Wire Codes, Magnetic Fields, and Childhood Cancer

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Childhood cancer has been modestly associated with wire codes, an exposure surrogate for power frequency magnetic fields, but less consistently with measured fields. We analyzed data on the population distribution of wire codes and their relationship with several measured magnetic field metrics. In a given geographic area, there is a marked trend for decreased prevalence from low to high wire code categories, but there are differences between areas. For average measured fields, there is a positive relationship between the mean of the distributions and wire codes but a large overlap among the categories. Better discrimination is obtained for the extremes of the measurement values when comparing the highest and the lowest wire code categories. Instability of measurements, intermittent fields, or other exposure conditions do not appear to provide a viable explanation for the difference between wire codes and magnetic fields with respect to the strength and consistency of their respective association with childhood cancer. *Bioelectromagnetics 18:99–110, 1997.*

Key words: epidemiology; misclassification; residential exposure; review

INTRODUCTION

Since 1979, several residential studies have reported results suggestive of a positive association between exposure to power frequency (50–60 Hz) magnetic fields and childhood cancer, particularly leukemia [Wertheimer and Leeper, 1979; Savitz et al., 1988; London et al., 1991; Feychting and Ahlbom, 1993]. These results relied largely, but not exclusively, on the use of an exposure surrogate, which estimates residential magnetic fields on the basis of proximity to overhead electric utility lines of various types and sizes. This surrogate has been referred to as the utility wiring configuration adjacent to the residence or, more simply, as the ''wire code.'' The odds ratios (ORs) associated with the higher exposure categories have ranged from about 1.5 to 3.0. Perhaps paradoxically, these studies revealed generally weaker associations between childhood cancers and fields measured contemporaneously in the available study homes. This paper's objectives are 1) to provide an understanding of the relationships between wire codes and residential magnetic fields and 2) to explore the implications of these relationships to the hypothesis that the stronger associations between cancer and wire codes are due to the improved ability of wire codes to capture long-term historical exposures to magnetic fields.

WIRE CODES, MAGNETIC FIELDS, AND CHILDHOOD CANCER

Wertheimer and Leeper [1979] first introduced wire codes as a surrogate index for residential exposure to magnetic fields. Each subject's exposure was categorized dichotomously (HCC/LCC; see Table 1). Based on cases between 1950 and 1973, Wertheimer and Leeper reported that childhood leukemia mortality, as well as childhood deaths from several other cancers, was associated with residence in HCC homes. The study did not include field measurements in study homes.

Subsequent studies used various combinations of exposure indices that included: refinements of the original wire code (Table 1); short- and long-term residential measurements; and fields computed from engineering models of the outdoor power lines. The expectations were that a surrogate based on contemporaneous magnetic field measurements would lead to increased ORs, if wire codes misclassified magnetic field exposure and if some measured aspect of the magnetic field environment was indeed the etiologic agent underlying the wire code associations. The results of the key studies of childhood leukemia and brain cancer are summarized in Tables 2 and 3.

Feychting and Ahlbom [1993] studied populations residing near transmission lines and used a variety

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TABLE 1. Wire Code

Wire code category	Type of external power line & distance to residence: Transmission line	3 phase primary distribution: ≥2	3 phase primary distribution: Thick	3 phase primary distribution: Thin	Secondary distribution: 1st span	Secondary distribution: ≥2nd span
HCC						
VHCC	<15 m	<15 m	<15 m	<7.5 m	n/a	n/a
OHCC	<40 m	<40 m	<40 m	<20 m	<15 m	n/a
LCC						
OLCC	n/a	n/a	n/a	<40 m	<40 m	<40 m
VLCC	none of the above and secondary service overhead					
UG	none of the above and secondary service underground					

of exposure metrics (spot measurements, distance to line, historic model). Their primary metric was based on a historic model in which the magnetic field in a residence due to nearby transmission lines was computed. The model took into account loads dating back over three decades, physical dimensions of the lines, and their distance from the residence. This study is included in the wire code columns of the tables, because exposure levels are based on ampacity and distance, except that the current is not a categorical variable (e.g., thick vs. thin conductors) but instead is a continuous variable based on annualized load data and actual line dimensions (e.g., phase height). Such data, though preferable to the inferred categories of the wire code, nonetheless represent a surrogate model.

Tables 2 and 3 indicate the ORs for analyses in which the full study populations were dichotomized into high and low categories and for analyses in which the lowest exposure category served as referent for the highest exposure group. These tables show, as stated above, a tendency for somewhat larger, somewhat more precise ORs for wire codes than for measurements; the improved precision is due to more residences available for wire coding than for measurements. In addition, comparison of groups at the extremes of the exposure scales do not produce ORs that are dramatically larger than those of the dichotomous exposure measures. Feychting and Ahlbom [1993] concluded that their data supported a potential etiologic role for the time-weighted average (TWA) magnetic field, because their model was based on transmission lines, and the associated fields are relatively steady over time. We deal below with the question of exposure metrics.

