standard deviation, 0.176); control mean = 0.099 μ T (standard deviation,

TABLE 3. Odds ratios for breast cancer according to residential wiring configuration code among subjects in a nested case-control study, Los Angeles County, California, 1993–2001

Wire code variable	Cases		Controls		Basic model*		Adjusted model†	
	No.	%	No.	%	OR‡	95% CI‡	OR	95% CI
Residence at reference date§								
Very low current configuration	77	10	74	11	1.00¶		1.00¶	
Underground wiring	107	14	69	10	1.40	0.90, 2.19	1.27	0.80, 2.00
Ordinary low current configuration	205	28	192	27	1.04	0.71, 1.51	0.99	0.68, 1.46
Ordinary high current configuration	267	36	261	37	0.96	0.67, 1.38	0.92	0.64, 1.34
Very high current configuration	87	12	103	15	0.81	0.52, 1.24	0.76	0.49, 1.18
Per category#	743		699		0.92	0.84, 1.01	0.92	0.84, 1.01
All residences occupied during the 10 years prior to reference date**								
Very low current configuration	73	13	62	13	1.00¶		1.00¶	
Underground wiring	94	16	54	12	1.50	0.87, 2.57	1.33	0.77, 2.32
Ordinary low current configuration	176	31	155	33	0.92	0.59, 1.44	0.89	0.56, 1.40
Ordinary high configuration	217	38	196	42	0.88	0.57, 1.35	0.82	0.52, 1.27
Very high current configuration	85	15	77	16	0.90	0.54, 1.51	0.84	0.50, 1.43
Total no. of residences	682		581					
Total no. of subjects	572		468					

* The basic unconditional logistic regression model included terms for age (continuous variable) and ethnicity (African American, Latina, or Caucasian).

† The adjusted unconditional logistic regression model included the terms in the basic model plus parity, age at first birth, number of children, age at menarche, menopause status, age at menopause, current hormone replacement therapy, breast cancer in a mother or sister, and alcohol consumption (g/day).

‡ OR, odds ratio; CI, confidence interval.

§ The reference date was the date of diagnosis for cases and a comparable date for controls. For subjects without interview data, their address from the baseline cohort questionnaire was considered their residence on the reference date.

¶ Referent.

Odds ratios are per category increase in the ordinal variable.

** Analysis was restricted to the 572 cases and 468 controls with a complete 10-year residence history from the interview who also had lived in Los Angeles County for that entire 10-year period. All residences occupied during the 10-year period prior to the reference date with wire code data were included. The odds ratios presented are those calculated for a subject spending 10 years in the given wire code category relative to a subject spending 10 years in the reference category (very low current configuration).

tion, 0.304); Wilcoxon $p = 0.34$). Breast cancer risk was not appreciably associated with broadband magnetic field measurements expressed as either the 7-day nighttime mean, the percentage of time above 0.4 μT , or the rate-of-change metric (table 4). When we divided subjects into quartiles, the odds ratio for the highest quartile ($>0.088 \mu\text{T}$) of exposure relative to the lowest ($\leq 0.026 \mu\text{T}$) was 1.31 (95 percent CI: 0.82, 2.09). Because it has been suggested that there may be a relation between childhood leukemia risk and magnetic fields only in the small proportion of the population with average fields over 0.4 μT (34), we also categorized subjects by 0.1- μT categories. There was no apparent increase in risk for the 22 subjects with mean exposures of 0.4 μT or higher. When we considered magnetic fields as a continuous variable, we found no apparent trend; the odds ratio for a 0.01- μT change in the mean value, based on the continuous variable, was 1.00 (95 percent CI: 0.94, 1.07).

It has previously been suggested that harmonic magnetic fields may be biologically relevant parameters in epidemiologic studies of cancer risk (31). We made 7-day measurements of harmonic magnetic fields and found no evidence of

association between breast cancer risk and nighttime harmonic magnetic fields measured in the bedroom over a period of 7 days (table 5). We also found no evidence of an association of either broadband or harmonic magnetic fields when we used 7-day measurements that included both daytime and nighttime measurements.

We examined the relation between broadband bedroom magnetic fields and breast cancer risk within levels of the design variable (ethnicity) and risk factors for breast cancer in these data. We identified no notable association between magnetic fields and breast cancer risk within any subgroup (table 6). We also examined the association according to estrogen receptor status among cases compared with all controls and found no evidence that magnetic fields were related to breast cancer risk within either subgroup (table 6).

