Occupational Exposure Assessment for Electric and Magnetic Fields in the 10-1000 Hz Frequency Range

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INTRODUCTION

Exposure assessment is the determination or estimate of the magnitude, frequency of occurrence and rate of exposure for an individual or group to an agent in the environment. The agents of interest in this case are electric and magnetic fields (EMF) in the extremely low frequency (ELF) range of 10-1000 Hz. There is increasing concern that exposure to ELF electric and magnetic fields may be associated with biologic and health effects. This concern has prompted numerous measurement projects and the development of instrumentation, methodologies, and exposure models: all directed at exposure assessment for EMF. The purpose of this paper is to review the status of EMF exposure assessment research and to identify remaining issues as they relate to occupational exposures. During this period of active research on EMF exposures it is difficult to keep abreast of the results and ramifications of all ongoing and recently completed projects. Rather than serve as a comprehensive catalog of research and results, this paper draws on past and recent results to emphasize the unique aspects of EMF exposures and to highlight research needs.

Characteristics of EMF

Power frequency electric and magnetic fields (EMF) are present wherever electricity is being generated, transmitted or used. Electric fields are related to the voltage (potential difference between two points) on the electric conductors, while magnetic fields are produced by currents (movement of charges in the conductors). Fields are vector quantities characterized by a magnitude, direction, and frequency. The frequency of the fields is determined by the frequency of the source. Electric systems operate such that the magnitude and direction of both voltage and current alternate over time. The power systems in the U.S., Canada and Mexico operate at 60 Hz (cycles per second), while 50 Hz is used elsewhere, including Europe. Fields at other frequencies arise when other power frequencies are used in special equipment or when nonlinear characteristics in electrical devices generate harmonics.

The magnitude of the electric field is directly related to the voltage of the source. Since voltages on field sources remain relatively constant, electric field levels vary from location to location in a predictable manner, but remain essentially constant over time. Electric fields are measured in units of volts/meter (V/m) or kilovolts/meter (kV/m).

Currents within an electrical system or used by equipment vary widely and frequently experience instantaneous, hourly, daily or seasonal variability. Magnetic fields, which are directly related to current levels, are highly variable not only from location to location but also over time at the same location. Magnetic fields are commonly expressed in units of tesla (T) or microtesla (μT). A common unit for magnetic field that has been used historically is the gauss (G) or milligauss (mG) where 1 G is 10^{-4}T or 1 mG = 0.1 μT. (Technically, the magnetic field or H-field is expressed in units of ampere/m (A/m) and the magnetic flux density or B-field is given in terms of tesla (T). For purposes of this paper, the term "magnetic field" refers to the B-field or magnetic flux density and is expressed in gauss or milligauss.)

Special Considerations for EMF Exposure Assessment

Although there is a systematic approach to exposure assessment (1), each environmental agent can present unique problems and ELF fields are no exception. There are numerous factors that make exposure assessment for ELF electric and magnetic fields complex and difficult.

ELF fields are not detectable by humans at levels found in most environments, making indirect assessments of exposure through questionnaires, or other means problematic.

EMF exposure situations are not memorable with the exception of electric blanket use and certain occupational settings. High exposure situations are generally fleeting and localized with little or no recognition of the event by the exposed party.

The lack of accepted definitions of *exposure* and *dose* for EMF leads to uncertainty in what to measure. Defining dose requires an understanding of the mechanism by which the agent interacts with the human body. For EMF, there is no widely accepted, demonstrable mechanism for this interaction. Consequently there is no accepted definition of dose for EMF. Even characterization of physical exposure is difficult. Without a known mechanism there is no guidance as to what attribute of the field should be measured: magnitude, frequency, variation, maximum, etc.

Unlike most other environmental agents, everyone is exposed to EMF to some degree. The presence of these fields in all environments where electric power is used makes exposure pervasive and compounds the difficulty of defining unexposed subjects.

Variety in the extent and magnitude of fields from different sources produces large spatial variations in field levels. For example, in occupational settings, magnetic fields can range from levels above 100 mG near electrical equipment to less than 1 mG in adjacent office areas. Such variation dictates caution in the selection of monitoring location and in the use of measurements to characterize EMF fields in a space.

Perturbation and shielding of the fields make consistent and meaningful measurements of electric field exposure difficult.

Magnetic fields can have substantial temporal variability as a function of power use in and around the environment under study. Equipment may be operated intermittently during the work day. There may be weekly, monthly or other seasonal patterns of use as well as long term changes associated with altered work practices and technologies. This variation of fields over time complicates the assignment and measurement of exposure.

The nature of many jobs requires workers to spend time near one or more pieces of electrical equipment on a sporadic basis. Consequently, the uncertainty introduced by source variation is compounded by subject movement and activity.

All of these factors make the assignment of contemporary, let alone retrospective, EMF exposure even more difficult than for many other environmental agents.

STATE OF KNOWLEDGE

Exposure assessments for ELF fields have utilized point-in-time and long term measurements, in specific locations, personal exposure measurements and surrogates. With the exception of electric utility environments, many of the electric and magnetic field measurements have been anecdotal. Exposure data that are now becoming available indicate that EMF exposures, even within an occupation, are diverse and that measurements made at only a few locations or with a few individuals will not be sufficient to accurately characterize the exposure of a group. The paucity of extensive data at power frequencies in occupations other than those associated with utilities and at other frequencies for all occupations can be attributed to the relatively recent interest in ELF fields as an environmental agent and also to the lack of any clearly demonstrable health effects.

Initial interest in ELF exposures centered on electric fields at power frequencies because of the relatively high levels of these fields near electric transmission facilities and because there are perceivable short term effects from electric fields. However, interest now has shifted to magnetic field exposures at power and other frequencies because of laboratory and epidemiology studies that have suggested possible health effects.

Electric Fields

Characterization of electric fields in the work environment has been mainly limited to the utility industry. Except for those relatively few occupations where high voltage sources are prevalent, electric fields encountered in the workplace have been shown to be similar to residential and non-work exposures.

Environment and Source Characterization

ITT Research (2) measured electric fields in 14 commercial and retail locations in rural Wisconsin and Michigan. The average electric field was 4.8 V/m with a standard deviation of 4.3 V/m. Median electric field was about 3.4 V/m. These values are about one third the values in residences reported in the same study. Power-frequency electric fields near video display terminals (VDT) are about 10 V/m, similar to other appliances (3). However, fields near VDTs are very dependent on the manufacturer and are being reduced in response to increasing public concerns and regulations in Sweden and elsewhere.

Electric fields in areas of occupational exposure near high voltage power transmission facilities have been thoroughly investigated. Levels of unperturbed electric field depend on the voltage class of the equipment, proximity to energized conductors, the presence of conducting objects, and distance above the ground. Typical maximum values for various installations at different system voltages are given in Table 1 and indicate the maximum 60-Hz electric fields in an occupational setting. The levels reported in a survey of utilities in 21 countries are consistent with measurements in U.S. facilities (4, 5). The range of fields in a high-voltage substation or similar facility is very great and a simple exposure metric cannot characterize the fields. For example, in a substation, the electric fields in most areas are considerably reduced from the maximum levels shown in Table 1.