Savitz and Kaune [1993] published a reanalysis of the original Savitz et al. [1988] data based on a modified and simplified wire code; details of the modification are given by Kaune and Savitz [1994]. The modified system (Table 4) consists of low, medium, and high wire code categories (LWC, MWC, and HWC) and ignores the distinction between thin and thick primary wires and first span and other secondaries. The modified code did not improve the ability of the Wertheimer-Leeper code to explain the variability of measured fields, but it produced more precise cancer-specific ORs.

Other studies have addressed the potential relationship between magnetic fields and childhood cancer with inconsistent results. However, the question of whether the childhood cancer risks associated with wire codes represent risks from magnetic field exposure has evolved primarily from the studies described above (Tables 2, 3). These observations led to specific questions about how well wire codes classify the magnetic field exposures of potential interest.

To shed more light on the exposure-related questions that emerged from the epidemiologic literature, several exposure assessment and measurement projects have been conducted. The results of these large-scale surveys, exposure assessments from epidemiologic studies, and other studies are reviewed below.

POPULATION DISTRIBUTION OF WIRE CODES

The distribution of homes by wire code category is shown in Figure 1 for six data sets, the control groups from the Savitz [Savitz et al., 1988], Stevens [Kaune et al., 1987], and London [London et al., 1991] epidemiologic studies, the ‘‘1,000 home’’ Nationwide Residential Survey carried out by HVTRC [Zaffanella, 1993], a random wire code sampling taken during the EMDEX Residential Project [Bracken and Rankin, 1994], and a survey carried out by American Electric Power in Columbus [Jones et al., 1993]. There is a marked trend of decreased prevalence moving from low to high wire code category. The combined VLCC/UG group represents about 40% of the homes, whereas the VHCC category accounts for about 5% of the homes. However, there are striking differences across the studies (Kruskal-Wallis test, $P = 0.0001$). The Los Angeles control group contains less than 20% of low

TABLE 2. Comparison of Results for Childhood Leukemia from Selected Studies

	High-low odds ratios						Dichotomous odds ratios					
	Wire code			Measurement			Wire code			Measurement		
Reference	Comparison	N	OR (95% CI)	Comparison	N	OR (95% CI)	Comparison	N	OR (95% CI)	Comparison	N	OR (95% CI)
Wertheimer & Leeper, 1979							HCC/LCC	63	3.0 (1.8–5.0)			
Savitz et al., 1988	VHCC/UG	7	2.8 (0.9–8.0)	≥2.5 mG/<0.7 mG	4	2.1 (0.6–7.2) low spot	HCC/LCC	27	1.5 (0.9–2.6)	2 mG cut pt	5	1.9 (0.7–5.6) low spot
					4	1.7 (0.5–5.7) high spot					7	1.4 (0.6–3.5) high spot
London et al., 1991	VHCC/UG + VL	42	1.7 (0.8–3.7)*	≥1.3 mG/≤0.3 mG	16	1.2 (0.5–2.8)** low spot	HCC/LCC	122	1.7 (1.1–2.5)**	0.7 mG cut pt	16	1.3 (0.7–2.3)** low spot
				≥2.7 mG/≤0.7 mG	20	1.7 (0.7–4.0) 24 hr				1.3 mG cut pt	39	1.1 (0.5–2.7)** low spot
										1.2 mG cut pt	44	1.2 (0.7–2.1)** 24 hr
										2.7 mG cut pt	20	1.7 (0.8–3.8)** 24 hr
Feychting & Ahlbom, 1993	≥3 mG/<1 mG	7	3.8 (1.4–9.3)*	≥2 mG/<1 mG	4	0.6 (0.2–1.8) low spot	≤50 m/>50 m	6	2.9 (1.0–7.1)	1 mG cut pt	5	0.4 (0.1–1.1)
	≤50 m/>100 m	6	2.9 (1.0–7.3)				1 mG cut pt	11	2.4 (1.2–5.1)	2 mG cut pt	4	0.8 (0.2–2.2)
							2 mG cut pt	7	2.5 (1.0–5.8)			

*Significant trend across categories.
**Unadjusted OR.
N = number of exposed cases