DISCUSSION

Our data do not support the hypothesis that the risk of breast cancer increases with higher exposure to residential magnetic fields. We found no consistent evidence that breast

TABLE 4. Crude and adjusted odds ratios for breast cancer according to nighttime bedroom broadband magnetic field measurements among subjects in a nested case-control study, Los Angeles County, California, 1993–2001

Magnetic field exposure variable	Cases		Controls		Basic model*		Adjusted model†	
	No.	%	No.	%	OR‡	95% CI‡	OR	95% CI
Mean measurement (μT)								
Continuous variable (per 0.1 μT)§	347		286		1.00	0.94, 1.07	1.00	0.94, 1.07
Quartile								
First (0.000–0.026)	79	23	71	25	1.00¶		1.00¶	
Second (0.027–0.044)	77	22	72	25	0.96	0.60, 1.53	0.98	0.60, 1.58
Third (0.045–0.088)	94	27	71	25	1.20	0.76, 1.88	1.32	0.82, 2.11
Fourth (>0.088)	97	28	72	25	1.17	0.75, 1.83	1.31	0.82, 2.09
Exposure group (μT)								
0.00–0.09	260	75	226	79	1.00¶		1.00¶	
0.10–0.19	56	16	37	13	1.30	0.82, 2.04	1.30	0.81, 2.10
0.20–0.29	11	3	9	3	0.99	0.40, 2.45	1.10	0.43, 2.83
0.30–0.39	8	2	4	1	1.82	0.53, 6.18	2.08	0.58, 7.45
≥ 0.40	12	3	10	3	1.03	0.44, 2.44	1.21	0.50, 2.96
Rate-of-change metric (μT)								
Continuous variable (per 0.1 μT)	347		286		0.95	0.56, 1.62	0.99	0.57, 1.71
Quartile								
First (0.000–0.004)	80	23	71	25	1.00¶		1.00¶	
Second (0.005–0.007)	78	22	72	25	0.92	0.58, 1.46	0.97	0.60, 1.57
Third (0.008–0.013)	97	28	71	25	1.17	0.75, 1.85	1.27	0.79, 2.04
Fourth (>0.013)	92	27	72	25	1.11	0.71, 1.74	1.23	0.77, 1.97
Any measurement $\geq 0.4 \mu\text{T}$	49	14	40	14	1.02	0.65, 1.61	1.05	0.66, 1.67
Percentage of measurements $\geq 0.4 \mu\text{T}$								
Reference (0.0%)	298	86	246	86	1.00¶		1.00¶	
First (0.1–0.5%)	16	5	10	3	1.27	0.57, 2.88	1.30	0.57, 2.98
Second (0.6–4.9%)	8	2	10	3	0.72	0.28, 1.87	0.71	0.27, 1.88
Third (5.0–44.9%)	14	4	10	3	1.17	0.51, 2.70	1.32	0.56, 3.10
Fourth (>44.9%)	11	3	10	3	0.90	0.38, 2.16	0.96	0.39, 2.35
Odds ratio per category#					0.99	0.84, 1.17	1.02	0.86, 1.21

* The basic unconditional logistic regression model included terms for age (continuous variable) and ethnicity (African American, Latina, or Caucasian).

† The adjusted unconditional logistic regression model included the terms in the basic model plus parity, age at first birth, number of children, age at menarche, menopause status, age at menopause, current hormone replacement therapy, breast cancer in a mother or sister, and alcohol consumption (g/day).

‡ OR, odds ratio; CI, confidence interval.

§ Odds ratio calculated for 0.1 μT from the model using the continuous variable.

¶ Referent.

Odds ratio from the model using the ordinal term.

cancer risk was increased by higher exposure to magnetic fields, as assessed either by direct measurements or indirectly via wiring configuration coding. Our study provides strong evidence for a lack of effect between residential wire code and breast cancer, because the study was conducted within a well-defined base population from an existing cohort study, and thus we were able to obtain data on this surrogate measure for over 99 percent of all eligible subjects. Thus, selection bias, a potential concern in case-control studies in which the base population is not well specified, is effectively eliminated in interpretation of these wire code

data. Because our subjects came from a well-characterized cohort, we had a substantial amount of additional data, including wire code and breast cancer risk factors, on subjects without magnetic field measurements. Therefore, we were able to evaluate the likelihood of important selection bias for the subset of subjects with magnetic field data, which cannot be done in standard case-control studies.