Other occupations besides utility workers that are associated with the proximity to electrical equipment have been assigned electric and magnetic field exposure in various epidemiologic studies. However, until recently there has been a paucity of actual field or exposure measurements for these so-called "electrical worker" categories (6,

7) Bowman et al. performed electric and magnetic field measurements at 114 work sites corresponding to the "electrical worker" occupations that have been presumed to have elevated electric and magnetic field exposures in epidemiologic studies. In this study one or two measurements were taken near the worker and arithmetically averaged to produce a field value for each site. The geometric mean field measured for 67 "electrical worker" environments was 4.6 V/m while measurements in the work areas of four secretaries indicated fields in the range of 2 to 5 V/m. Certain environments related to electrical work did exhibit higher electric field levels: overhead lines for power line workers (n=2), 160 V/m; transmission (n=3) and distribution (n=3) substations for power station operators, 298 V/m and 72 V/m, respectively; and repair shops for radio and TV repairers (n=11), 45 V/m. Electric fields associated with other "electrical worker" environments were found to be comparable with office or residential levels.

Table 1

Range of Maximum Electric Fields Near High Voltage Facilities

	System Voltage (kV)	Transmission Lines (kV/m)	Substations (kV/m)
a) Worldwide (4) Gary et al, 1986			
	330	5	7.5 - 10
	400	3.0 - 11.5	11.0 - 22.5
	500	6.5 - 10	8.5 - 15
	750	8.0 - 15	9.0 - 25
b) US (5) Deno and Zaffanella, 1982			
	23	0.01 - 0.05	
	115	0.1 - 2.0	
	345	2.3 - 5.6	7.5
	500	8	8.5
	765	10	9

Stuchly and Lecuyer (8) measured 60 Hz electric fields near arc welders and found them to be very low (<1 V/m) in most cases. The highest electric field at an operator location was 300 V/m for one device. All others produced fields less than 100 V/m with most less than 1 V/m.

Personal measurements of electric field exposure during the Electric Power Research Institute's (EPRI) EMDEX Project Occupational Study were collected in eight work and three non-work environments and can be considered as indicative of the area where they were recorded subject to limitations discussed below (9). The results are shown in Table 2. The measurements in each environment were analyzed in two ways: first as individual measurements aggregated over all periods in each environment, and second as "partition" means, defined as the arithmetic average of all measurements during a contiguous period in the environment. For example, for the transmission line environment there were 296,892 individual measurements of electric field recorded during 364 partitions or periods in that environment. As expected the transmission line, distribution line and substation environments have the highest measured electric fields with measurements in the office and shop work environments characterized by lower fields. The electric field measurements used to characterize the environments were collected with personal exposure meters and are limited in their interpretation as discussed in a subsequent section. As with other measurements made during the EMDEX Project, the distribution of electric field measurements within the environments is highly skewed and not adequately described by any single statistical descriptor.

Because of different methodologies, it is not possible to compare the area measurements of Bowman et al. (7) for a relatively small number of sites with the environmental characterizations provided by the personal exposure measurements of the EMDEX Project. However, the two investigations are consistent in confirming those environments where high electric fields are present and in indicating a large disparity in fields between these environments and other work environments.

Table 2

Electric Field Distribution for Environments in kV/m: a) by partition mean; b) by all measurements

a) by Partition Mean

Electric Partition Means by Environment

Occupied Environment	n	min	5%	25%	50%	75%	95%	max	mean	geo mean
Generation	729	0.001	0.002	0.003	0.005	0.008	0.021	0.595	0.009	0.006
Transmission	364	0.001	0.003	0.006	0.026	0.173	1.897	11.534	0.410	0.035
Distribution	736	0.001	0.002	0.004	0.008	0.032	0.437	2.761	0.076	0.014
Substation	1325	0.001	0.002	0.007	0.020	0.066	0.351	10.261	0.098	0.023
Office	1571	0.001	0.002	0.003	0.004	0.007	0.015	0.064	0.006	0.005
Shop	1052	0.001	0.001	0.003	0.004	0.007	0.015	0.146	0.006	0.005
Travel	3687	0.001	0.001	0.003	0.004	0.007	0.018	0.473	0.007	0.005
Other	1057	0.001	0.001	0.003	0.005	0.008	0.024	0.791	0.010	0.005
Home	1395	0.001	0.002	0.004	0.007	0.011	0.022	0.183	0.009	0.007
Travel (nonwork)	2067	0.001	0.001	0.003	0.004	0.006	0.013	0.319	0.005	0.004
Other (nonwork)	653	0.001	0.001	0.003	0.004	0.008	0.022	1.872	0.015	0.005

b) by 10-Second Measurement distributions

Electric 10-Second Measurements by Environment

Occupied Environment	n	min	5%	25%	50%	75%	95%	max	mean	geo mean
Generation	998092	0.001	0.001	0.001	0.003	0.005	0.018	29.174	0.008	0.004
Transmission	296892	0.001	0.001	0.003	0.005	0.029	1.718	78.524	0.444	0.011
Distribution	552040	0.001	0.001	0.003	0.003	0.012	0.272	29.854	0.074	0.006
Substation	1069854	0.001	0.001	0.003	0.005	0.016	0.335	45.186	0.115	0.007
Office	1091882	0.001	0.001	0.003	0.003	0.005	0.016	3.350	0.006	0.003
Shop	629312	0.001	0.001	0.001	0.003	0.005	0.018	2.723	0.006	0.004
Travel	1056530	0.001	0.001	0.001	0.003	0.005	0.018	7.674	0.007	0.003
Other	418614	0.001	0.001	0.003	0.003	0.008	0.025	10.351	0.012	0.004
Home	1371725	0.001	0.001	0.003	0.005	0.010	0.027	3.199	0.009	0.005
Travel (nonwork)	523377	0.001	0.001	0.001	0.003	0.005	0.014	3.428	0.006	0.003
Other (nonwork)	333143	0.001	0.001	0.001	0.003	0.008	0.018	4.842	0.007	0.004

Bracken, 1990 (9)

Personal Exposure Measurements

Measurements made with a conducting vest as a sensor for a personal exposure meter yielded average equivalent fields of 3.7 and 5.7 V/m for grocery or other stores and shopping malls, respectively (10). Electric field exposures for farming near transmission lines were also investigated using the vest (10). Although large electric fields are expected on the right-of-way, the actual time spent in such fields is small. For example, Silva estimated that a 345-kV line with a maximum field of 4.3 kV/m contributes approximately 80 hours per year of exposure in fields above domestic levels (50 V/m). In other words, farmers can experience the peak levels found under transmission lines, but do so only a very small proportion of the time. Modern mechanized equipment with enclosed cabs can also reduce electric field exposures substantially.