TABLE 3. Comparison of Results for Childhood Brain Cancer from Selected Studies

	High-low odds ratios						Dichotomous odds ratios					
	Wire code			Measurement			Wire code			Measurement		
Reference	Comparison	N	OR (95% CI)	Comparison	N	OR (95% CI)	Comparison	N	OR (95% CI)	Comparison	N	OR (95% CI)
Wertheimer & Leeper, 1979							HCC/LCC	30	2.4 (1.1–5.1)			
Savitz et al., 1988	VHCC/UG	3	1.9 (0.5–8.0)	≥2.5 mG/<0.7 mG	2	1.5 (0.3–7.3) low spot	HCC/LCC	20	2.0 (1.1–3.8)	2 mG cut pt	2	1.0 (0.2–4.8) low spot
					3	1.3 (0.3–4.9) high spot					3	0.8 (0.2–2.9) high spot
Feychting & Ahlbom, 1993	≥3 mG/<1 mG	2	1.0 (0.2–3.9)	≥2 mG/<1 mG	5	1.5 (0.4–4.9) low spot	≤50 m/>50 m	1	0.5 (0.0–2.6)	1 mG cut pt	13	2.0 (0.8–4.7)
	≤50 m/>100 m	1	0.5 (0.0–2.8)				1 mG cut pt	4	0.8 (0.2–2.3)	2 mG cut pt	5	1.1 (0.3–2.9)
							2 mG cut pt	2	0.7 (0.1–2.6)			
Preston-Martin et al. 1996	VHCC/VL + OLCC*	31	1.2 (0.6–2.1)	≥1.5 mG/≤0.4 mG	16	0.5 (0.2–1.1) front spot	HCC/LCC	128	0.8 (0.5–1.1)	2 mG cut pt	16	1.2 (0.5–2.8)
				≥2.5 mG/≤0.6 mG	13	1.4 (0.5–3.8) 24 hr				3 mG cut pt	12	1.7 (0.6–5.0)
Gurney et al., 1996	VHCC/UG	4	0.5 (0.2–1.6)				HCC/LCC	23	0.9 (0.5–1.5)			

*As reported by Preston-Martin et al. If UG is used as reference OR = 0.6.
N = number of exposed cases

TABLE 4. Modified Wire Code

Wire code category	Transmission line & 3 phase primary distribution line	Open secondary line	Spun secondary line
HWC	<20 m	n/a	n/a
MWC	<46 m	<26 m	n/a
LWC	all other homes		

Reference: Kaune and Savitz, 1994.

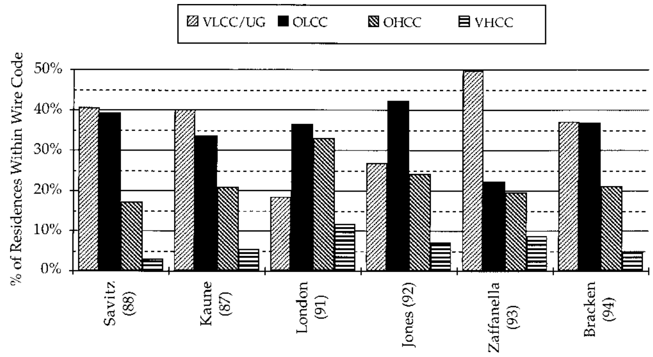

Fig. 1. Distribution of wire code categories by study.

VLCC/UG category homes, with a much larger proportion of high category homes. Indeed, nearly 45% of the Los Angeles homes are in either the VHCC or the OHCC category, nearly double the proportion found in the rest of the studies. This finding was confirmed by a later study conducted in Los Angeles [Preston-Martin et al., 1996], which found about 20% of control homes to be in the VLCC/UG category and more than 50% in the high category (11% VHCC and 44% in OHCC).

In addition to the differences between cities, the wire code distribution is associated with urban/rural status, based on data available from two surveys. The HVTRC study homes [Zaffanella, 1993] were randomly selected customers of 25 utilities across the United States. Each home was identified by the participants as either urban, suburban, or rural. In the AEP Columbus study [Jones et al., 1993], researchers selected three areas—inner city, urban, and suburban—and identified a study population as all residences served by one electrical distribution circuit in each area. Both studies show a larger percentage of ''high code'' (VHCC and OHCC) homes in the urban/inner city area (33% for HVTRC and 50% for Columbus) than in rural/suburban areas (23% for HVTRC and 22% for Columbus).

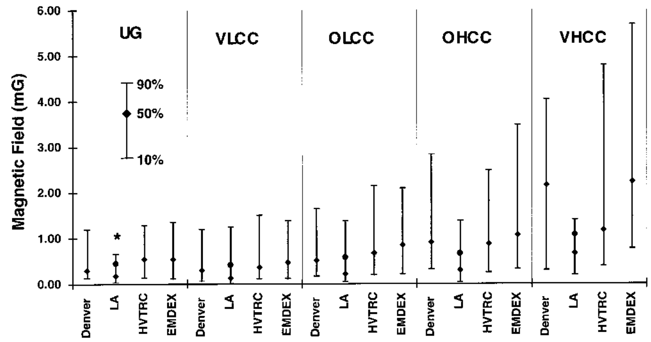

Fig. 2. Spot measurements of magnetic fields across studies. *Median of 24 h measurements in LA data.