This study was unique among studies of breast cancer and magnetic fields in that a majority of our subjects came from two underrepresented groups, African Americans and Latinas. There was no evidence of an association in either of

TABLE 5. Odds ratios for breast cancer according to harmonic magnetic fields measured in the bedroom at nighttime over 7 days among subjects in a nested case-control study, Los Angeles County, California, 1993–2001

Harmonic exposure variable	Cases		Controls		Basic model*		Adjusted model†	
	No.	%	No.	%	OR‡	95% CI‡	OR	95% CI
Mean measurement								
Continuous variable (per 0.1 μ T)§	338		278		0.99	0.96, 1.02	0.99	0.96, 1.02
Quartile (μ T)								
First (0.0000–0.0007)	95	28	69	25	1.00¶		1.00¶	
Second (0.0008–0.0061)	63	19	70	25	0.63	0.40, 1.01	0.63	0.39, 1.03
Third (0.0062–0.0143)	89	26	69	25	0.91	0.58, 1.43	0.87	0.55, 1.39
Fourth (>0.0143)	91	27	70	25	0.90	0.58, 1.41	1.00	0.64, 1.59
Any measurement >95th percentile (0.0465 μ T)	67	20	54	19	1.02	0.68, 1.53	1.10	0.73, 1.66
Percentage of measurements >95th percentile (0.0465 μ T)								
Continuous variable					1.03	0.90, 1.19	1.06	0.92, 1.22
Category								
Reference (0.0%)	271	80	224	81	1.00¶		1.00¶	
First (0.01–0.19%)	11	3	13	5	0.70	0.31, 1.60	0.71	0.30, 1.67
Second (0.20–2.90%)	16	5	13	5	1.03	0.48, 2.20	1.09	0.50, 2.37
Third (3.00–29.9%)	22	7	14	5	1.28	0.64, 2.56	1.45	0.71, 2.97
Fourth (>29.9%)	18	5	14	5	1.06	0.51, 2.19	1.12	0.53, 2.36

* The basic unconditional logistic regression model included terms for age (continuous variable) and ethnicity (African American, Latina, or Caucasian).

† The adjusted unconditional logistic regression model included the terms in the basic model plus parity, age at first birth, number of children, age at menarche, menopause status, age at menopause, current hormone replacement therapy, breast cancer in a mother or sister, and alcohol consumption (g/day).

‡ OR, odds ratio; CI, confidence interval.

§ Odds ratio calculated for 0.1 μ T from the model using the continuous variable.

¶ Referent.

these groups. Our population was somewhat more highly exposed than the subjects in the previous study with direct magnetic field measurements (18). For measured fields, our top quartile was 0.089 μ T or higher, as compared with 0.073 μ T or higher in the Seattle study (18). In addition, 52 percent of our controls resided in homes in the two highest-exposure wire code categories, as compared with 23 percent in the Seattle study. This enhanced our power to find associations with measured fields and wire codes.

Our results are in agreement with those of the only other published study that evaluated breast cancer risk with direct magnetic field measurements (18). The results are also in agreement with those of previous studies of breast cancer incidence that used indirect estimates of magnetic field strength based on distance to power lines (11–17).

In a study from Sweden in which exposure was based on fields calculated from wire configurations, no increased risk was observed overall (16). However, a markedly increased risk of breast cancer of borderline statistical significance (odds ratio = 7.4, 95 percent CI: 1.0, 178.1) was seen within the subgroup of 27 case women under age 50 years with estrogen receptor-positive breast tumors. In that registry-based study, age less than 50 years provided a surrogate measure for premenopausal status. Our cohort was an older cohort with few premenopausal case women, including only

19 who were also estrogen receptor-positive. We did not find any association in this small group. However, the study by Davis et al. (18) included 129 premenopausal case women who were positive for both estrogen and progesterone receptors, and it found no evidence of an association with magnetic fields in this group. Among postmenopausal women, we found no evidence of effect modification by estrogen receptor status, which is consistent with the findings of the two previous studies (16, 18).