Exposure measurements made on high-voltage utility workers in several studies indicate that very little time is spent in fields above 1 kV/m. Bracken (11) found that the median time above 0.4 kV/m was only 13 minutes per day for Bonneville Power Administration workers near 500-kV equipment. For lower voltages, the median time above this threshold field was reduced correspondingly. In this study 295 utility employees wore a small exposure meter and generated 3098 days of exposure data. Measured exposures of 47 electrical workers over 319 days in the United Kingdom showed that the median time spent in fields greater than 0.4 kV/m was about 6 minutes per day or less for all job categories except linemen, who spent a median time of about 9 minutes per day above 0.4 kV/m (12). On average for these workers, 2.1 minutes per day or less was spent in fields greater than 4.5 kV/m. The two studies were consistent in their measurements of overall exposure, in associating higher fields with higher voltages and in emphasizing the relatively small amount of time spent in the maximum fields cited in Table 1. However, even with this small portion of time spent in higher fields, the electric fields that high-voltage workers encounter are definitely discernible from those encountered in an office environment: Time-integrated exposures for the high-voltage workers in the BPA study were two to three orders of magnitude greater than in a control group working inside an office (11).

Using a small 60-Hz dosimeter, Deadman et al. (13) measured occupational exposures over a one week period for 20 utility workers and 16 office workers. The geometric mean of the time integrated weekly exposures during work for the 20 utility workers was 48.3 V/m compared to 4.9 V/m for the office workers. The transmission lineman (n=2, 420 V/m) had the highest geometric mean exposures. These results are consistent with the previous studies that used less sophisticated instrumentation.

Electric field exposure data were collected for 998 electric utility employee volunteers during 2082 workdays as a part of the EPRI EMDEX Project (9). Absolute field levels cannot be placed on the resulting exposures because of limitations in the interpretation of recorded data. However, relative comparisons between job classifications can be made as shown in Figure 1. Because the sample of utility workers was not drawn randomly these results must only be considered suggestive of the industry as a whole.

As with the earlier studies, the electrical occupations of line worker, substation operator and utility electrician, all of whom work near energized high voltage equipment, showed the highest exposures. Utility occupations associated with generation facilities did not exhibit relatively high electric field exposures. Figure 1 also indicates that among those with high electric field exposures the distribution of workday exposures is highly skewed. The arithmetic mean of these distributions can be strongly influenced by a few high exposure days, and thus, may not be an appropriate indicator of central tendency for the group as a whole.

Magnetic Fields

Information on occupational exposures to 60-Hz magnetic fields has increased substantially over the past few years. Initial measurements took the form of point-in-time measurements near specific sources or in general work environments. However, with the advent of more sophisticated computer-based instrumentation and heightened interest in magnetic fields, the amount of data has increased substantially.

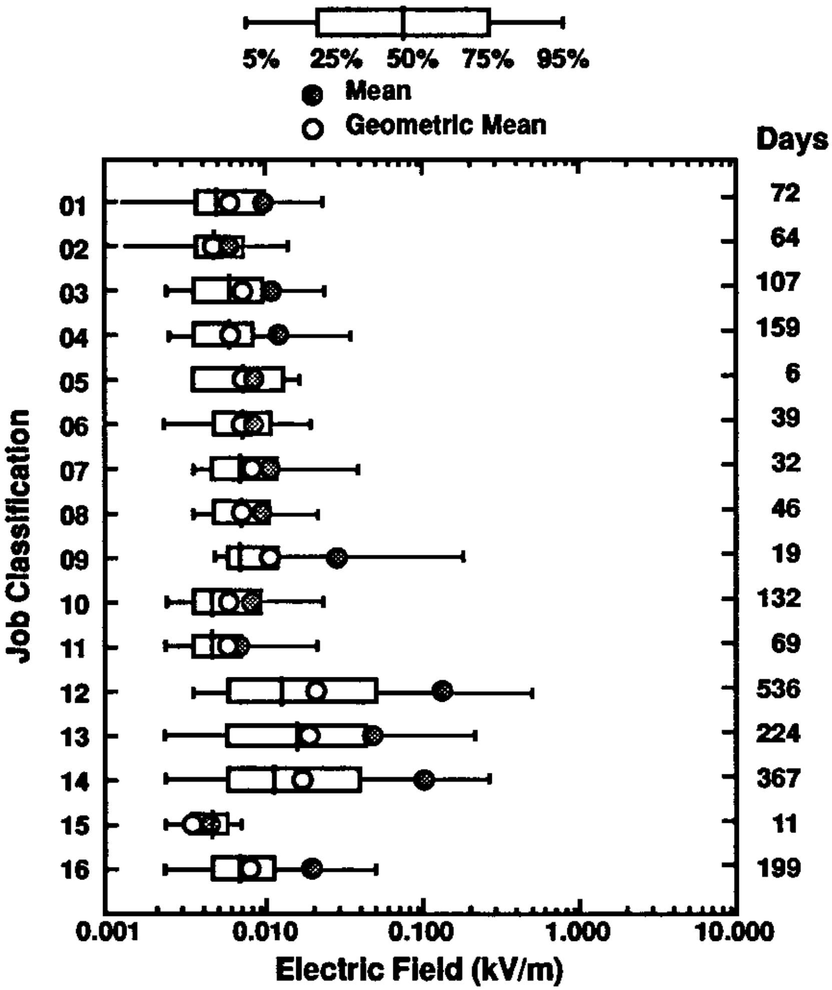

Figure 1. Distributions of electric field workday means by job classification. Arithmetic means can be dependent on a few high values and thus may not be indicative of values for the group as a whole.

Job classification Key:

01 - Mgrs & Supvsrs w/o comp
02 - Mgrs & Supvsrs w/comp
03 - Prof & Tech w/o comp
04 - Prof & Tech w/comp
05 - Cler w/o computer
06 - Cler w/computer
07 - Support Svce Occ
08 - Outside Cust Svce Op
09 - Drivers and Equip Op
10 - Gen Fac Op
11 - Gen Fac Mech
12 - El Pwr Line Workers
13 - Substation
14 - Electricians
15 - Welders
16 - Other Const Occ

(9) Bracken, 1990

Environment and Source Characterization

Magnetic fields measured in 14 commercial and retail locations in rural Wisconsin and Michigan had a mean value of 1.1 mG (SD=2.0 mG) (2). Stuchly et al. (14) reported levels of 0.5 and 1.25 mG in a Canadian office and laboratory, respectively. In the same study, 60-Hz magnetic field levels 0.3 m in front of VDTs ranged from 1.5 to 7 mG. (A color television had a measured field of 12.5 mG at 0.3 m.) Measurements near seven VDTs indicated a range of 2.5 to 4.4 mG at 0.3 m from the terminals (15). As with electric fields, the fields near VDTs are very dependent on manufacturer and are being reduced by many manufacturers in newer models.