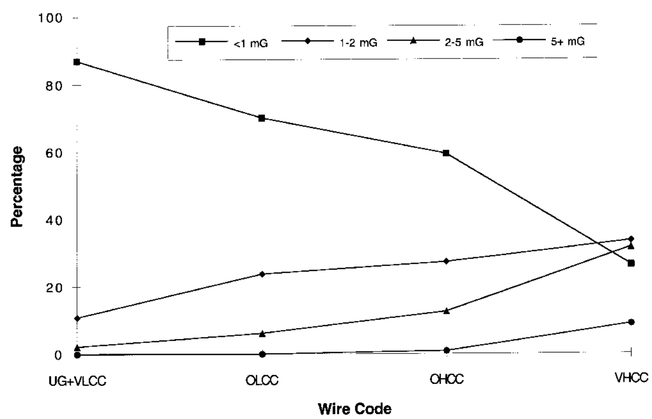

Fig. 3. Percentage of homes within each wire code categorized by inside mean (i.e., average spot measurement), based on EMDEX residential study weighted sample [Bracken and Rankin, 1994].

WIRE CODES AND MAGNETIC FIELDS

Average 60 Hz Residential Fields and Exposures

Data on residential magnetic fields have been generated from epidemiologic studies and measurement surveys. Figure 2 displays the ranges of measurements by wire code category for four substantial data sets, the control groups from the Savitz [Savitz et al., 1988] and London [London et al., 1991] studies, the EMDEX Residential Project [Bracken et al., 1994], and the HVTRC survey [Zaffanella, 1993]. There is a positive relationship between the mean of the distributions and wire code, but there is a large overlap among the various categories. We have evaluated relationships between wire codes and measured fields in the data sets available to us (EMDEX, HVTRC, and London). The relationships were quite similar across data sets; therefore, only selected examples are presented below.

As is shown in Figure 3 for the EMDEX Residential Project data, high wire codes are useful in identifying homes with high magnetic fields. For example, the majority of homes with interior mean measurements of 5 mG or above fall into the VHCC category. Although most of the misclassification occurs from homes in high wire code categories having low measurements [see Kheifets, 1990], the VHCC category still performs reasonably well in excluding homes with low measurements. Although homes with measurements of below 1 mG represent almost 90% of all homes in the lowest wire code category (UG + VLCC), these homes make up less than 30% of the VHCC category. The relationship between wire codes and measured fields becomes very weak for fields in the midrange (1–2 mG) and for OLCC and OHCC categories. These wire code categories and field levels are quite common and are largely responsible for the poor wire code/measurement correlation.

To explore further the association between wire codes and measured fields, we calculated an ''exposure odds ratio'' (EOR), explained in a Table 5 footnote. Table 5 presents EORs for the HTVRC data by wire code categories and for a variety of lower and upper cut points. For example, for an upper cut point of 2 mG, a comparison could be made to lower cut points of 0.25 or below, 0.5, 1.0, and 2 mG (the last comparison is one utilized in several epidemiologic studies, i.e., above and below 2 mG). High fields are more common among high wire code categories regardless of the cut points used (reflected by an EOR above 1). For VHCC compared to UG + VLCC, EORs monotonically increased with an increase in the upper and decrease in the lower cut points used. The highest EOR is achieved when extremes of the distribution are compared, i.e., when homes with measurements of above 5 mG are compared to homes whose measured fields were below 0.25 mG. The lowest EOR in all categories occurs when homes of more than 0.5 mG are compared to homes of less than 0.5 mG.

Whereas upper cut points have been varied in some epidemiologic studies [see, e.g., Feychting et al., 1995], variation in lower cut points has not been explored. We would expect that maximizing the contrast should lead to a higher but less stable estimate of risk. This can be tested in several completed studies.

Field and Exposure Stability

Dovan et al. [1993] studied the repeatability of residential magnetic field measurements and wire codes. In 1990, they measured 81 (about equal numbers of HCC and LCC) Colorado homes that had been measured in 1985 as part of the Savitz study of childhood cancer. They found the wire code status in agreement for 73 of the 81 homes. In the same study, house average magnetic field measurements at any particular time of day were reasonably well correlated (r = 0.75–0.9) with measurements at any other time. Average spot measurements repeated in 56 residences were correlated with similar measurements made in 1985 (r = 0.7).

Two pilot studies of methods for assessing children's long-term exposure to magnetic fields provided some data on the association between wire codes and magnetic fields. Kaune and Zaffanella [1994] conducted a pilot study to develop methods for estimating children's long-term personal exposure. As part of this study, the authors conducted two rounds of measurements separated by 6–9 months in 35 homes. These included spot field measurements, 24 h stationary measurements, and personal exposure measurements for children using an integrating meter (AMEX 3D). For the two visits, Kaune and Zaffanella found a high degree of correlation (r = 0.8–0.9) between the 24 h recordings (log transformed) and a good correlation (r = 0.71) between the spot measurements (log transformed). There was essentially no correlation between personal exposures measured for the two visits, whether at home or at school. Kaune and Zaffanella suggested a model in which magnetic field exposure comprises both a stable and a random component. Because spot and 24 h measurements capture the stable component better than personal exposure, they might be better predictors of exposure than personal exposure measures.