A potential limitation of this study was the relatively low level of participation in the 7-day magnetic field measurements. However, we were able to assess evidence of selection bias, because we had additional data on virtually all of the subjects who did not allow these measurements—both wire code and information on known breast cancer risk factors from the baseline cohort questionnaire. The distribution of wire codes was virtually identical between subjects with 7-day measurements and those without them. Among the 286 controls with magnetic field measurements, the percentage of homes by wire code was as follows: 11 percent very low, 10 percent underground, 29 percent ordinary low, 36 percent ordinary high, and 14 percent very high. Among the 413 controls without measurements, these percentages were 10 percent very low, 9 percent underground, 26 percent ordinary low, 38 percent ordinary high, and 15 percent very

TABLE 6. Odds ratios for breast cancer per 0.1- μ T increase in mean nighttime* bedroom broadband magnetic field measurements, according to potential effect modifiers, among subjects in a nested case-control study, Los Angeles County, California, 1993–2001

Effect modifier	No. of cases	No. of controls	Odds ratio†	95% confidence interval
All subjects	347	286	1.00	0.94, 1.07
Age (years) at reference date				
Less than median (<64.2)	173	160	0.99	0.92, 1.07
Median or higher (\geq 64.2)	174	126	1.04	0.85, 1.28
Ethnicity				
African American	142	105	1.02	0.89, 1.16
Latina	135	113	1.28	0.98, 1.69
Caucasian	70	68	0.97	0.87, 1.09
Parity				
Nulliparous	72	44	1.42	0.83, 2.43
Parous	272	237	0.97	0.90, 1.05
Age (years) at first birth				
<21	107	87	0.95	0.75, 1.20
\geq 21	163	148	0.97	0.89, 1.05
Age (years) at menarche				
<13	191	135	1.10	0.93, 1.29
\geq 13	119	111	0.97	0.88, 1.07
Menopause status				
Premenopausal	35	30	0.85	0.53, 1.37
Postmenopausal	304	251	1.01	0.94, 1.08
Age (years) at menopause				
<50	184	162	1.26	1.01, 1.56
\geq 50	107	78	0.91	0.74, 1.11
Hormone replacement therapy at baseline				
No	246	210	1.05	0.93, 1.20
Yes	95	75	0.97	0.89, 1.06
Family history of breast cancer (mother/sister)				
No	287	252	0.99	0.93, 1.06
Yes	60	34	1.36	0.82, 2.25
Alcohol consumption				
No	209	172	1.08	0.93, 1.24
Yes	42	44	0.97	0.88, 1.06
Estrogen receptor status				
All women				
Positive	143	286	1.02	0.95, 1.10
Negative	46	286	0.98	0.86, 1.13
Postmenopausal women				
Positive	121	251	1.02	0.95, 1.10
Negative	41	251	1.01	0.89, 1.14
Premenopausal women				
Positive	19	30	1.05	0.63, 1.75
Negative	4	30		

* Nighttime was defined as the usual period of time spent sleeping (calculated separately for weekdays and weekends). This information was obtained from the questionnaire.

† Odds ratio from the unconditional logistic regression model including terms for age (continuous variable), ethnicity, parity, age at first birth, number of children, age at menarche, menopause status, age at menopause, current hormone replacement therapy, breast cancer in a mother or sister, and alcohol consumption (g/day). Analyses of effect modifiers (except age) excluded that modifier as a covariate.

high. In addition, the subset of subjects who allowed 7-day measurements was quite similar to the overall study group with respect to risk factors for breast cancer (table 2). The availability of these additional data on the entire study population suggests that our results for 7-day measurements in relation to breast cancer were not appreciably affected by selection bias.

We measured magnetic fields over a 7-day period. This provided a more stable assessment of residential exposures than has been present in previous studies of residential magnetic fields and risk of breast cancer or other cancers. The only previous study of breast cancer included 48 hours of weekday measurements (18). Theoretically, exposure misclassification is a potential issue, because home measurements of magnetic fields do not completely capture personal exposure. In general, residential exposures are much lower than exposures documented in some occupational settings, including those of electrical workers, welders, and train conductors (35). However, few women hold these jobs entailing high levels of exposure (36). Another limitation of this study, as well as of the previous one (18), was that we assessed magnetic field exposure during the 10 years prior to diagnosis. The relevant etiologic period may be earlier in life, perhaps in childhood or adolescence.