Lovsund et al. (16) surveyed magnetic fields in the electro-steel and welding industries in Sweden. Steel production with electric furnaces resulted in 50-Hz fields of from 1 to 100 G in work areas. Fields near 50-Hz welding machines exhibited a similar range of values.

Stuchly and Lecuyer (17) measured magnetic fields near 76 induction furnaces, 13 of which operated at frequencies below 1000 Hz. The average operator exposure for all 13 of these units exceeded 29 mG with a high of over 1 G. Given the distribution of operating frequencies for these units, induction furnaces are definitely a potential source of ELF exposures at other frequencies than the power frequency. Stuchly and Lecuyer (8) measured electric and magnetic fields at 60 Hz and its harmonics near 22 arc welders. Magnetic flux densities at six locations on the body of the welder averaged a few tens of mG with a range of 5 mG to 4.4 G. They cited welding machines as a likely source of high occupational magnetic field exposures. Most of the welders had the highest fields at 60 Hz but some produced the strongest fields at 120 and 180 Hz. Typical use of an arc welder entails having a current carrying cable very near the body which can cause very high localized fields.

Electrically powered vehicles are also a potential source of non-power frequency magnetic field exposures in work environments. Magnetic fields associated with an electric traction railway in Germany were reported by Paul et al. (18). The 16.67 Hz fields on a platform directly above the contact wire for the vehicle were in the range of 100-200 mG when a train passed. Preliminary results of an extensive set of measurements on and near an experimental Maglev vehicle in Germany have been reported by Cummings and Robertson (19). At the floor of the vehicle the magnetic fields are in the range of 100-300 mG while at head height they have diminished to less than 10 mG. The frequency of the fields is determined by the excitation frequency for the train which is dependent on vehicle speed.

Stuchly (14) in a review of human exposure to static and time-varying magnetic fields cited several measurements near electric transmission facilities. Four Canadian generating stations exhibited localized magnetic fields of 2.7 G with typical levels ten times lower. In six Canadian substations, maximum fields were in the range of 50 to 180 mG with typical levels of 10 to 50 mG. Fields of 1 to 120 G were reported for locations of possible worker occupation in generating plants in the Federal Republic of Germany. The same study also estimated magnetic fields above a superconducting cable carrying 13 kA were 1.4 G and .45 G for burial depths of 0.75 and 1.4 m, respectively. Bracken (20) reported magnetic field measurements along an inspection route in a 230 kV substation of up to 200 mG with a mean of about 40 mG.

More extensive occupational environment magnetic field measurements have been reported by Bowman et al. (7). The geometric mean field from 105 magnetic field measurements at "electrical worker" job locations was 5.0 mG. "Electrical worker" environments that showed elevated magnetic field levels (i.e., geometric mean greater than 20 mG) were: near industrial power supply for an electrician (n=1), 103 mG; near underground (n=3) and overhead (n=2) lines for powerline workers, 57 and 42 mG, respectively; near ac welding machines for welders (n=4), 41 mG; in transmission (n=3) and distribution (n=3) stations for power station operators, 39 and 29 mG, respectively; and near sputtering systems for electronic assemblers (n=1), 24 mG.

For secretaries in the same Bowman study the geometric mean field was 3.1 mG for those using video display terminals (n=6) and 1.1 mG for those not using VDT's (n=3).

From the limited measurements of Bowman et al. (7), it is clear that elevated magnetic field levels are found in occupational settings both inside and outside the electric utility industry. They also demonstrate that there are some "electrical worker" environments where magnetic field levels are comparable with the lower fields found in the residential or office environment.

Classification of magnetic field personal exposure measurements made during the EMDEX Project according to the environment in which they were recorded produces the results shown in Table 3 (9). As with electric fields, magnetic fields in this study were highest in utility-specific environments. In addition to the transmission line, distribution line and substation environments noted for higher electric fields, the generation facility environment also exhibited elevated magnetic fields relative to other occupational environments.

Sources of fields in the office environment which have been identified but not formally documented are electrical distribution transformers and wiring in vaults that are located inside large office buildings directly below work areas. For large heating, cooling and lighting loads these circuits can carry large currents resulting in relatively high 60 Hz fields (>100 mG) in the space directly above the vault. Such fields are often manifested by interference with VDTs (18).

Personal Exposure Measurements

The availability of small personal exposure meters has resulted in several investigations of occupational magnetic field exposure. In a Canadian study, the geometric mean of the time-weighted average of the weekly work exposure of 20 utility workers was 16.6 mG compared to 1.6 mG for 16 office workers (13). The geometric mean field for the office exposures was comparable to that observed during non-work periods for office workers and comparable to that for both groups during sleep when the exposure meter was not worn. Utility workers in all six of the job categories sampled showed elevated fields compared to a group of office workers. Transmission apparatus electricians (n=3) showed the highest geometric mean exposures, 34 mG. Given that personal exposure measurements tend to be lower than point-in-time measurements and the small numbers of samples involved, the results for the personal exposure measurements (13) and the area measurements (7) appear to be consistent although hardly conclusive.

Bracken (20) estimated the average field for eight transmission substation-operator workdays to be 6 mG based on measurements with a single-axis magnetic field exposure meter. This level was five to six times greater than the average field estimated for 9 office-worker days in the same study.

The results of personal exposure measurements of magnetic field in the EMDEX Project Occupational Study for 1882 utility worker volunteers during 4411 workdays are shown in Figure 2 (9). The jobs associated with utility operations (Jobs 10-14) generally have higher exposures than other occupations. This is most pronounced when the 75th and 95th percentiles of the workday means are compared. In general, the most highly exposed Job Classifications in Figure 2 appear to be substation operators and utility electricians.

The higher exposures for utility-specific occupations are also manifest in the analysis of measurements in occupied environments (Table 3). The tendency for higher exposures in utility-related work environments is true regardless of measure considered (measurements, partition mean or workday mean) and regardless of metric examined (median, arithmetic mean or geometric mean). Although certain combinations of measure and metric exhibit this pattern more dramatically than others, the utility-specific categories tend to be higher than their counterparts for all indices. In a study of telephone worker exposures, Breysse et al. (21) have also examined exposure rank among various telephone worker groups as a function of exposure index.

