Assessing Human Exposure to Power-Frequency Electric and Magnetic Fields

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This paper reviews published literature and current problems relating to the assessment of occupational and residential human exposures to power-frequency electric and magnetic fields. Available occupational exposure data suggest that the class of job titles known as electrical workers may be an effective surrogate for time-weighted-average (TWA) magnetic-field (but not electric-field) exposure. Current research in occupational-exposure assessment is directed to the construction of job-exposure matrices based on electric- and magnetic-field measurements and estimates of worker exposures to chemicals and other factors of interest. Recent work has identified five principal sources of residential magnetic fields: electric power transmission lines, electric power distribution lines, ground currents, home wiring, and home appliances. Existing residential-exposure assessments have used one or more of the following techniques: questionnaires, wiring configuration coding, theoretical field calculations, spot electric- and magnetic-field measurements, fixed-site magnetic-field recordings, personal- exposure measurements, and geomagnetic-field measurements. Available normal-power magnetic-field data for residences differ substantially between studies. It is not known if these differences are due to geographical differences, differences in measurement protocols, or instrumentation differences. Wiring codes and measured magnetic fields (but not electric fields) are associated weakly. Available data suggest, but are far from proving, that spot measurements may be more effective than wire codes as predictors of long-term historical magnetic-field exposure. Two studies find that away-from-home TWA magnetic-field exposures are less variable than at-home exposures. The importance of home appliances as contributors to total residential magnetic-field exposure is not known at this time. It also is not known what characteristics (if any) of residential electric and magnetic fields are determinants of human health effects. — Environ Health Perspect 101(Suppl 4):121–133 (1993).

Key Words: 60–Hz, health effects, epidemiology, tutorial

Introduction

This paper first discusses methods and data that pertain to occupational exposures. It then reviews the literature on residential exposures and exposure assessment, describing known sources of residential power-frequency fields and the methods that have been used to assess residential exposures. This paper also identifies and discusses current problems in occupational and residential exposure assessment, with the twin goals of drawing conclusions where possible and developing working hypotheses for future study. Finally, this paper proposes areas where future research might prove of value.

Methods for Occupational Exposure Assessment

Job Titles

All occupational epidemiology studies to date have assessed exposure by using job titles or categories of job titles. Wertheimer and Leeper (*1*) mentioned in the very first epidemiology paper concerned with magnetic fields that they had examined published data on occupations and cause of death and had found an elevation in the cancer rate of electrical workers relative to the general population. This category of workers included job titles such as power station operators, linemen and servicemen, electricians, and welders.

The first major study was reported by Milham (*2*), who stratified deaths by occupation in the state of Washington for the period 1950 through 1979 and found that electrical workers tended to have higher than expected mortality from leukemia. His classification of electrical workers was similar to that used by Wertheimer and Leeper.

Perhaps because occupational studies like the two described above require little field work and are, therefore, relatively inexpensive to perform, a substantial number have been reported in the literature. Several reviews of these studies have been published (*3–6*). Many of these studies found elevated rates of certain cancers among individuals holding electrical-worker job titles.

Because none of these studies reported exposure measurements, the connection between electrical-worker job titles and elevated exposures to electric and/or magnetic fields, while plausible, was unproven. Two occupational exposure studies have been performed that deal with this question (*7,8*).

Occupational Exposure Measurements

Deadman et al. (*7*) had 20 workers, with six electric utility jobs that were deemed to involve elevated exposure to power-frequency electric and magnetic fields, wear personal-exposure meters for periods of 1 week. This group consisted of 10 distribution linemen, three transmission substation electricians, two transmission linemen, two cable splicers, two apparatus mechanics, and one power plant worker. In addition, the authors had 16 electric-utility office workers from two different buildings wear meters for 1-week periods. The resulting data were divided into work,

Table 1. Measured work, nonwork, and sleep exposures of electric utility workers whose jobs involve, or do not involve, work near facilities used to generate, transmit, and distribute bulk electric power (*7*).

	Geometric mean electric field, V/m			Geometric mean magnetic field, μT		
Group	Work	Nonwork	Sleep	Work	Nonwork	Sleep
Exposed utility workers	48*	11	11	1.7*	0.31	0.16
Office workers	5	11	19	0.16	0.19	0.14

*Exposed group significantly higher than office workers

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nonwork, and sleep periods. (During sleeping, the meter was not worn but was placed near the bed.) Time-weighted-average (TWA) exposures were calculated for each subject for these three periods.

The 20 electric utility workers studied by Deadman et al. would, in all likelihood, be included in anyone's definition of electrical workers. Consistent with this assignment, Deadman et al. found that these workers were exposed more highly while at work (Table 1). However, the nonwork and sleep exposures of the utility and office workers were the same (Table 1).

The results of Deadman et al. suggest that job titles might be a good surrogate for electric and magnetic field exposures. However, these data cover only a few highly exposed job titles within the much larger cohort of electrical workers and, therefore, do not provide a very strong test of this hypothesis.

Bowman et al. (*8*) measured spot electric and magnetic fields at 105 electric utility, aerospace, municipal government, motion picture theater, and television repair work sites. Their survey included at least one worker from every job title in Milham's 1982 electrical-worker category except for aluminum workers and conductors and motormen on urban rail systems. To provide a basis for comparison, electric and magnetic fields also were measured at 181 sites in 18 residences. The electric- and magnetic-field data are summarized in Tables 2 and 3, respectively.

The geometric mean electric and magnetic fields measured in the job sites of electrical workers were 5 V/m (Table 2) and 0.5 μT (5 mG) (Table 3), respectively. The comparable numbers for the residential measurements were 2.5 V/m and 0.06 μT (0.6 mG). The difference in electric-field exposures was due entirely to utility jobs that involved work around high voltages (overhead line and transmission and distribution substation workers). Apparently, the job-title class electrical worker is not an effective surrogate for electric-field exposure.

The difference between the occupational and residential magnetic fields in Table 3 was reliable statistically. All of the electrical workers had higher measured fields at their work sites except for electrical engineers and technicians working in offices and calibration laboratories, radio dispatchers, and microelectronic assemblers. Apparently, electrical workers, as a group, are exposed somewhat consistently to elevated magnetic fields.

There are several large projects currently examining exposures that occur in the telephone and electric utility industries. Consequently, it should be possible in a few years to discuss much more intensively occupational exposures to power-frequency electric and magnetic fields.

Table 2. Occupation and residential exposures to ELF electric fields (*8*).

			Magnetic field, μT	
Job class	Environments	*N*	Geometric mean	Range
Electricians	Industrial power supply	1	4	—
Power line workers	Underground lines	2	0.8	0.5–1.2
	Overhead lines	2	158	120–206
	Home hook-ups	13	4	0–71
Welders/flame cutters	TIG	1	2	—
Power station operators	Transmission stations	3	290	165–621
	Distribution substation	3	72	22–222
	Generating station	7	0.4	0–4
	Control rooms	4	1	0.3–24
Electronic assemblers	Sputtering	1	6	—
	Soldering	2	8	8–9
	Microelectronics	2	2	0.8–3
Projectionists	Xenon arc	4	1	0–2
Forklift operators	Battery powered	1	0.2	—
Electronics engineers and technicians	Laser lab	4	2	0.6–8
	Calibration lab	4	2	0.5–4
	Office	1	1	—
Radio and TV repairers	Repair shops	11	45	4–110
Radio operators	Dispatchers	1	1	—
Electrical workers	All	67	5	0–620
Residential	In homes	178	2.5	0–79

Table 3. Occupation and residential exposures to ELF magnetic fields (*8*).