Koontz et. al. [1994] also carried out a pilot study on methods for assessing childhood exposure in 28 children from Frederick, MD. They measured personal expsures on a small sample of these children (n = 10) on two consecutive days in the winter and then again on two consecutive days in the following spring. Our analyses of log TWA exposure for this sample show statistically significant correlations (r = 0.79, winter; r = 0.66, spring) for consecutive days, and no significant correlations across season (r = 0.28–0.58). These data suggest larger variability across season than across consecutive days.

Raw data from the EMDEX Residential Project [Bracken et al., 1994] provided us with an opportunity to address how wire codes and contemporaneous personal exposure and area measurements may relate to historic personal exposure. From 1990 to 1992, the investigators conducted multiple visits to the homes of employee volunteers representing 39 electric utility companies. The measurement period of each visit lasted for approximately 3 days and included spot measurements (SPOT) made at the start of the data collection period, personal measurements (PE) by EMDEX worn while at home on the first and third days of the visit, and fixed-site measurements (LT) when the resident was asleep or off the property and when the EMDEX was left in a designated location on the second day. Data were collected for 396 residences, visited an average of 3.9 times each, with an average of 136 days between successive visits. The study's sampling strategy, which purposely overrepresented the higher wire code categories (OHCC and VHCC), led to an overrepresentation of homes close to transmission lines in the VHCC category. Thus, one should interpret these data with caution.

We have examined how wire codes (which remain largely invariant over time) and TWA LT measurements [Bracken et al., 1994], spot measurements, and TWA PE measurements from visit 4 estimate TWA PE measurements from visit 1. To offset purposeful sampling, categorical cut points for the measurement data were selected to correspond exactly by percentile to the distribution of residences across wire code categories after lumping UG and VLCC into a single category.

The kappa statistic [Fleiss, 1981] was calculated as an index of agreement between the categorization of subjects by the surrogates and by personal exposure. This statistic has the desirable features that it adjusts for agreement due to chance and is independent of the distribution characteristics of the continuous measurement data (SPOT, LT, and PE). Although the absolute values of the kappa coefficients are affected by the distribution of wire codes in the sample, the relative values allow us to compare the fidelity of various surrogates. A kappa of 1 indicates perfect agreement and a kappa of ≥0 indicates agreement greater than or equal to chance (kappa may also have negative values, indicating an absence of agreement).

The results are shown in Table 6. For visit 4 measures, the agreement with visit 1 PE is highest for contemporaneous personal exposure and lowest for wire codes. We also computed the fraction of total log-transformed exposure variance explained with the surrogate categories established above (Table 6). Wire codes explained by far the least amount of exposure variance. Similar results are obtained when comparing data from visit 2 to data from visit 1 (with larger numbers; data not shown).

To obtain a better estimate of long-term exposure, we averaged measurements of visits 1–3 and compared the integrated exposure to data from visit 4. The results were consistent with those discussed above and suggest that wire codes integrate exposure over the previous year more poorly than the other surrogates. These data suggest that wire codes are not superior (and perhaps are inferior) to contemporary measurements in predicting prior exposure. Therefore, if these data apply more generally, we would expect wire codes to produce greater misclassification of prior TWA exposure than contemporaneously measured fields (LT, SPOT, and PE).

Field and Exposure Intermittence

An ''intermittent'' magnetic field exposure is defined as exposure to a field that undergoes a change in its steady-state value for a specified interval of time. The onset and offset of an intermittent exposure are often accompanied by a transient field, which is defined as a rapid change in time of the magnetic field during a change of the steady state. Transients result from electrical switching operations, such as from a household appliance or from switching operations on distribution systems (capacitive bank closing) [Guttman et al., 1994]. The results of several laboratory, human clinical, and epidemiology studies have suggested that biological and, possibly, health effects may be related

TABLE 5. Exposure Odds Ratios of Wire Codes & Measured Fields by Various Cut Points*

	Wire code														
	OLCC					OHCC					VHCC				
Upper cut point [measured field (mG)]	Lower cut point [measured field (mG)]														
	0.25	0.50	1.00	2.00	5.00	0.25	0.50	1.00	2.00	5.00	0.25	0.50	1.00	2.00	5.00
0.25	2.0					3.2					16.5				
0.50	2.1	1.5				3.8	2.5				19.1	3.2			
1.00	2.5	1.9	1.7			5.7	3.7	3.0			35.4	6.0	5.2		
2.00	4.5	3.3	3.0	2.9		9.7	6.2	5.1	4.2		105.0	17.9***	15.5	12.9	
5.00	3.8	2.8	2.5	2.4	2.3	11.1	7.2	5.8	4.8	4.3	163.3	27.8	24.1	20.1	14.7

*Based on average spot measurements from HVTRC study (Zaffanella, 1993).
**UG + VLCC used as comparison.
***i.e., EOR = 17.9 is a ratio of odds of getting a measurement above 2 mG for the VHCC home to odds of getting a measurement below 0.5 mG for the UG + VLCC home.

to exposure to intermittent magnetic fields [see Kavet, 1992].