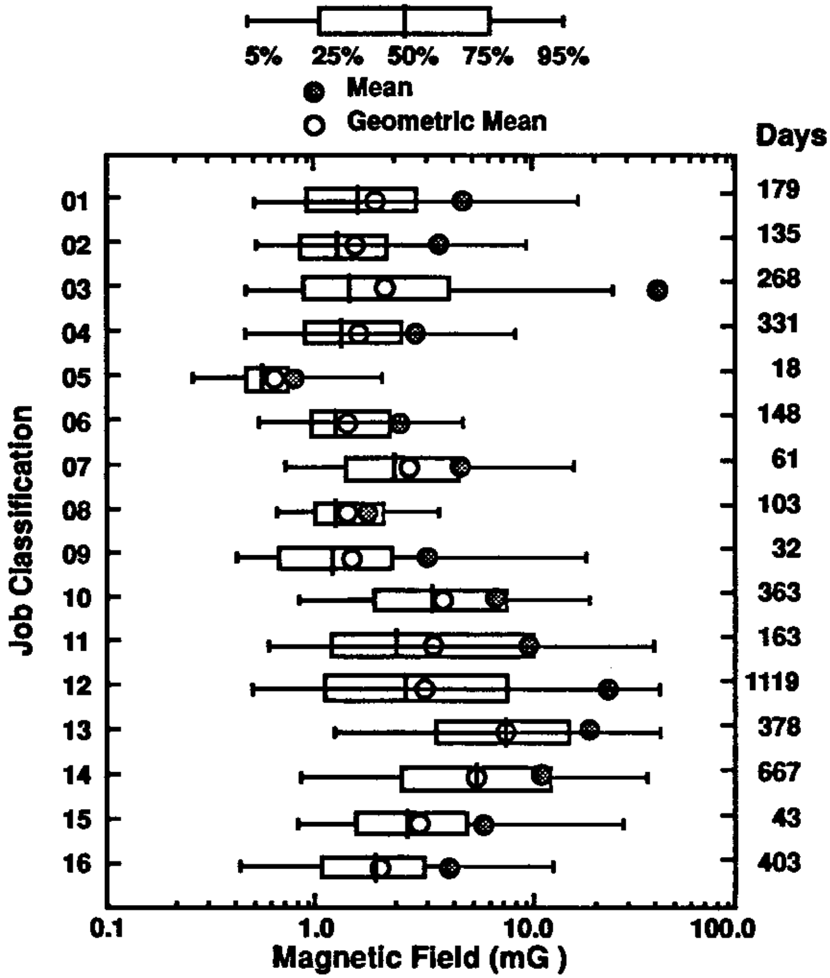

Figure 2. Distributions of magnetic field workday means for job classifications. Arithmetic mean values can be dependent on a few very high readings and thus may not be indicative of measures for the group as a whole.

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06 - Cler w/computer
07 - Support Svce Occ
08 - Outside Cust Svce Op
09 - Drivers and Equip Op
10 - Gen Fac Op
11 - Gen Fac Mech
12 - El Pwr Line Workers
13 - Substation
14 - Electricians
15 - Welders
16 - Other Const Occ

(9) Bracken, 1990

The appropriate choice of metric and summary measure is not clear for EMF exposures.

In the EMDEX Project Occupational Study, the arithmetic mean was used to express daily exposure for volunteers because it has a definite physical meaning: the time averaged exposure for an individual for a day. However, whichever metric and summary measure is selected for exposure data, it is clear that distributions of the quantity will be skewed.

Table 3

Magnetic Field Distributions for Environments in mG
a) by Partition Mean; by All Measurements

a) by Partition Mean

Magnetic Partition Means by Environment

Occupied Environment	n	min	5%	25%	50%	75%	95%	max	mean	std dev	geo mean	geo std dev
Generation	1814	0.09	0.51	1.28	2.63	7.04	37.34	1973.99	13.17	75.51	3.25	3.86
Transmission	712	0.15	0.35	1.87	5.98	15.42	61.62	630.56	18.22	50.82	5.44	4.77
Distribution	1771	0.09	0.26	0.66	1.58	6.11	63.68	14386.52	24.56	350.49	2.31	5.55
Substation	2360	0.09	1.09	4.57	10.56	22.06	63.11	26582.43	54.80	886.70	9.87	3.57
Office	3803	0.09	0.30	0.59	0.98	1.76	5.05	274.79	1.81	6.26	1.07	2.39
Shop	2243	0.10	0.30	0.67	1.15	2.16	5.68	244.93	2.45	9.81	1.23	2.60
Travel	7618	0.09	0.46	0.86	1.32	2.16	6.02	21474.04	5.46	247.08	1.44	2.25
Other	2328	0.09	0.25	0.59	1.11	2.43	10.97	1944.48	4.25	43.09	1.26	3.20
Home	3307	0.09	0.21	0.44	0.73	1.33	4.01	489.72	1.63	10.03	0.81	2.51
Travel (nonwork)	4790	0.13	0.45	0.85	1.18	1.67	3.43	388.00	1.61	5.96	1.21	1.88
Other (nonwork)	1494	0.09	0.23	0.53	0.88	1.62	5.03	43.57	1.56	2.55	0.96	2.49

b)by 10-Second Measurement Dstributions

Magnetic 10-Second Measurements by Environment

Occupied Environment	n	min	5%	25%	50%	75%	95%	max	mean	std dev	geo mean	geo std dev
Generation	2365435	0.09	0.22	0.57	1.24	3.51	26.61	42169.65	8.35	117.04	1.55	4.29
Transmission	524275	0.09	0.17	0.60	2.79	11.09	51.88	3672.82	15.70	59.49	2.73	6.22
Distribution	1238612	0.09	0.17	0.38	0.97	3.59	63.83	43151.91	47.38	841.56	1.41	6.59
Substation	1753215	0.09	0.45	2.37	7.00	17.58	59.57	42169.65	34.43	629.49	6.17	4.45
Office	2690502	0.09	0.17	0.43	0.75	1.46	5.96	25409.73	2.07	83.61	0.82	2.84
Shop	1367358	0.09	0.17	0.45	0.88	2.02	6.84	34276.78	2.87	55.67	0.98	3.15
Travel	2056525	0.09	0.17	0.41	0.79	1.76	7.16	36728.23	3.09	139.02	0.88	3.14
Other	879383	0.09	0.17	0.38	0.79	1.97	9.44	25409.73	3.46	91.06	0.93	3.55
Home	3320924	0.09	0.17	0.33	0.61	1.22	4.32	3427.68	1.47	8.73	0.65	2.90
Trvl(nonwrk)	1165844	0.09	0.17	0.38	0.73	1.46	4.73	3845.92	1.56	11.67	0.77	2.86
Othr(nonwrk)	701983	0.09	0.17	0.36	0.61	1.27	5.19	1011.58	1.36	3.24	0.68	2.91

Bracken, 1990 (9)

The skewness of exposures and measurements within a group is demonstrated in Figure 3. The distributions of workday mean exposure and of all measurements collected by volunteers primarily assigned to transmission line environments are shown. These distributions range over several orders of magnitude with most values at low fields. The variability of magnetic field exposure experienced