			Magnetic field, μT	
Job class	Environments	*N*	Geometric mean	Range
Electricians	Industrial power supply	1	10	—
Power line workers	Underground lines	3	5.7	3.8–9.1
	Overhead lines	2	4.2	3.2–5.7
	Home hook-ups	14	0.11	0.004–1.2
Welders and flame cutters	AC	4	4.1	2.4–9.0
	DC	4	0.65	0.4–1.6
Power station operators	Transmission stations	3	3.9	1.6–7.2
	Distribution substation	3	2.9	0.7–5.4
	Generating station	12	0.60	0.01–12
	Control rooms	8	0.21	0.1–0.4
Electronic assemblers	Sputtering	2	2.4	1.4–4.3
	Soldering	2	0.13	0.13–0.16
	Microelectronics	3	0.003	0.001–0.006
Projectionists	Xenon arc	7	1.4	0.1–4.5
Forklift operators	Battery powered	9	1.2	0.09–125
Electronics engineers and technicians	Laser lab	9	1.1	0.2–20
	Calibration lab	4	0.06	0.05–0.07
	Office	1	0.02	—
Radio and TV repairers	Repair shops	11	0.63	0.1–2.6
Radio operators	Dispatchers	3	0.03	0.02–0.04
Electrical workers	All	105	0.50	0.001–125
Residential	In homes	181	0.06	0.005–1.1

Sources of Residential Fields

The Electric Power Research Institute (EPRI) is executing a program to identify and characterize residential and nonresidential sources of power-frequency magnetic fields. This program started with a pilot study (*9*), and it is continuing with the characterization of the fields in 1000 residences selected randomly from a clustered sample of EPRI-member utilities. The pilot study identified the following five classes of residential fields sources: electric power transmission lines, electric power distribution lines, ground currents, home wiring, and household appliances. These are discussed in the next five sections.

Electric Power Transmission Lines

Electric power transmission lines operate at very high voltages (usually ≥50,000 volts, abbreviated 50 kilovolts or 50 kV) and may carry currents of many hundreds of amperes. Thus, these lines can produce relatively strong electric and magnetic fields. The exterior walls and roofs of most homes are fairly effective shields for electric fields (*10*), but they have little, if any, effect on the magnetic fields produced by power lines.

The magnetic field produced by a three-phase transmission line outside its right-of-way, where most human exposure occurs, usually can be calculated satisfactorly using the following formula (*11*):

$$B = \frac{I}{5R^2}\sqrt{\frac{S_{12}^2 + S_{13}^2 + S_{23}^2}{2}}, \qquad [1]$$

where B is the field's resultant flux density in µT, I is the current in amperes carried by each of the three phase conductors (these currents almost are equal for transmission lines), R is the distance in meters from the line to the point where the field is being calculated, and S_{ij} is the transverse distance in meters between the ith and jth conductors. This formula is valid when R is substantially larger than any of the S_{ij}.

The most common transmission line configuration has all three conductors arrayed in either a horizontal or a vertical plane. Equation 1 then simplifies to

$$B = \sqrt{3}sI/(5R^2) \qquad [2]$$

where s is the distance between adjacent conductors.

Figure 1 shows the fields produced 1 m above ground level by typical 115 kV (lower voltage) and 345 kV (higher voltage) transmission lines carrying currents of 300 A. Magnetic flux densities are shown for various horizontal distances from the lines. Note that fields ≥0.1 µT (≥1 mG) are produced up to about 70 m and 100 m from the 115 kV and 345 kV lines, respectively.

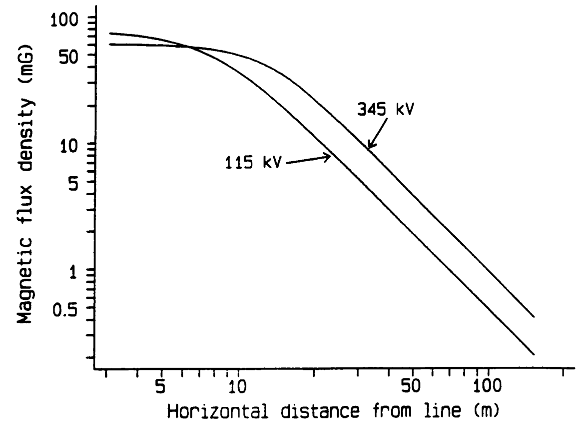

Figure 1. Magnetic fields produced by typical 115-kV and 345-kV transmission lines carrying

Electric Power Distribution Lines

Electric power generally is carried by electric power transmission lines to receiving substations located within a few kilometers of the ultimate consumers. At these substations, the voltage is reduced from transmission to distribution levels (4–34 kV), and the power is distributed on primary distribution lines to the immediate vicinity of the consumers. At this point, distribution transformers further reduce the voltage to the level of ultimate consumption (110–220 V for residential customers, 110–480 V for most commercial customers). Power is carried from distribution transformers on secondary distribution lines. Service drops to each customer are connected normally to the secondary distribution lines. Some may originate directly from the distribution transformer. While most primary and secondary distribution in the United States is by overhead lines, it is common for new installations to be underground.

Primary distribution lines can be either three-phase, two-phase, or single-phase. The first two of these categories are subdivided further into those lines with and without associated neutral conductors. Neutral conductors are operated at zero voltage (but not zero current) by connecting them to the earth (usually at many points) using ground rods or equivalent structures.

Because of their lower voltages, the conductors of distribution lines are placed much closer together than the conductors of transmission lines. Also, it is usual for distribution currents to be considerably less than transmission-line currents. Consequently, Equation 1 predicts that distribution lines will not, in most cases, produce magnetic fields much above ambient levels in areas that normally would be occupied by people. However, in practice, this is not always true because of the existence of net currents on some distribution lines.

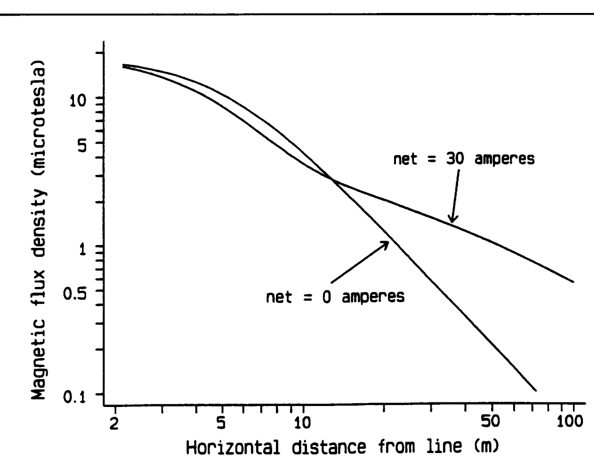

Figure 2. Magnetic field produced by typical primary distribution line carrying 100 A of load current in each phase conductor and net currents of either 0 or 30 A.

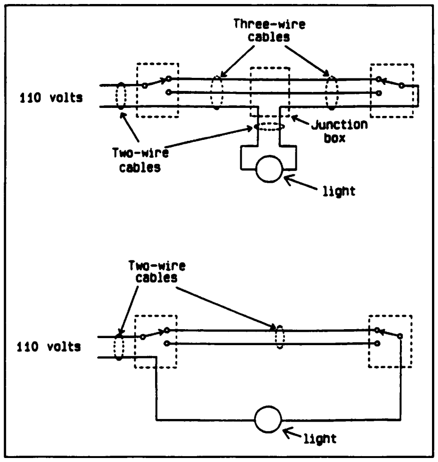

Figure 3. Alternative methods to control an electric light with two different (3-way) switches. The bottom installation could be a significant residential source of magnetic fields.