Given this possibility, it is logical to inquire whether a measure of intermittency might be related to wire code. Unfortunately, very few data addressing this question are available. A parameter termed the ''personal exposure first difference'' was established in the EMDEX project as a possible measure of intermittence [Bracken et al., 1994]. Its value is the average of the absolute change of the field measured every 10 s. Although the median first difference was a bit higher for VHCC homes, there were no statistically significant differences reported across wire code.

Koontz and Niang (1994, unpublished) examined measures of intermittency as they related to wire code. The authors constructed both absolute and relative measures of intermittency. The absolute measures included the first difference described above in addition to others, such as the fraction of consecutive differences above particular thresholds. Relative measures reflected differences between consecutive measures normalized either to the daily mean exposure or to the field at the time the first difference occurred. All absolute measures of intermittency increased across wire code, whereas all relative measures decreased. The contrast between these findings on intermittency and those of Bracken et al. [1994] is quite likely the result of the strong correlation Koontz et al. [1994] reported between wire code and residential fields (see below), a finding inconsistent with those of Bracken's study and of the other studies conducted thus far of wire code's relation to fields. Nonetheless, the kind of findings Koontz and Niang report could be relevant to those wishing to construct biologically based exposure parameters.

In just such an exercise, Thomas et al. [1995] developed an exposure variable based on a toxicokinetic model proposed by Litovitz and colleagues [1992]. According to the model, temporal changes in the magnetic field alter rate constants in an mRNA synthesis-degradation pathway, and the mRNA integrated over time in the model is the exposure parameter. Thomas et al. [1994] adapted this model to the data acquired in the childhood leukemia study of London et al. [1991]; this study (see above) reported a statistically significant trend of increasing risk with wire code but not with measured fields. In univariate analyses, the kinetic model index, and several other exposure variables that were constructed for these analyses (e.g., 50 s autocorrelation coefficient) were not strongly related to leukemia. However, in multivariate analyses, several associations emerged. The relationship of these constructs to biological activity remains hypothetical, and they do not appear to explain the wire code association. In addition, the significantly lower value of the kinetic index in VHCC residences (compared to all other residences), together with the index's negative correlation across wire code, is paradoxical in relation to hypothetical predictions.

Field and Other Exposure Conditions

Two recent papers address specific exposure conditions that might explain potential associations of cancer with magnetic fields in the context of wire codes. Wertheimer et al. [1995] used the wire code and the three-axis spot-measured field data from the Denver study of Savitz et al. [1988], together with information on whether residential grounding (i.e., water service lines) in the homes studied was conductive or not, to assess the association with cancer of fields resulting from ground currents. In both matched and unmatched analyses, Wertheimer et al. [1995] report increased risks for all cancers associated with either HCC alone (independent of conductive plumbing) or conductive plumbing alone (independent of HCC). The relationships were strongest using matched analyses for cases and controls with stable addresses from reference date (date of diagnosis for the cases and the equivalent for matched controls) to the interview date; the largest association was for HCC and conductive plumbing combined. Also, Wertheimer et al. defined fields $\geq$0.5 mG (roughly the median for Denver fields) and less than 55° from the horizontal (as derived from three-axis field measurements) as elevated nonvertical (ENV) fields. They report a positive association between ENV and cancer, with a matched analysis producing the highest risk estimate.

In contrast to these findings, Peters et al. [1991] report, in an expanded presentation of the study of childhood cancer in Los Angeles [London et al., 1991], no increasing trend of risk with magnetic field measured over the water pipe, which is a measure of the ground-associated field. Finally, in the Back-to-Denver study, which was also based on the original study of Savitz et al. [1988], Kaune [1994] observed no apparent association between ground current and case-control status. This study, though, was somewhat limited by sample size.

Bowman et al. [1995] adopted a geomagnetic resonance theory, based on the results of a number of laboratory experiments, to analyze the childhood leukemia, wire code, and field measurement data from the childhood cancer study in Los Angeles [London et al., 1991]. Briefly, the theoretical construct predicts biological effects of AC fields when subjects are also exposed to a narrow range of geomagnetic fields (i.e., static fields) ''tuned'' to resonance with the calcium ion. They report that, for all homes occupied within

TABLE 6. Surrogates in Brackon et al. [1994] (from visit 4) as Predictors of Prior Personal Exposure (from visit 1)

Surrogate variable	Kappa statistic (visit 4 surrogates vs.) Visit 1 PE*	Kappa statistic (visit 4 surrogates vs.) Visit 1–3 PE**	Variability in personal exposure explained by surrogate (visit 4 surrogates vs.) Visit 1 PE*	Variability in personal exposure explained by surrogate (visit 4 surrogates vs.) Visit 1–3 PE**
WC	0.22	0.20	19.1%	15.0%
LT	0.29	0.39	44.4%	46.4%
SPOT	0.31	0.46	45.1%	54.3%
PE	0.40	0.46	55.4%	66.2%

*n = 136 residences.
**n = 89 residences.

these bands for at least 80% of the etiologic period, leukemia risk with field magnitude increased in a statistically significant manner. For homes within the resonant ranges, Bowman et al. [1995] report a statistically significant increasing trend of risk with increasing wire code category. Clearly, this analysis is exploratory, with much of its substance dictated by practical considerations (e.g., sample size) and with its theoretical foundation largely unconfirmed. Similar analyses performed in the Los Angeles brain tumor study [Preston-Martin et al., 1995] did not find any evidence to support the geomagnetic fields resonance theory.