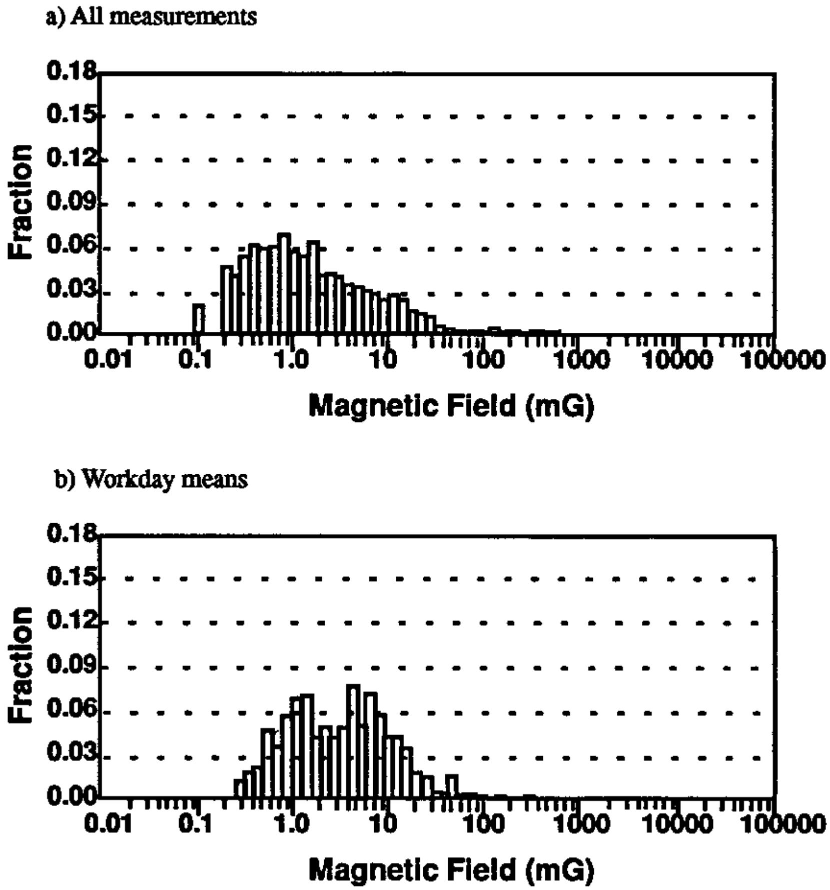

Figure 3. Distributions of magnetic field exposure measurements for workers with transmission lines as a primary work environment: a) all measurements n=1,209,371; b) workday means n = 357 days.

by a DC arc welder during a single workday is displayed in Figure 4. The magnetic field was recorded by an EMDEX worn at the waist of a DC welder operator. Thus, there is a large range of exposures experienced within a day, and even collapsing these measurements into daily means does not eliminate the large range of exposures exhibited by individuals within groups. The skewness of the distributions of exposure measures raises interesting questions as far as presentation and summarization and also has far reaching implications for study design. In particular care must be taken to acquire an adequate and diverse sample for estimating ELF exposures.

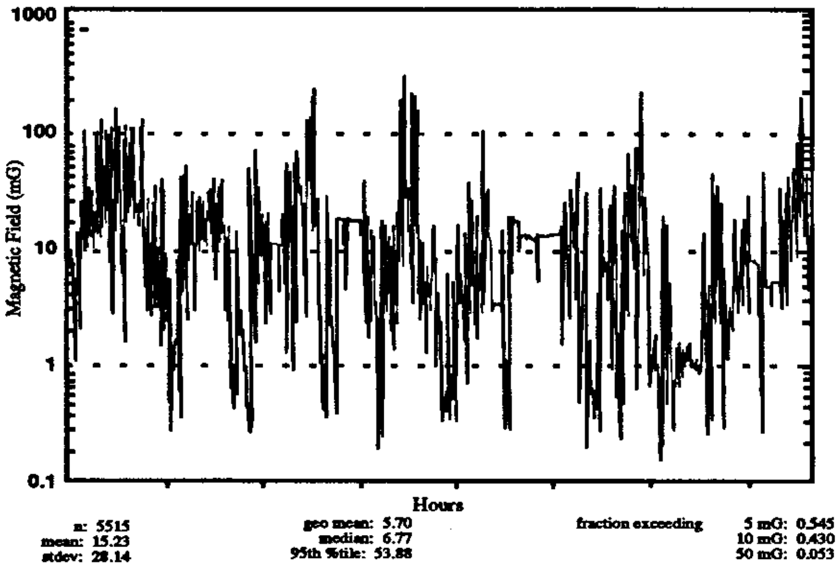

Figure 4. 60 Hz magnetic field exposure measurements for DC welder during workday

Besides indicating the skewness of exposure distributions, the large number of exposure days in the EMDEX study also provided estimates of variance which can be used to determine sample sizes for future exposure assessment studies (9). For example, the number of measurement days required to estimate a single generation facility worker's workday mean exposure to within 5 mG is 29 days; the number of subjects (with 2 days of measurements) required to estimate the workday mean to within 2 mG (5 mG) for generation facility workers is 239 or (39) volunteers.

Instrumentation

Instrumentation for exposure assessment varies with the type of measurement proposed. For point-in-time measurements and source characterization, survey meters are indispensable. They need to be portable, easy to read and reasonably accurate. For personal exposure assessment, light weight and durability are essential. For long-term measurements at a specific location of field variability, stationary recording systems can benefit from multi-sensor capability to simultaneously monitor fields and other parameters in many areas.

Electric field survey meters for area measurements related to exposure assessment are usually of the free-body type (22). The meters are suspended in free space by means of an insulated handle and the current induced between two electrodes (usually the case of the instrument) is detected and visually read by means of an analog or digital display. For accurate readings of the electric field, it is necessary to keep the meter away from the observer and other conducting objects. Although some commercially available meters have band widths of several hundred Hz, they have been designed primarily for use at power frequencies and their harmonics. Measurements over the entire frequency range from 10-1000 Hz require custom instrumentation.

There are numerous hand held magnetic field meters commercially available which can be used for characterizing sources and making point-in-time measurements. Survey meters and personal exposure instruments and survey meters for magnetic field were evaluated and compared at a recent workshop held under the auspices of the IEEE AC Fields Working Group (23).

A personal computer-based measurement system has been developed under EPRI sponsorship that is capable of capturing and analyzing wave forms in the ELF frequency range (24). This type of device, although not portable, does allow recording of data at several locations through the use of multiple probes. Although developed primarily for analyzing magnetic fields, the spectral content of electric fields can also be characterized.

Several small personal exposure meters have been developed for measurement of electric and magnetic field exposures (13, 25, 26, 27). For electric field exposures, these devices, like their survey meter counterparts, sense the electric-field induced current between two conducting surfaces. The induced current is proportional to the incident electric field and is recorded in one of several ways to serve as a measure of exposure. Magnetic fields are sensed with single or multiple coils that generate a voltage proportional to the instantaneous magnetic field. In the case of multiple orthogonal coils, the resultant magnetic field is computed from the square root of the sum of the squares of the fields from the three coils, or with one prototype device, as a true rms superposition of the field components.