The net current, I_{net}, being carried by a power line is defined to be the algebraic sum of all the conductor currents. (This sum must be calculated taking into account both the magnitudes and phases of the individual currents.) In principle, I_{net}, = 0 for transmission and distribution lines. While this is nearly true for most transmission lines, it can be far from correct for primary and secondary distribution lines because of ground currents.

Net current is important because the magnetic field, B_{net}, produced by it depends on distance, R, from the line as $1/R$ and is, therefore, spatially more persistent than the magnetic fields produced by normal power-line currents. This is illustrated in Figure 2, which shows the fields produced by a distribution line carrying a load current 100 A and a net current of either 0 or 30 A.

Ground Currents

Ground and net currents produce spatially persistent fields. A point where current frequently enters the ground is at the service entrance of a residence because safety codes require that the neutral conductor be grounded at this point. This ground may be to a rod driven into the earth, but it is often to a metal water pipe. Often, the electrical service entrance is at the rear of a home, and the water main is in front of the home, so ground current in the water system must pass under the home. This current is not compensated by any return current in the vicinity, so its magnetic field is proportional to $1/R$. Individuals in a home may be exposed to magnetic fields from this source.

Wiring in a Home

Home wiring is not usually a significant source of magnetic-field exposure because the two wires connecting to a household load (e.g., a light or appliance) are located very close together and carry equal and opposite currents. However, there are unusual wiring configurations where this is not true. Of those known to the author, the most common are some three-way switch installations and homes having two or more separated circuit breaker panels.

Three-way switches are used where it is desired to control a load from multiple points. The most common application is probably lights that can be turned on or off from either end of a hall or stairway. Figure 3 shows two alternative ways that an installation could be made to control a light from two different switches. In the upper diagram, the various wires are routed in multiwire cables so that the net current in any of the cables is zero. Consequently, the magnetic fields from the conductors in any cable largely cancel, with the result that this installation would not be a significant source of residential magnetic fields. A different installation—one requiring less total wire—is shown in the lower panel of Figure 3. Here, a separate wire is routed from each switch directly to the light, and the direct connections between switches are made with a two-wire cable. However, this cable, and the wires connecting to the light, will carry a net current—the entire current required to energize the light. If these two elements are separated significantly, the magnetic field in their vicinity could be significant. (The author has studied a home where turning on a hall light raised the field from about 0.01 μT to 0.5 μT.)

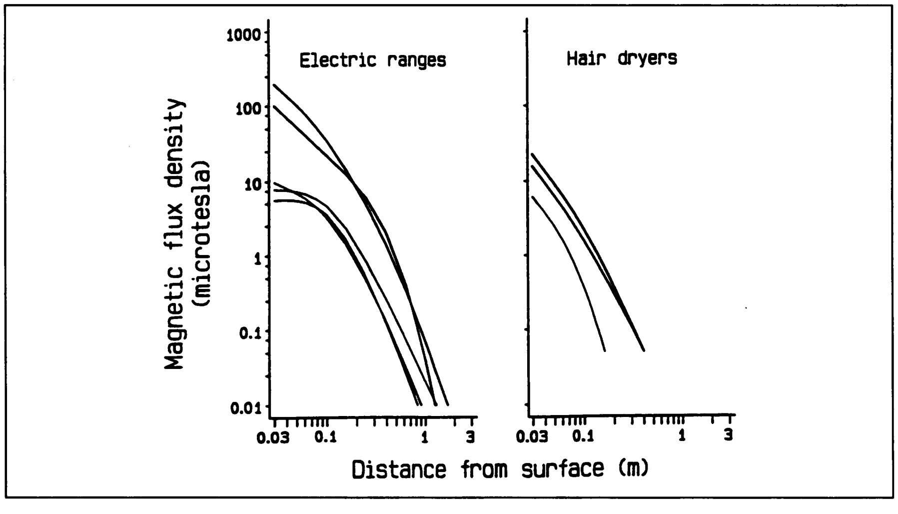

Figure 4. Magnetic fields produced by five electric ranges and three hand-held electric hair dryers. Fields are shown as function of distances from surfaces of appliances.

As mentioned earlier, U.S. building codes require that the neutral bus in the main circuit-breaker (or fuse) panel protecting a home's electrical system be grounded. Some homes have multiple panels, usually because an addition to the home required more electric power than could be supplied by the original panel. Many electricians automatically will ground the neutral bus in these subpanels, creating two routes for current flow between the main and grounded subpanel, one through the neutral conductor connecting the two panels, the other through the ground. In this way, local net currents can be formed with the production of spatially more persistent fields, as explained above.

Home Appliances

The magnetic fields produced by many home appliances can be quite strong in their immediate vicinity, but these fields also are localized in space. Figure 4 shows magnetic-field data from Gauger (*12*) for five electric ranges (left graph) and three hand-held electric hair dryers. Note that the fields produced by these appliances were all less than 0.1 μT (1 mG) at distances from them exceeding 1 m. This is a characteristic of the fields from most household appliances (*12*) because of their small size, and because the magnetic fields produced by localized current sources decay as $1/R^3$ when R is large (*13*).

At this time, the relative importance of home appliances as sources of human exposure to magnetic fields is controversial. Some maintain that home appliances are important, if not the dominant, sources of exposure of humans to residential magnetic fields, while others argue that most appliance sources are unimportant. Although this controversy continues, there is general agreement that a few home appliances do contribute significantly to exposure. For example, most electric blankets clearly lead to significant whole—or near whole—body exposure because the distance between a

Table 4. Methods used to assess exposure to power-frequency electric and magnetic fields in published epidemiological studies.

Reference	Disease	Questionnaire	Wiring configuration	Theoretical estimates	Spot measurements	Fixed-site recordings	Geomagnetic field measurements
Wertheimer and Leeper (*1*)	Childhood cancer		yes[a]				
Fulton et al. (*18*)	Childhood leukemia			yes			
Wertheimer and Leeper (*14*)	Adult cancer		yes[b]				
McDowall (*33*)	Cancer			yes			
Tomenius (*19*)	Childhood cancer			yes	Outside front door		
Wertheimer and Leeper (*34*)	Fetal development	On electric blanket use					
Coleman et al. (*35*)	Adult leukemia			yes			
Severson et al. (*21*)	Adult leukemia	On appliance use	yes[b]		Inside home		
Savitz et al. (*17*)	Childhood cancer	On appliance use	yes[b]		Inside home		
Preston-Martin et al. (*36*)	Adult leukemia	On electric blanket use					
Myers et al. (*37,20*)	Childhood cancer			yes[c]			
Verreault et al. (*38*)	Testicular cancer	On electric blanket use					
London et al. (*25*)	Childhood leukemia	On appliance use	yes[b]		Inside and outside home	24-hr in bedroom	In child's bedroom

[a] Using the two-category Wertheimer-Leeper code

[b] Using the four-category Wertheimer-Leeper code

[c] Calculated magnetic field on basis of distance and line loading

Table 5. Published research studies on methods to assess human exposure to residential power frequency electric and magnetic fields.