These two new analyses advance hypotheses concerning the nature of magnetic fields implicated in cancer risk and suggest how at least part of that risk could be captured in a wire code metric. The two approaches are quite different, and neither is particularly successful in explaining the wire code and cancer association.

Field and Personal Monitoring

Only the EMDEX residential project discussed earlier systematically evaluated the relationship between wire codes and personal exposure using adult volunteers (see Fig. 4). The wire code association with personal exposure and the ability of high wire codes to select high personal exposures were poorer than for measured field parameters; i.e., a high measured field is more predictive of high exposure than a high wire code. This is likely due to the significant contributions to personal exposure from residential fields that are not associated with wire code categories. Because the EMDEX Project sample was not randomly selected, care should be exercised in generalizing the results to the population at large.

More limited data, applicable to children, come from two pilot studies mentioned above. Kaune and Zaffanella showed that the Wertheimer and Leeper (WL) wire code explained about 35% of the variability in personal exposures and that WL codes and spot

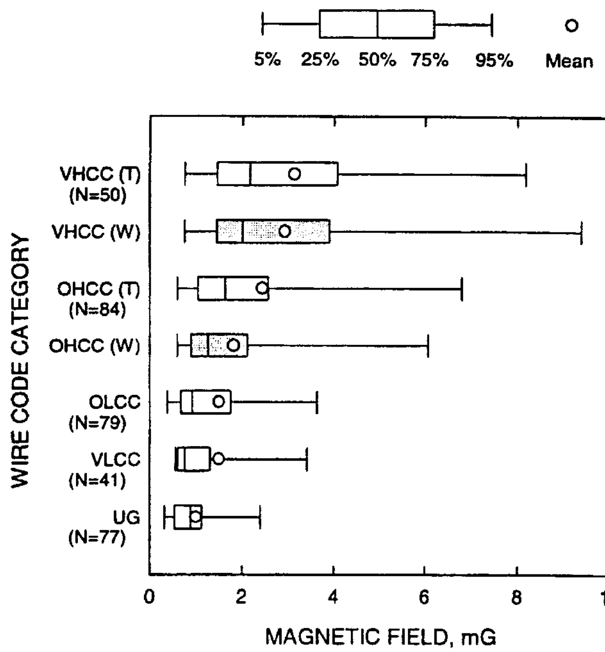

Fig. 4. Distribution of personal exposures from the EMDEX residential study by wire code category. T, targeted sample; W, weighted sample [Bracken and Rankin, 1994].

measurements were similarly effective in explaining the variability in residential personal exposures. Unlike previous studies, Koontz et al. [1994] reported a high correlation between wire code and measured residential fields ($r = 0.81-0.94$) and personal exposure at home ($r = 0.79$). Both of these studies were very small, and the participants were not randomly selected. This likely led to an overestimation of the strength of the association between wire codes and measured fields.

DISCUSSION

Significant uncertainty in the epidemiologic studies of EMF can be ascribed to the lack of consistency in findings, to stronger associations with a crude surrogate, to lack of convincing biologic evidence regarding an aspect of magnetic field exposure that might be most potent, and to the difficulties inherent in the evaluation of historic exposures that are ubiquitous, nonmemorable, and highly variable. All attempts to minimize this uncertainty through better measurements have so far been unsuccessful; wire codes remain the most consistent anchor to explore the potential association between EMF and cancer. To achieve a better understanding of this association, this paper reviews and presents available data on the nature and distribution of wire codes and measured fields.

Although the distribution of wire codes varies among regions and studies, VHCC homes are the least prevalent of all wire code categories, which leads to small numbers and imprecise risk estimates for this category in most studies. The VLCC/UG category used as a reference in some epidemiologic studies is quite common in all regions examined. Based on engineering principles as well as measurements, the VLCC and UG categories are quite similar in terms of magnetic fields; combining them to obtain a more stable referent group appears reasonable.

A deliberate preselection in some studies of neighborhoods and homes to ensure sufficient numbers in all wire code categories has led to biased estimates of association between wire codes and measured fields. Convenience sampling within wire code categories can also lead to bias, such as an overrepresentation of homes near transmission lines in the VHCC category. Random sampling strategies or proper adjustment for purposeful sampling would help significantly in overcoming these problems.