Meters that are currently being used in exposure studies employ either microprocessor-based data storage of the fields three orthogonal components (13, 27) or a simple device that integrates the induced current (E-field) or voltage (B-field) over the period the device is worn to produce a single value of time integrated exposure (25, 28).

The EPRI-funded EMDEX (Electric and Magnetic Field Digital Exposure) meter is capable of monitoring and recording electric and magnetic field exposures for extended times (27). The data are stored in the memory of an on-board computer and can be down loaded to a personal computer for viewing and analysis. The EMDEX measures about 15x10x4 cm, has a mass of about 0.45 kg, and is usually worn in a belt-mounted pouch around the waist. The device measures magnetic fields up to 25,000 mG and electric fields up to 500 kV/m. The band width of the EMDEX is 40-400 Hz.

A second version of the EMDEX which is currently in production will measure the maximum as opposed to the resultant field and have the capability to measure harmonics up to 1000 Hz. (28).

Similar in function to the EMDEX is the "ElectroMagnetic Dosimeter" originally developed at the Institute de Recherche d'Hydro-Québec (IREQ) and now available commercially (13). This device measures and records five variables: electric field (50 or 60 Hz), three axes of magnetic field (50 or 60 Hz) and "electromagnetic disturbances" (5-20 MHz). Measurements are classified in 16 amplitude bins along a logarithmic scale covering 84 db. The upper limit of field readings is 40 kV/m for the electric field and about 4000 mG for the magnetic field. The three magnetic field readings are combined into a single bin for the resultant field prior to display and analysis.

The nature of electric fields introduces uncertainty in the electric field measurements made by any of these small exposure meters. The human body acts as a conductor and perturbs the electric field resulting in enhanced fields on certain parts of the body and attenuated fields at other locations on the body. Consequently, the measurement of electric field is fraught with uncertainty — it depends strongly on where the meter is worn, the orientation of the meter with respect to the field source, and the presence of any conductors near the meter. There have been few investigations of the variability of electric field measurements between persons for the same exposure or between days for the same person. The low sensitivity of practical electric field meters combined with the generally low levels of electric field present result in most measurements falling within the lowest scales of possible readings. This restricts the ability to measure or describe differences in exposure. The conversion of electric field measurements at the surface of the body to an equivalent unperturbed electric field is in most cases tenuous at best. Each activity, and even each person, has a different conversion factor and there is no simply exact mechanism to determine a conversion value.

Because of these limitations, reported electric field values should be considered only approximately representative of actual unperturbed field values. It is more appropriate to use electric field exposure measurements for an instrument in a relative sense to compare exposures between categories, rather than to suggest absolute field levels.

In an effort to overcome some of the shortcomings in measuring electric field exposures with exposure meters of small physical dimensions, a conducting vest was used as a sensor to investigate the effects of various activities on exposure measurements (29). However, there are practical constraints to a large scale deployment of such a device.

Exposure Models and Surrogates

As with other environmental agents, direct measures of EMF exposures are not always possible and it is necessary to use modeling or surrogates to estimate contemporary or retrospective exposures.

Modeling of fields and exposures can be used for several purposes:

- To estimate fields/exposures for situations that have not been measured;
- To evaluate exposure surrogates; or
- To construct prior exposures based on current data.

To support the initial research interest in electric fields associated with transmission lines, computer models were developed to calculate these fields. As interest in magnetic fields increased, computations of magnetic field were added. These models have been demonstrated to be accurate and useful because the geometry and currents of transmission lines are simple and the computations of electric and magnetic fields are well understood. Substations and electrical equipment are not as easily analyzed and attempts at computer calculations of fields from these sources for exposure assessment purposes are not tractable. Consequently, estimates of fields in most occupational environments must, of necessity, rely on measurements.

Because of the complex and variable nature of EMF exposure, there can be large differences in exposure during the course of a day, between days for an individual and between individuals within a particular job category. This suggests that accurate assignment of individual exposure through modeling may require time-activity modeling. In this approach it is necessary to consider the uncertainties introduced by both the field measurements and the time estimates. Often the uncertainty in the latter overwhelms the precision of carefully documented field measurements. The need to carefully consider the allocation of time in various occupations is shown in

Figure 5 where the fraction of the workday spent in various environments is shown for the job categories of the EMDEX Project (9). Although the utility worker categories of generation facility operator (Job 10) and lineman (Job 12) are both electrical workers, the generation worker spends over 90% of their time in the generation environment while the lineman spends 50% of their time in high exposure utility-specific areas and approximately 25% of their time traveling.

In examining occupational exposures it is also important to examine exposures in non-work environments encountered by the study of the population. Although occupational exposures are occasionally much higher than exposures encountered elsewhere, the contribution of para-occupational and residential exposures can be significant in many cases. Electric blanket use is one example of significant non-occupational exposure. For the EMDEX Project, the estimated relative contributions of work exposure to total time-integrated magnetic field exposure varied from 17% for clerical workers without a computer to 74% for substation operators (9). The expected contribution from work if all environments have equivalent fields is 27%. Thus, models should account for all significant avenues of exposure appropriately.

Surrogates are parametric or non-parametric schemes that are used to estimate the exposure of an individual to fields. Surrogates can be used to provide information on past, present or future exposure estimates. Appropriate analyses, preferably supported by measurements, link the surrogate to the exposure metric and provide the foundation for use of the surrogate. Surrogates that have been used for EMF occupational exposure measurements include job title, point-in-time measurements, and industry.

To date, one of the shortcomings of EMF exposure assessments has been the lack of confirming measurements for surrogates. There are, however, several research projects that are investigating methods other than personal exposure measurements for assigning exposure and that are verifying existing or proposed surrogate methodologies.