Reference	Wiring configuration	Theoretical estimates	Spot measurements	Fixed-site recordings	Personal exposure measurements
Caola et al. (*39*)			yes		
Kaune et al. (*15*)	yes[a,b]		yes	In bedroom and family room	
Male et al. (*40*)			yes	In home	
Deadman et al. (*7*)					7-day at home and work
Bowman et al. (*8*)			yes		
Barnes et al. (*16*)	yes[a]	yes	yes		
Dlugosz et al. (*26*)	yes		yes		
Delpizzo (*28*)		yes			
Mader et al. (*41*)		yes			
Kaune et al. (*27*)	yes[a]		yes	yes	24-hr AMEX-3D at home and school
Kavet et al. (*22*)		yes	Inside and outside home	24-hr in bedroom	24-hr EMDEX at home and work

[a] Using the four-category Wertheimer-Leeper code

[b] Developed an alternative code

Table 6. Definition of Wertheimer-Leeper Wiring Code.[a]

Wiring structure	VHCC	OHCC	OLCC
Transmission line Thick 3-phase primary ≥ 6 primary phase wires	≤50 ft (15.2 m)	≤130 ft (39.6 m)	
Thin 3-phase primary	≤25 ft (7.6 m)	≤65 ft (19.8 m)	≤130 ft (39.6 m)
First-span secondary		≤50 ft (15.2 m)	≤130 ft (39.6 m)
Second-span secondary (not end pole)			≤130 ft (39.6 m)

[a]Houses not falling in VHCC, ONCC, or OLCC categories are in VLCC

user and an electric blanket is small relative to the blanket's dimensions (so the $1/R^3$ law does not apply) and because blankets are used by many for the entire nighttime period. (Recently, manufacturers have developed new blanket designs that greatly reduce their magnetic fields.)

Methods of Residential Exposure Assessment

Most research related to the assessment of residential exposures to power-frequency electric and magnetic fields has occurred in conjunction with on-going epidemiologic studies. Table 4 is a list of epidemiologic publications from these studies that present exposure-assessment data and techniques. Table 5 provides a list of publications whose primary purpose is to report results related to exposure assessment.

All residential assessments of exposure to power-frequency fields have used one or more of the following techniques: questionnaire, wiring configuration coding, theoretical estimation of fields produced by nearby electrical facilities, spot electric- and magnetic-field measurements, electric- and magnetic-field recordings at fixed locations covering periods of time from hours to days, personal-exposure measurements, and geomagnetic-field measurements. The exposure-assessment methods used by published residential studies are enumerated in Tables 4 and 5.

Questionnaires

Questionnaires have been used in residential studies to assess exposure to the power-frequency magnetic fields produced by electric blankets and other home appliances. Typically, a case or control subject (or a relative or care giver) would be questioned about their (or the subject's) pattern of use of these sources.

Wiring Configuration Coding

The first method developed for exposure assessment was the wiring configuration coding system of Wertheimer and Leeper (*1,14*). Originally criticized by many, this method has stood the test of time. Research has shown that wiring code is correlated with measured magnetic fields (but not electric fields) in residences (*15,16*). The code now normally in use was defined originally in Wertheimer and Leeper's 1982 paper (*14*). The types of overhead electrical wiring that enter into the code are transmission lines, three-phase primary distribution lines, and secondary distribution lines.

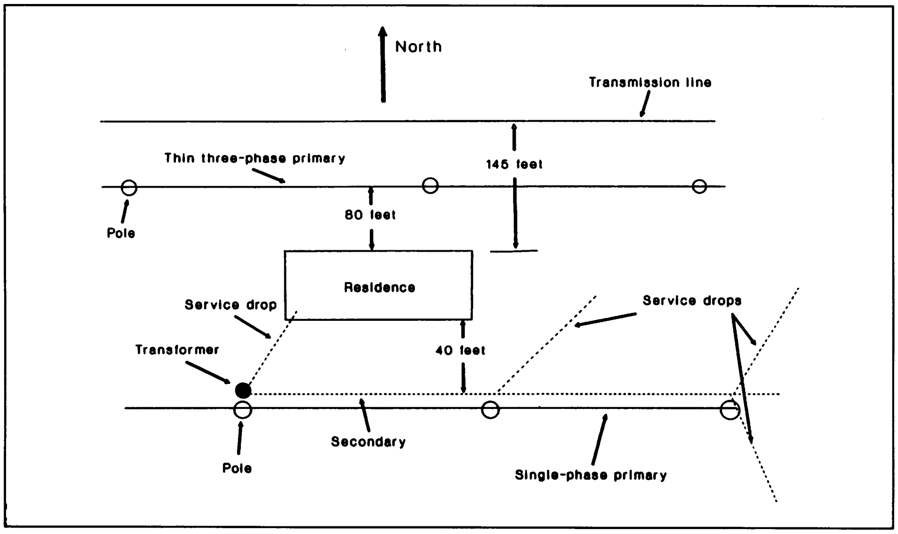

Figure 5. Schematic plan view of residence and electric power transmission and distribution wiring in its vicinity. Distances are not to scale.

Primary distribution lines are divided into thick and thin lines according to whether or not their phase conductors are clearly larger in diameter than the standard secondary wire used in the Denver, Colorado, area (*14*). An alternative and more quantitative definition of thick and thin has been developed in terms of the ampacities (i.e., current-carrying capacities) of conductors used for primary distribution (*15*). This technique is appropriate when the wire materials and gauges can be determined. Visual discrimination of thick and thin conductors is the most subjective element in wire coding.

Sections of secondary distribution lines are further categorized as being first-spans or second-spans. A first-span secondary is that length of an overhead secondary distribution line extending from the pole on which the line's distribution transformer is located to an adjacent pole, which also is carrying electric power to more than two residential loads or one or more commercial loads. Secondaries not meeting this condition are called second-span secondaries. (Sometimes, the term short first-span secondary is used for a first-span not supplying sufficient load to be classed a first-span secondary.)

Wire coding consists of identifying transmission and distribution lines and measuring the distance of closest approach of each to the home being coded. Table 6, then, can be used to code each structure, and the final code for the home is taken as the highest of the codes for each of the lines. There are four possible codes: very high current configuration (VHCC), ordinary high current configuration (OHCC), ordinary low current configuration (OLCC), and very low current configuration (VLCC).

The process of wire coding is illustrated in Figure 5, which shows a schematic-plan view of a residence and the electrical wiring surrounding it. A transmission line passes within 145 ft (44.2 m) of the home. According to Table 6, this structure would be coded VLCC. The thin three-phase primary line passing 80 ft (24.4 m) north of the home is coded OLCC. The single-phase primary passing 40 ft south of the home is not coded at all in the Wertheimer-Leeper system (only three-phase primaries are coded). The pole southeast of the home has a transformer mounted on it that supplies a secondary line that passes by the home. The segment of this secondary passing by the house carries the power for three service drops. Consequently, this segment is a first-span secondary and is coded OHCC. Because the highest structure code is OHCC, the home is coded OHCC.

In practice, wire coding can sometimes be difficult. The most difficult and time-cosuming part of wire coding is the identification of first-span secondaries. The wires in a secondary often are bundled together, making it difficult to see details from the ground, and the coder's view of these wires often is obscured by trees. It also is sometimes difficult to determine where one secondary ends and another starts. Nevertheless, with all these difficulties, it is possible to train technicians to code reliably electrical wiring using the Wertheimer-Leeper method. For example, Savitz et al. (*17*) obtained 95% agreement between independent codings of homes made by trained technicians.