It is possible that there are population subgroups with special sensitivity to the effects of magnetic fields. For example, a recent study in the Seattle area found that higher nighttime magnetic field measurements were weakly associated with lower urinary melatonin levels primarily among women who were taking several medications that may interfere with melatonin production, such as beta blockers, calcium channel blockers, and psychotropic medications, and only at times of the year with the fewest hours of darkness (4). We did not have data on the use of these medications. However, even among these medication users, magnetic fields were only weakly associated with melatonin levels. Thus, it seems very unlikely that we would have found an effect of magnetic fields on breast cancer risk among women using medications that interfere with melatonin, a subset we cannot identify. Although melatonin has been hypothesized to influence breast cancer risk, there are few data supporting this hypothesis, and none in humans. Given the available data, it does not seem likely that minor variation in melatonin levels that might be caused by exposure to magnetic fields among women using certain medications would have any strong effect on breast cancer risk. In an experimental study using the MCF-7 breast cancer cell line, administration of melatonin did not inhibit estradiol-induced proliferation (37). In another study, melatonin inhibited oxidative damage in MCF-7 cells only at pharmacologic concentrations; no effect was seen at physiologic levels (38).

Our results tend to rule out modest effects of exposure to residential magnetic fields, at levels experienced by the vast majority of the population, on breast cancer risk. Given the distribution of exposure and the sample size, the study had 80 percent power to detect a 10 percent increase in risk and 98 percent power to detect a 15 percent increase in risk per 0.1 μ T for the nighttime bedroom broadband magnetic field measurement at the $p = 0.05$ level of significance. Given the

distribution of bedroom magnetic fields, with 0.2 μ T corresponding to the 90th percentile and 0.4 μ T being rare, even if there were a true 10–15 percent increase in risk per 0.1- μ T increase in magnetic fields, only an extremely small proportion of breast cancers would be due to magnetic field exposure. Our study would have 90 percent power to detect relative risks of 3 or 4 for effects at 0.3 μ T or 0.4 μ T, respectively. Within the distribution of bedroom magnetic fields among controls, 0.2 μ T corresponds to the 90th percentile, and approximately 3 percent of controls have fields above 0.4 μ T. Thus, even if there were a true 10–15 percent increase in risk per 0.1- μ T increase in magnetic fields or there was an effect at very high exposures, only an extremely small proportion of breast cancers could be explained.

There has been some controversy recently regarding the use of wiring configuration codes in epidemiologic studies (34). Wire codes are not a perfect surrogate measure for magnetic fields and thus will introduce some misclassification of magnetic field exposure (28). The use of wire codes dates to the childhood leukemia study by Wertheimer and Leeper in Denver, Colorado (26). In subsequent studies, associations with childhood leukemia were found in Denver, Los Angeles, Canada, and Mexico but not in all locations in North America (19, 24, 27). In Los Angeles, the relation between wire code and leukemia persisted after adjustment for measured fields, and wire code was more strongly associated with leukemia risk than it was in a more complex prediction model using additional data from local utilities (22). However, the wire code that we used is not applicable to studies in all locations, because wiring practices differ (27). It has no relevance in Europe, where power distribution lines are generally buried and only the rarer high-voltage transmission lines are above ground. In contrast, many people in the United States live in close proximity to overhead primary distribution lines, especially in Los Angeles, where 15 percent of our subjects were classified in the highest wire code category (very high current configuration). Furthermore, wire codes in Los Angeles, as in other locations in North America, have a modest correlation with magnetic fields and distinguish between magnetic field exposures in the lowest categories (very low and underground) and those in the highest category (very high current configuration), thus providing a useful surrogate measure when magnetic field measurements cannot be made (27, 28). Because of the correlation with magnetic fields and the previous association with childhood leukemia risk in Los Angeles, which persists despite attempts to assess selection bias and confounding by other factors such as traffic density (39, 40), wire code is an important exposure metric in this Los Angeles study. The absence of an association between breast cancer risk and wire code in Los Angeles is a pertinent negative finding, especially given the absence of selection bias in our nested case-control design.