Although wire codes are poor overall at explaining variability in measured fields, they appear to perform much better in identifying homes with high fields. In other words, homes with high wire codes have greater probability of high measured fields and lower probability (compared to other wire code categories) of low measured fields. However, low fields are so common that they are quite prevalent even in the VHCC category. The discrimination of fields afforded by wire codes improves as one moves toward the extremes of the distribution, i.e., with higher upper cut points and with lower lower cut points. The poor overall correlation is dominated by the more prevalent middle categories, and this correlation does not capture the ability of the extreme wire code categories to separate homes with low and high measurements.

There are several reasons for a discordance between wire code and measurement classifications (see Table 7; for simplicity, a dichotomous classification scheme is used). For example, although number and thickness of wires reflect the total current-carrying capacity of a system of wires, this does not take into account actual loading patterns, current balance, and differences in line geometries. Thus, high wire code homes may actually have relatively low fields. Similarly, low wire code homes may exhibit high readings due to high field levels from nonpower line sources or from very heavily loaded external sources.

The notion that the measured fields predict risk poorly due to their lack of stability (compared to wire codes) has not been confirmed. Although wire codes are quite stable historically, their application is not always straightforward and is not error free. Furthermore, their ability to capture personal exposures is limited by the focus on in-home fields from outside wiring at the expense of fields from grounding systems, appliances, and exposure outside the home. The potential for exposure misclassification when wire codes are used as an exposure surrogate appears to be as great as or greater than that for contemporaneously measured fields. On the other hand, measurements, including 24 h and spot sampling, appear to be fairly stable for as long as 5 years past. Thus, in our judgment, the stability of wire codes or the instability of measurements is unlikely to be the primary explanation for the generally weaker association of measurements (compared to wire codes) with childhood cancer risk.

In addition to average fields, other field parameters and exposure conditions (such as intermittence) have been proposed to be biologically active. It has been suggested that these conditions may explain the wire code's ability to predict risk. For this to be true, the wire codes would have to predict these conditions and do so better than measured average fields. Unfortunately, relatively little is known about the occurrence of these conditions and their relationship to wire codes and measured fields. The available data, as described above, are limited to the examination of several indices of intermittence. Based on these data, wire codes do not appear to be strong correlates of intermittence in large populations. To date, there is no experimental support for a biologically based exposure parameter that provides a satisfactory explanation for the wire code association.

Two hypotheses relating to other exposure conditions (nonvertical fields and geomagnetic resonance theory) have been proposed as potential explanations of an association between magnetic fields and/or the wire code and childhood cancer. No studies have been designed to test these hypotheses and these findings have not been confirmed in existing data sets. At this point it remains unclear how these two different approaches might converge to a common principle. Nev-

TABLE 7. Possible Explanations for Disagreements Between Wire Coding and Measurements in Classifying Homes, Assuming No Measurement Error in Either

	Measurement	
Wire code	High	Low
High		• power line source lightly loaded • power line source well balanced • low-field power line geometry • cancellation in multiple power line sources (unlikely) • cancellation of power line field by field from internal sources (unlikely)
Low	• Significant contributions from non-power line sources (high ground currents, unusual home wiring, appliances) • Power line sources (netcurrent/zero sequence current, heavy loading)	

ertheless, the wire code association remains after adjustment for these exposures.

Although intuitively attractive, the implementation of personal exposure assessment is problematic in case-control studies, which are inherently retrospective. This might be especially true for children, because potential changes in both behavior patterns and EMF exposure with age could make personal measurements a poor surrogate for historic exposures. This argues for use of recently diagnosed cases only and for performing the measurements as close to ascertainment date as possible. Additional difficulties include implementation and compliance problems associated with wearing a personal monitor and a possibility of altered behavior when wearing the monitor. Most importantly, personal exposure assessment could perhaps lead to differential misclassification when the disease alters the behavior of a case and that behavior changes exposure. Furthermore, personal exposure data are unlikely to clarify the observed association between wire codes and cancer, because the correlation between wire codes and personal exposures is poorer than the correlation between wire codes and measured fields (EMDEX residential study, data not shown).

In conclusion, the lack of a consistent relationship between the risk of childhood cancer and measurements of magnetic field exposure, contrasted with the more consistent relationship with wire codes, remains paradoxical. Based on the available data, we are unable to conclude that this occurs because wire codes provide a better, more stable estimate of average magnetic field exposure for case-control studies. Furthermore, the limited research to date on wire codes as better markers of an aspect of the magnetic field other than TWA field levels has not been entirely fruitful. Recent results suggest that transient net currents in the service drop are of larger magnitude in VHCC residences compared to LCC residences [Guttman et al., 1996a, b], and that the fields associated with such currents may have dosimetric characteristics that merit further investigation regarding their biological potential [Sastre et al., submitted]. Nevertheless, high wire codes appear to perform well in separating the high and low ends of the magnetic field exposure distribution, a feature that is not captured by the overall measures of correlation between wire codes and measured fields. An attempt to capture and contrast these ends of the exposure distribution better both in the design of future epidemiologic studies and in reanalyses of completed studies may lead to a clearer understanding of these complex relationships.

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