Houses served by underground primary wiring were placed in the VLCC category by Wertheimer and Leeper (*14*). Other researchers have chosen to treat houses with underground wiring as a fifth category (*17*).

Because magnetic fields are produced by electric currents, the overt purpose of wire coding is to discriminate between wiring configurations that carry, on the average, different levels of current. As described earlier, transmission lines are significant sources of magnetic fields, so their treatment in the Wertheimer-Leeper wiring code seems reasonable. This conclusion is not certain for primary and secondary distribution lines because, as noted earlier, net currents on these lines often are the primary sources of their magnetic fields, and net currents depend on the type of distribution line (whether or not it has a neutral) and local grounding practices. It may be that there is a statistical association between the total and net currents carried by distribution lines, which could explain the apparent ability of the Wertheimer-Leeper code to capture magnetic field levels produced by distribution lines.

Theoretical Estimation

The strength of the electric and magnetic fields produced by electrical facilities, such as power lines, transformers, and substations, depends in a known way on the system voltage, current, and geometry. Thus, assuming these parameters are known, one can calculate the electric and magnetic field produced at any distance from a source. Several studies have used this approach to assess magnetic-field exposure in residences located close to power lines.

Fulton et al. (*18*) used a combined theoretical and empirical method for their exposure assessment. They determined the closest distance, *R*, of approach of every power line passing within 45.7 m (150 ft) of a house under study. They placed the wires of each line into one of the following four classes: high tension (i.e., belonging to a transmission line), large-gauge (thick) primary, small-gauge (thin) primary, and secondary. They assigned to these classes nominal field values based on data published in Wertheimer and Leeper's original 1979 paper. They then weighted these nominal values by the quantities $1/R^2$ to allow for different distances between sources and the home under study, and they summed the weighted contributions from all sources.

Tomenius (*19*) simply noted in his study whether there was a visible electrical facility (6–200 kV high-voltage wires, substations, transformers, electric railroads, and subways) within 150 m of each home. (The actual epidemiological analysis performed by Tomenius defined exposure solely in terms of proximity to electric power transmission lines.)

Myers et al. (*20*) measured the distances between homes occupied by subjects of their study and all power lines (secondaries, primaries, and transmission lines) located in their immediate vicinities. In conjunction with the utilities operating these power lines, the authors estimated the load currents in each line, assumed these currents were balanced (i.e., equal currents in all phase conductors of a line), and calculated the resulting magnetic fields 1 m above ground at the center of each dwelling.

Spot Electric and Magnetic Field Measurements

A spot measurement is defined to be a measurement at a fixed location (usually inside a residence) that occurs over a period of time less than a few minutes. Survey meters customarily have been used for these measurements, but some studies now in progress are using personal exposure meters for this purpose. Savitz et al. (*17*) and Severson et al. (*21*) used identical plastic fixtures to position Model 113 survey meters (Electric Field Measurements Company, Lenox, MA) in three orthogonal directions to measure the three vector components of electric field and magnetic flux density.

Savitz et al. (*17*) and Severson et al. (*21*) jointly introduced the notion of low- and high-power spot measurements. Low-power spot measurements were made after electric power consumption in a home was reduced (by turning off lights and appliances) to as low a level as practical. These measurements were interpreted as being most reflective of magnetic fields produced by sources outside the residence under study. Similarly, high-power measurements were made after as many lights and appliances as possible were energized. These latter measurements were thought to contain maximal contributions from field sources inside the home.

Fixed-Site Magnetic-Field Recordings

Kaune et al. (*15*) made the first published fixed-site recordings in 43 Seattle residences using a data acquisition system constructed for this purpose. Three magnetic field sensors and one electric field sensor were located at fixed positions in each home, and data from these sensors were recorded on magnetic tape at 2-min intervals for a 24-hr period.

With the advent of small, battery-powered data acquisition systems, such as the EMDEX family of meters, longer term measurements have become much less intrusive and, thus, more practical. Tables 4 and 5 list studies that have reported fixed-site recordings.

Personal Exposure Measurements

Although EMDEX and IREQ/Positron personal exposure meters have been available for several years, only two studies that the author is aware of have published residential personal exposure data (Table 5). In both of these, subjects were asked to wear personal-exposure meters for periods from 24 hr (*22*) to 7 days (*7*). There are currently several studies underway that are collecting large amounts of personal exposure data.

Geomagnetic Field Measurements

Blackman et al. (*23*) published a paper reporting that a biological response elicited in the laboratory by exposure to extremely low frequency electric and magnetic fields was apparently also affected by the strength of the static geomagnetic field (i.e., earth's magnetic field). These authors found that the response occurred only when the frequency of the alternating exposure fields lay in certain bands, and they showed that the frequencies of these bands were dependent on the geomagnetic field (i.e., the static-magnetic field, usually due largely to the earth's magnetic field). Because this model has had considerable success in describing a variety of laboratory results [summarized by Liboff et al. (*24*)], some have decided to incorporate geomagnetic field measurements as part of their residential exposure assessment protocol (*25*).

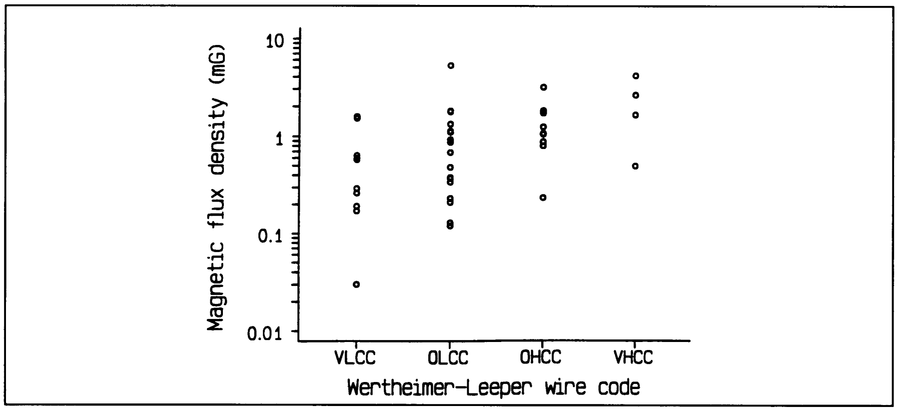

Figure 6. Scatter plot of 24-hr-average house magnetic flux densities and Wertheimer-Leeper wiring code. Data from Kaune et al. (*15*).

Current Issues in Exposure Assessment

This section discusses issues of current interest concerning the assessment of human exposure to power-frequency electric and magnetic fields.

Occupational Exposure Assessment

As related in the section "Job Titles," all published occupational studies have used job titles as surrogates for electric- and/or magnetic-field exposure. Separate research indicates that the exposures of electrical workers are, in fact, elevated relative to those received in most other occupations and at home (*7,8*). However, job titles, by themselves, must be regarded as a crude measure of exposure. There are certainly exposure differences within the general category of electrical workers or even within workers holding the same job title, differences that could perhaps be exploited to help detect the presence of confounders or dose–response effects.