It has been suggested that the previous findings for childhood leukemia and wire code in several US locations, which persisted after adjustment for magnetic fields (19), might reflect a parameter of magnetic fields that has not been measured in previous studies, such as the harmonic magnetic field, which correlates with wire code (31). Therefore, we measured harmonic magnetic fields in this study, but we

found no association with breast cancer risk. These results are in agreement with those reported by Davis et al. (18).

We believe that the most compelling interpretation of our results is that residential magnetic field exposures experienced by the vast majority of US women do not play an etiologic role in breast cancer. The findings of this study, along with those of the previous study with magnetic field measurements (18), should provide some reassurance to the public regarding this ubiquitous low-level exposure.

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REFERENCES

1. Thun-Battersby S, Mevissen M, Loscher W. Exposure of Sprague-Dawley rats to a 50-Hertz, 100-microTesla magnetic field for 27 weeks facilitates mammary tumorigenesis in the 7,12-dimethylbenz[*a*]-anthracene model of breast cancer. *Cancer Res* 1999;59:3627-33.
2. Fedrowitz M, Westermann J, Loscher W. Magnetic field exposure increases cell proliferation but does not affect melatonin levels in the mammary gland of female Sprague Dawley rats. *Cancer Res* 2002;62:1356-63.
3. Juutilainen J, Stevens RG, Anderson LE, et al. Nocturnal 6-hydroxymelatonin sulfate excretion in female workers exposed to magnetic fields. *J Pineal Res* 2000;28:97-104.
4. Davis S, Kaune WT, Mirick DK, et al. Residential magnetic fields, light-at-night, and nocturnal urinary 6-sulfatoxymelatonin concentration in women. *Am J Epidemiol* 2001;154:591-600.
5. Stevens RG, Davis S. The melatonin hypothesis: electric power and breast cancer. *Environ Health Perspect* 1996;104(suppl 1):135-40.
6. Caplan LS, Schoenfeld ER, O'Leary ES, et al. Breast cancer and electromagnetic fields—a review. *Ann Epidemiol* 2000;10:31-44.
7. Vena JE, Graham S, Hellmann R, et al. Use of electric blankets and risk of postmenopausal breast cancer. *Am J Epidemiol* 1991;134:180-5.
8. Gammon MD, Schoenberg JB, Britton JA, et al. Electric blanket use and breast cancer risk among younger women. *Am J Epidemiol* 1998;148:556-63.
9. Vena JE, Freudenheim JL, Marshall JR, et al. Risk of premenopausal breast cancer and use of electric blankets. *Am J Epidemiol* 1994;140:974-9.
10. Laden F, Neas LM, Tolbert PE, et al. Electric blanket use and breast cancer in the Nurses' Health Study. *Am J Epidemiol* 2000;152:41-9.
11. McDowall ME. Mortality of persons resident in the vicinity of electricity transmission facilities. *Br J Cancer* 1986;53:271-9.
12. Wertheimer N, Leeper E. Magnetic field exposure related to cancer subtypes. *Ann N Y Acad Sci* 1987;502:43-54.
13. Schreiber GH, Swaen GM, Meijers JM, et al. Cancer mortality and residence near electricity transmission equipment: a retrospective cohort study. *Int J Epidemiol* 1993;22:9-15.
14. Verkasalo PK, Pukkala E, Kaprio J, et al. Magnetic fields of high voltage power lines and risk of cancer in Finnish adults: nationwide cohort study. *BMJ* 1996;313:1047-51.
15. Li CY, Theriault G, Lin RS. Residential exposure to 60-Hertz magnetic fields and adult cancers in Taiwan. *Epidemiology* 1997;8:25-30.
16. Feychting M, Forssen U, Rutqvist LE, et al. Magnetic fields and breast cancer in Swedish adults residing near high-voltage power lines. *Epidemiology* 1998;9:392-7.
17. Coogan PF, Aschengrau A. Exposure to power frequency magnetic fields and risk of breast cancer in the Upper Cape Cod Cancer Incidence Study. *Arch Environ Health* 1998;53:359-67.
18. Davis S, Mirick DK, Stevens RG. Residential magnetic fields and the risk of breast cancer. *Am J Epidemiol* 2002;155:446-54.
19. Greenland S, Sheppard AR, Kaune WT, et al. A pooled analysis of magnetic fields, wire codes, and childhood leukemia. Childhood Leukemia-EMF Study Group. *Epidemiology* 2000;11:624-34.
20. London SJ, Thomas DC, Bowman JD, et al. Exposure to residential electric and magnetic fields and risk of childhood leukemia. *Am J Epidemiol* 1991;134:923-37.
21. Savitz DA, Wachtel H, Barnes FA, et al. Case-control study of childhood cancer and exposure to 60-Hz magnetic fields. *Am J Epidemiol* 1988;128:21-38.
22. Thomas DC, Bowman JD, Jiang L, et al. Residential magnetic fields predicted from wiring configurations: II. Relationships to childhood leukemia. *Bioelectromagnetics* 1999;20:414-22.
23. Bowman JD, Thomas DC, Jiang L, et al. Residential magnetic fields predicted from wiring configurations: I. Exposure model. *Bioelectromagnetics* 1999;20:399-413.
24. Wartenberg D. Residential EMF exposure and childhood leukemia: meta-analysis and population attributable risk. *Bioelectromagnetics* 2001;suppl 5:S86-104.
25. Kolonel LN, Henderson BE, Hankin JH, et al. A multiethnic cohort in Hawaii and Los Angeles: baseline characteristics. *Am J Epidemiol* 2000;151:346-57.
26. Wertheimer N, Leeper E. Electrical wiring configurations and childhood cancer. *Am J Epidemiol* 1979;109:273-84.
27. IARC Working Group on the Evaluation of Carcinogenic Risks to Humans. Non-ionizing radiation, part 1: static and extremely low-frequency (ELF) electric and magnetic fields. *IARC Monogr Eval Carcinog Risks Hum* 2002;80:1-395.
28. Tarone RE, Kaune WT, Linet MS, et al. Residential wire codes: reproducibility and relation with measured magnetic fields. *Occup Environ Med* 1998;55:333-9.
29. Wertheimer N, Leeper E. Adult cancer related to electrical wires near the home. *Int J Epidemiol* 1982;11:345-55.
30. Kleinerman RA, Linet MS, Hatch EE, et al. Magnetic field exposure assessment in a case-control study of childhood leukemia. *Epidemiology* 1997;8:575-83.
31. Kaune WT, Dovan T, Kavet RI, et al. Study of high- and low-current-configuration homes from the 1988 Denver Childhood Cancer Study. *Bioelectromagnetics* 2002;23:177-88.
32. Wilson BW, Lee GM, Yost MG, et al. Magnetic field character-