What is needed in future occupational studies is a job-exposure matrix. In its simplest form, the rows of this matrix would be labeled by job titles, and a single column would contain exposure estimates for each job title. A more complex matrix could contain several columns, each for a different definition of exposure (i.e., a different exposure metric) or different latency periods for disease onset after exposure. A complete job-exposure matrix also should contain information about exposures unrelated to electric and magnetic fields. In particular, because many jobs that fall within the electrical workers category also involve the use of chemicals and possible exposures to fumes, it is important that data on these factors be included in the job-exposure matrix.

The construction of a complete job-exposure matrix is a daunting task. Electric- and magnetic-field measurements of current exposure in the job titles under study will be necessary in many, if not most, studies. In case–control studies, the exposure of interest occurred in the past. Consequently, historical changes in exposure patterns will have to be assessed during the construction of the job-exposure matrix. Such historical changes may be more pronounced for chemicals than for electric and magnetic fields.

Between-Study Variation of Spot and Fixed-Site Measurements

Magnetic field data from spot measurements and fixed-site recordings are summarized in Table 7 for seven studies. The low-power and high-power data (all from spot measurements) are from the Denver, Seattle, and Los Angeles metropolitan areas in the United States and seem reasonably consistent. However, the normal power data, consisting of spot measurements (*8,26*) and fixed-site recordings (*7,15,25*) show considerable differences between studies. For example, the geometric means measured by Deadman et al. (*7*) are about three times larger than those measured by Kaune et al. (*15*) and Bowman et al. (*8*). It is unknown if this difference is attributable to geographical differences, measurement protocol differences, or instrumentation differences. The data from Dlugosz et al. (*26*) are much larger than the other normal power data. However, these measurements were taken on the sidewalks outside homes and may reflect more strongly sources under and above city streets.

Wiring Codes and Measured Electric and Magnetic Fields

The Wertheimer-Leeper wiring code was developed to provide a surrogate measure of long-term historical exposure to power-frequency magnetic fields that could be obtained without entry into residences (*1,14*). Three studies have now been performed that report a statistically elevated risk of cancer for children living in high-current-configuration homes. Two of these studies (*1,17*) were performed in the Denver, Colorado, area, with different groups of children. The third study was performed in Los Angeles County (*25*). These findings have stimulated a strong interest in wire codes and in various physical factors that might be associated with wire codes.

Several published studies have found that wiring configuration is associated statistically

Table 7. Summary of published arithmetic and geometric means of magnetic field measurementsin and near residences.

	Magnetic flux density, µT					
	Low Power		Normal power		High power	
Study	AM[a]	GM[b]	AM[a]	GM[b]	AM[a]	GM[b]
Savitz et al. (*16,17*)	0.08[c,d]	—	—	—	0.11[c,d]	—
Severson et al. (*21*)	0.09[c,d]	—	—	—	0.11[c,d]	—
Kaune et al. (*15*)	—	—	0.10[d,e]	0.05[d,e,f]	—	—
Deadman et al. (*7*)	—	—	—	0.15[g,h]	—	—
Bowman et al. (*8*)	—	—	—	0.06[c,d]	—	—
Dlugosz et al. (*26*)	—	—	0.53[c,i]	0.40[c,i]	—	—
London et al. (*25*)	0.06[c,g]	0.03[c,g]	0.11[e,g]	0.10[e,g]	—	—

[a] Arithmetic mean
[b] Geometric mean
[c] Spot measurement
[d] Home average
[e] From 24-hr recording
[f] Estimated using median field
[g] Measurement in bedroom
[h] Recorded during sleeping period
[i] Measurement on street corner

with magnetic fields measured in homes. Wertheimer and Leeper, in both of their original studies (*1,14*), present magnetic-field data, measured outside homes, that show an association between wire code and magnetic-field levels. Kaune et al. (*15*) recorded electric- and magnetic-field data for 24-hr periods in the bedrooms and family rooms of 43 homes in Seattle, Washington. These authors observed no relationship between wire code and measured residential electric-field levels. However, there was an association between wiring code and residential magnetic fields (Fig. 6): Log-transformed averages of 24-hr mean magnetic fields were significantly different for different codes, with the largest differences being between the VLCC and OLCC taken as one group and the OHCC and VHCC as the other group. However, this model left unexplained 79% of the total variation between homes.

Barnes et al. (*16*) analyzed magnetic-field spot-measurement and wiring-configuration data from the Savitz et al. (*17*) study and reached a similar conclusion. These authors state:

> The proportion of variance in fields explained by the wire codes, however, is a rather modest 19%. In combination, these findings indicate that the relationship between fields and wire codes is well beyond chance but that the correlation is far from perfect.

In addition, London et al. (*25*) have reported recently that a relationship between the Wertheimer-Leeper wiring code, spot, and 24-hr magnetic-field measurements has been observed in Los Angeles County. This is interesting because utility distribution practices are different in many areas of Los Angeles County from those in the Seattle or Denver areas. In particular, the grounding system for a distribution line in Seattle and Denver is integrated along its entire length and typically might include 1000 to 2000 homes, whereas in Los Angeles, the grounding system for a secondary distribution line (typically serving 1–10 homes) may be electrically isolated. Thus, the Seattle, Denver, and Los Angeles results suggest that ground currents may not be an important source of residential magnetic fields or, at least, of that component of a residential field captured by the Wertheimer-Leeper code.

There is evidence that wiring codes only are associated weakly with spot measurements and fixed-site recordings of residential magnetic fields. It is tempting to conclude that, for epidemiological purposes, wiring code is a poor measure of magnetic-field exposure. While this conjecture ultimately may be proven true, its validity is not certain at this time. For epidemiological purposes, exposure generally is placed in categories (e.g., low and high) and the definitive test of wiring configuration (or any other surrogate measure of exposure) is its ability to place individual exposures in the correct category. It is important to realize that the ability of a measure to explain variability between homes is not the same as its ability to place homes correctly in exposure categories.

Relative Effectiveness of Wire Codes and Spot Magnetic Fields

Several authors have discussed the possibility that wire codes are better predictors of long-term historical exposure to magnetic fields than are spot or 24-hr measurements of the present magnetic fields in a residence (*4,1,14*). This notion is discussed in this section.

Wire codes seldom change over periods of months or years because utilities seldom change their transmission and distribution systems. In fact, the historical stability of wire codes is the reason most often advanced to explain their hypothetical superiority in assessing historical magnetic-field exposure. However, it seems that this property of wire codes will only be of virtue if long-term magnetic-field exposure is, itself, historically stable.

Assuming that long-term exposure is historically stable, we still need to explain why spot (or 24-hr) magnetic-field measurements are not historically stable indicators of human exposure to residential magnetic fields. There seem to be three possibilities: *a*) Spot measurements exhibit such large short-term variability that they are very poor indicators of mean magnetic-field levels, whether in the present or the past. *b*) The spatial variability of residential magnetic fields is so large that spot or 24-hr measurements, even if temporally stable, could not be used to assess present or past human exposure. *c*) Spot or 24-hr rmeasurements exhibit much greater long-term variation than does personal magnetic-field exposure. These three possibilities are discussed in the following paragraphs.

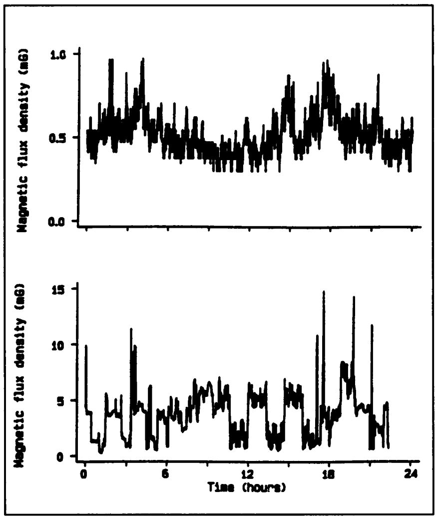

Figure 7. Magnetic fields measured in bedrooms of two homes during 24-hr periods.

Short-term Temporal Variability of Spot Measurements. Figure 7 shows magnetic field records, covering approximately 24 hr, taken in the bedrooms of two homes. These records, which consist of a large number of spot measurements taken one after another, clearly show short-term, apparently almost random, variation. Although the variability shown in this figure seems large, several groups have found that spot measurements taken at different times are strongly correlated.

Dlugosz et al. (*26*) made spot magnetic-field measurements during seven successive evenings on 33 street corners in Buffalo, New York. The intraclass correlation between these seven measurements was 0.94, indicating a high degree of stability

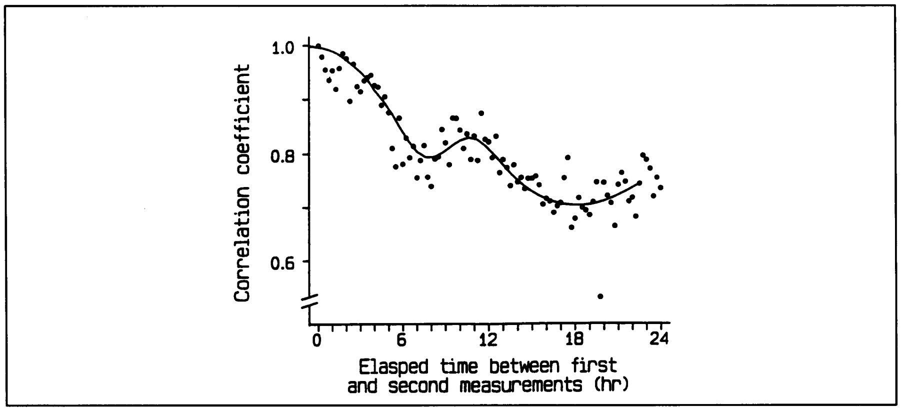

Figure 8. Correlation between spot measurements made at two different times in bedrooms of 29 homes.

Table 8. Geometric statistics for at-home and away-from-home personal exposures measured for young children by Kaune et al. (*27*) and Kavet et al. (*22*).

	Kaune et al.		Kavet et al.	
	Geometric mean, µT	Geometric, S.D.	Geometric mean, µT	Geometric, S.D.
At-home exposure	0.096	2.38	0.148	1.79
Away-from-home exposure	0.100	1.42	0.182	1.41

during the week. It should be noted that these data, alone, are far from conclusive because they were measurements taken outside homes where fields may be more stable.

Kaune et al. (*27*) recently obtained 24-hr EMDEX records in the bedrooms of young children living in 29 homes. These records were regarded as a series of spot measurements made every 15 min over 24-hr periods, and the correlations between two spot measurements separated in time by varying intervals were computed. Figure 8 shows the results of this analysis. Clearly, there is considerable stability between spot measurements made at two times separated by as little as 15 min or as much as 24 hr.

Delpizzo et al. (*28*) tested the ability of spot magnetic-field measurements to correctly classify exposure. In this case, exposure was defined in terms of the 24-hr average magnetic field measured in 40 homes. Exposure was termed either high or low, depending on whether it was greater than or less than 0.075 µT (0.75 mG). The authors then classified exposure using a single spot measurement and found that this technique had at least an 80% chance of classifying homes correctly. Furthermore, this probability was not significantly increased as the number of spot measurements used to estimate exposure was increased above one.

Thus, available data suggest that spot measurements may be rather stable over periods up to one week in length.

Correlation of Spot and Personal Exposure Measurements. The second possibility enumerated above to explain why wiring coding might be a better estimator of historical long-term exposure than a spot or 24-hr measurement is that the spatial variability of the magnetic fields in a residence might be so great as to render a spot value ineffective as a measure of residential human exposure. However, available data suggest that this might not be the case.

Kaune et al. (*27*) found that a time-weighted average of a bedroom spot (or 24-hr) measurement, a kitchen spot measurement, and a family-room spot measurement were well correlated with the measured personal exposures (measured using AMEX-3D meters) of 29 young children. (The correlation coefficient between the log-transformed measured and predicted exposures was 0.8.) Wiring code, on the other hand, was associated weakly with the measured exposures.

Kavet et al. (*22*) made the following measurements in 45 homes: spot measurements in at least three rooms of each home, 24-hr fixed-site bedroom measurements, and 24-hr personal exposure obtained by asking an adult resident to wear an EMDEX meter. Thirty of the 45 subjects lived close to transmission lines, so their data may not be representative. Limiting analysis to those 15 who lived away from transmission lines, the correlation between the measured at-home log-transformed exposures and the log-transformed averages of the spot measurement taken in each home was 0.77. (The comparable correlation for the entire sample of 45 homes was 0.76.)

Two exposure assessment studies, both with only small numbers of subjects, do not provide a substantial basis on which to make any firm conclusions. Nevertheless, if the trend continues—spot measurements predict contemporaneous exposures better than wiring code—it will become progressively more difficult to argue that wiring code is a better predictor of long-term magnetic-field exposure than spot measurements.

Long-term Variation of Spot Measurements. The third possibility introduced above to explain why wire codes might work better than spot measurements to assess long-term historical exposure of people to residential magnetic fields is that spot measurements might exhibit more long-term variability than does exposure. This issue has been examined experimentally for the first time by a recent study (*29*) in which a new set of measurements were made during 1990 in 80 Denver-area homes that were part of the original Savitz study (*17*). This study found correlations of 0.71 and 0.75 respectively, between their log-transformed low- and high-power spot measurements and those made by Savitz et al. in 1985. This level of correlation was present in both high-current configuration and low-current configuration strata. Linear regression analysis showed that the slopes of the relationships between the 1985 and 1990 low-power and high-power spot measurements were near 1.0. Apparently, spot measurements in Denver are remarkably stable over a 5-year period.

Let us now return to the original question: Are wiring codes or spot measurements a better method of assessing long-term historical exposure to power-frequency magnetic fields? First, evidence from three studies suggest that short-term variability in spot measurements is not large enough to render them ineffective estimators of TWA exposure. Second, evidence from two studies suggest that spot measurements are as, or more, effective than wire codes in assessing concurrent TWA exposure. Third, one study found that spot measurements made in 80 Denver homes about five years apart are correlated well. These results, while far from conclusive, seem to offer evidence suggesting that spot measurements may be at least equivalent to, if not superior to, wire codes as measures of historical TWA exposure to residential magnetic fields.

At-Home and Away-From-Home Exposures

Two new studies have measured separately the residential and nonresidential components of the total exposure of children and adults to power-frequency magnetic fields. Kaune et al. (*27*) had 29 young children (ages 4 months through 8 years) wear AMEX-3D meters for 24-hr periods. Each child was given two meters, one to be worn while at home, the other while away from home. The cumulative exposure measured by each meter was divided by the total time it was worn, yielding the TWA magnetic field to which it was exposed. Table 8 presents geometric means and standard deviations summarizing these two components of total exposure. Note that the geometric mean exposures at home and away from home were both about 0.1 µT (1 mG), but that the geometric standard deviations for these two exposures were very different, with the at-home component being much more variable than the away-from-home component. That is, most of the differences in exposure between subjects occur during their time at home rather than when away from home.