- istics of electric bed-heating devices. *Bioelectromagnetics* 1996;17:174–9.
33. Pike MC, Kolonel LN, Henderson BE, et al. Breast cancer in a multiethnic cohort in Hawaii and Los Angeles: risk factor-adjusted incidence in Japanese equals and in Hawaiians exceeds that in whites. *Cancer Epidemiol Biomarkers Prev* 2002;11:795–800.
 34. Ahlbom A, Day N, Feychting M, et al. A pooled analysis of magnetic fields and childhood leukaemia. *Br J Cancer* 2000;83:692–8.
 35. Floderus B, Persson T, Stenlund C. Magnetic-field exposures in the workplace: reference distribution and exposures in occupational groups. *Int J Occup Environ Health* 1996;2:226–38.
 36. Forssen UM, Feychting M, Rutqvist LE, et al. Occupational and residential magnetic field exposure and breast cancer in females. *Epidemiology* 2000;11:24–9.
 37. Baldwin WS, Travlos GS, Risinger JI, et al. Melatonin does not inhibit estradiol-stimulated proliferation in MCF-7 and BG-1 cells. *Carcinogenesis* 1998;19:1895–900.
 38. Baldwin WS, Barrett JC. Melatonin attenuates hydrogen peroxide toxicity in MCF7 cells only at pharmacological concentrations. *Biochem Biophys Res Commun* 1998;250:602–5.
 39. Langholz B, Ebi KL, Thomas DC, et al. Traffic density and the risk of childhood leukemia in a Los Angeles case-control study. *Ann Epidemiol* 2002;12:482–7.
 40. Langholz B. Factors that explain the power line configuration wiring code-childhood leukemia association: what would they look like? *Bioelectromagnetics* 2001;suppl 5:S19–31.