Kavet et al. (*22*) measured residential and nonresidential exposures for 45 adults. Geometric statistics summarizing the at-home and away-from-home exposure fields for the 15 subjects who did not live close to transmission lines also are given in Table 8. The same pattern is observed in these adult data: The at-home component of exposure is more variable than the away-from-home component.

The results discussed in the preceding two paragraphs were quite surprising. They suggest the possibility that total time-weighted exposures of children and adults can be categorized accurately by studying only their residences. If valid, this would be a very important result; but at this time, it should be regarded only as a working hypothesis. Considerable additional research is needed to test this result among other populations.

Table 9. Statistics for at-home personal exposure measurements and residential spot measurements made in 45 homes by Kavet et al. (*22*).

	Arithmetic statistics		Geometric statistics	
	Mean μT	S.D. μT	Mean μT	S.D.
At-home personal exposure	0.18	0.12	0.15	1.79
Spot measurements	0.13	0.13	0.08	2.95

Table 10. Correlation among selected magnetic field exposure indices during nonwork hours (*32*).

Exposure index	Correlation with TWA exposure
Geometric mean	0.74
Median	0.69
Peak (largest recorded field)	0.64
99th percentile	0.69
90th percentile	0.80
Percent above 0.78 μT	0.68
Percent below 0.20 μT	0.79
Percent in range 0.78–1.56 μT	0.57
Percent in range 0.20–0.39 μT	0.69

[a] Data are from 36 subjects

Contribution of Home Appliances to Residential Exposures

Questions about the importance of home appliances to residential exposures have been raised for years. It is well known that appliances such as hair dryers, curling irons, and electric razors can deliver substantial short-term partial-body exposures to their users. However, it is not clear that TWA exposure is affected substantially by these sources. Delpizzo (*30*) has performed a theoretical analysis of exposure to electric blankets, waterbed heaters, and concrete slab heaters, and concludes that these sources can make significant contributions to total exposure.

One way to examine this question is to compare magnetic fields measured with a personal-exposure meter (which presumably captures appliance contributions) to spot measurements (which are generally made to exclude appliance contributions). This comparison can be performed using the data (Table 9) of Kavet et al. (*22*). A *t*-test on log-transformed data confirms that the at-home exposure values are significantly larger (p = 0.0004) than the spot fields, suggesting the presence of significant appliance contributions to personal exposure. However, many additional data are needed to confirm this observation.

Exposure Metrics

An exposure metric is a function of an applied electric or magnetic field that yields a value useful for predicting or describing a biological response of interest. The simplest and most widely used metric is TWA exposure, in this case, the average electric or magnetic field during the period of exposure. But there are other possibilities. For example, exposure assessment for radio-frequency electromagnetic fields commonly uses the square of the electric- or, sometimes, of the magnetic-field strengths.

Past epidemiological studies, as well as most laboratory studies of electric and magnetic fields, have used TWA-field strength as their explicit or implicit measure of exposure. The validity of this approach is currently being questioned because of several recent developments: *a*) Some biological responses observed in the laboratory exhibit a complex dependence on intensity and frequency of the exposure field (e.g., intensity and frequency windows) as well as on the strength of the static magnetic field. *b*) Some biological systems may be sensitive to a power-frequency magnetic field only when its strength is abruptly changed (*31*). *c*) The use of TWA magnetic-field exposure to explain the relationship between wire code and childhood leukemia has not proven fruitful (*25*).

Because of the considerations listed in the preceding paragraph, some effort has been devoted to identifying characteristics of residential or occupational magnetic fields, other than TWA exposure, that might serve as alternative exposure metrics. Presumably it would be desirable to identify metrics that are not correlated strongly with TWA exposure, but this might be a difficult goal to achieve. Armstrong et al. (*32*) calculated correlations between a wide variety of electric- and magnetic-field exposure indices and found, for nonwork exposures, that many were well correlated with TWA exposure (Table 10).

One alternative that was not considered by Armstrong et al. (*32*), and is discussed frequently, is exposure to temporally fluctuating magnetic fields. This concept is illustrated in Figure 9, which shows actual 24-hr magnetic-field recordings taken in two homes (*27*). In both cases the TWA fields were about 0.36 μT (3.6 mG), but the short-term variability of the field in the upper chart was clearly much greater than that in the lower. It would not be difficult to invent a metric function to discriminate between these two exposures.

Research Recommendations

This section identifies research areas where progress can be made to improve and clarify exposures and exposure-assessment methods related to power-frequency electric and magnetic fields.

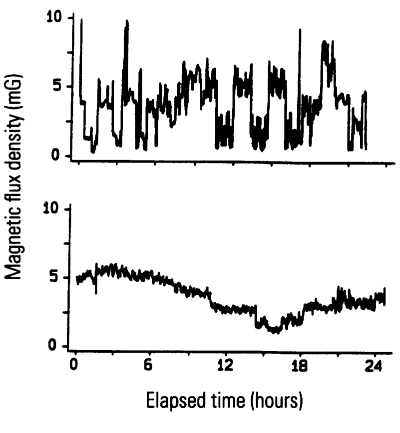

Figure 9. Twenty-four-hour records of magnetic fields in two homes. Time-weighted-average exposure was 0.36 μT for both homes.

Development of Job-Exposure Matrices for Electrical Workers

Because a number of studies have found elevations in the rate of mortality from various cancers in electrical workers, it would be appropriate to develop detailed job-exposure matrices for both electric-field, magnetic-field, and chemical exposures received by members of this group. With such a matrix, electrical-worker job titles that were exposed to fields could be separated from those that were not, and confounding exposures could be evaluated.

Prediction of Historical Exposure

The ability of wiring codes and spot measurements to predict long-term historical exposure needs to be thoroughly evaluated. In addition, techniques need to be investigated that possibly could utilize available historical information, such as residential billing records and utility loading data, to sharpen historical residential-exposure estimates.

Alternate Exposures Associated with Wiring Codes

Because of the possibility that the Wertheimer-Leeper Code is detecting some underlying factor that is unrelated to magnetic fields, an intensive and multidisciplinary search for environmental correlates of wire codes is needed.

Between-Studies Variability in Spot and Fixed-Site Magnetic Field Measurements

Spot measurements and fixed-site recordings of residential magnetic fields show considerable differences between studies, particularly for normal-power measurements (Table 7). Research is needed to determine if these differences are due to geographical, measurement protocol, or instrumentation differences. In this context, the latter two possibilities are of particular concern because they imply the existence of measurement errors that are not understood.

Residential and Nonresidential Exposures

As discussed earlier, there are data suggesting that the nonresidential exposures of children, and perhaps adults, are considerably less variable than residential exposures. This finding could be of great importance, but it needs to be confirmed in different geographical areas with a variety of different groups of adults and children.

Temporal Variability of Residential Exposure

No direct data exist on the variability or stability of residential exposure over time periods greater than 24 hr. It was inferred from spot measurements previously that exposure might be, in fact, stable over periods of years, but this hypothesis needs to be tested with direct measurements.

Alternate Exposure Metrics

Biological hypotheses that include specification of the appropriate exposure metrics need to be developed for testing in future epidemiological studies. Although much of the rationale for a particular model must come from laboratory research with in vivo and in vitro models, exposure-assessment research may contribute by identifying metrics that are associated with wiring codes.

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