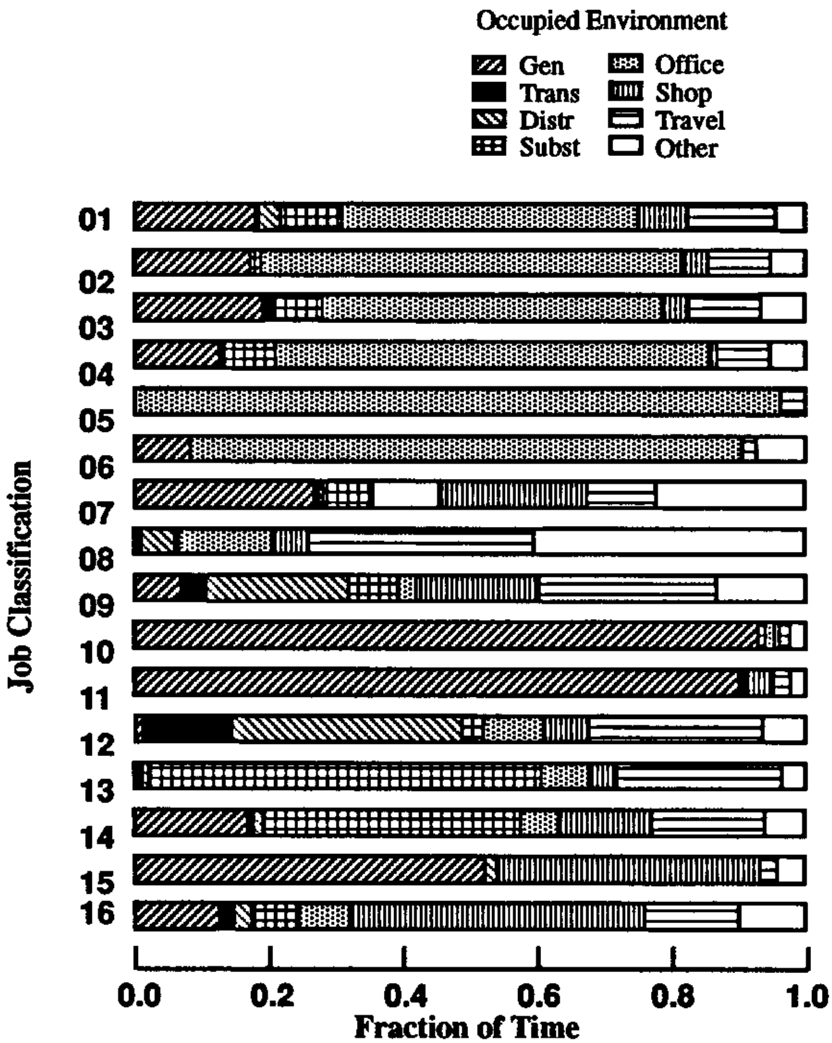

Figure 5. Fraction of workday spent in work environments as a function of job classification

Job classification Key:

01 - Mgrs & Supvsrs w/o comp
02 - Mgrs & Supvsrs w/comp
03 - Prof & Tech w/o comp
04 - Prof & Tech w/comp
05 - Cler w/o computer
06 - Cler w/computer
07 - Support Svce Occ
08 - Outside Cust Svce Op
09 - Drivers and Equip Op
10 - Gen Fac Op
11 - Gen Fac Mech
12 - El Pwr Line Workers
13 - Substation
14 - Electricians
15 - Welders
16 - Other Const Occ

(9) Bracken, 1990

The EMDEX Project analyses of electric and magnetic field exposures by job category (Figures 1 and 2) indicated that certain job titles within the utility industry do experience higher exposures. Similarly, the investigation of exposures for traditional "electrical worker" job titles is indicating that electrical workers as a group do have higher exposures (30). In addition to personal exposure measurements, this study is also utilizing expert panels to determine the time spent in performing various tasks, walk through inspections with point-in-time measurements and area measurements at the work site. The time data will then be combined with area measurements to generate an exposure matrix for each job title. Loomis et al. (31) have compared the results of 8-hour personal exposure measurements for 134 utility workers with the exposure assignments made by a panel of experts on the basis of job title. There was agreement between the ranking of exposures as low, medium, and high by the panel and the measured values thus providing confidence in this method of assigning qualitative exposures.

Ongoing research

There is an active research effort on exposure assessment in the United States and other countries. Of 126 EMF research projects underway, approximately 15 are related to occupational exposures (32). The Electric Power Research Institute (EPRI) is the most active sponsor with five active projects that include an exposure assessment component. These projects include: an assessment of magnetic and electric field exposure by job category (30); a study of telephone linemen to determine leukemia and other cancer risks from EMF (21); an electric and magnetic field measurement project for utilities, the EMDEX Project (33); an epidemiology study of utility workers (34); and an AC field exposure study that includes instrumentation development and modeling (28). Occupational exposure data from the EMDEX Project has just been released and the job category assessment and telephone workers study will be completed soon.

There is an exposure assessment component to a large utility worker epidemiology study being conducted jointly by Ontario Hydro, Hydro Quebec and Eléctricité de France. In this study, exposures will be measured using the IREQ developed personal dosimeter.

Additional EMF occupational exposure assessment projects are underway in Canada, Finland, Netherlands, Sweden, Switzerland, United Kingdom and the United States. There is also an informal group of International EMF Research Managers which meets on an annual basis to exchange information on research planning.

SUMMARY

Over the past decade considerable data have been collected on electric and magnetic fields in occupational environments. These data have taken the form of area measurements, source characterizations, and personal exposure measurements. Occupational EMF levels are highly variable in space and time. Exposures associated with these fields exhibit similar large variations during a day, between days and between individuals within a group. The distribution of exposure measures are skewed over several decades with only a few values occurring at the maximum field levels. The skewness of exposure measures implies that large sample sizes may be required for assessments and that multiple statistical descriptors are preferred to describe individual and group exposures.

Except for the relatively few occupational settings where high voltage sources are prevalent, electric fields encountered in the workplace are probably similar to residential exposures. Consequently, high electric field exposures are essentially limited to utility environments and occupations. Within the electric utility industry, it is definitely possible to identify occupations with high electric field exposures relative to those of office workers or other groups. The highly exposed utility occupations are linemen, substation operators and utility electricians. The distribution of electric field exposures in the utility worker population is very skewed even within a given occupation.

As with electric fields, magnetic fields in the workplace appear to be comparable with residential levels, unless a clearly defined high-current source is present. Since high-current sources are more prevalent than high-voltage sources, environments with relatively high magnetic field exposures encompass a more diverse set of occupations than do those with high electric fields. Within the electric utility industry, it is possible to identify occupational environments with high magnetic field exposure relative to the office environment. Utility job categories with the highest exposures are generation facility workers, substation operators, utility linemen and utility electricians. There are also higher exposures among traditional "electrical worker" job categories.

Outside the electrical utility industry, potential sources of high occupational magnetic field exposures at ELF are induction furnaces, welding machines, electrical transportation systems, and electrical distribution vaults. However, the use of low power electrical equipment such as small motors in close proximity to workers and possibly for long periods of time could also lead to high exposure situations.

Hand held survey instruments are available to perform area measurements at power frequencies but not at all frequencies within the ELF range. Sophisticated personal computer-based instruments are available to characterize areas and sources across the entire frequency range.

Personal exposure meters are commercially available for power frequencies and harmonics up to about 500 Hz. However, conversion of measurements with these devices to absolute electric field values is uncertain. The personal exposure meters, however, can be used to establish relative exposures between groups and individuals.

Exposure models and surrogates for EMF exposure are being developed and traditional exposure assessment methodologies such as job titles, time-activity analyses, and expert panels are being verified. Job title appears to be an indicator of average exposure but because of variability, a complete job history is preferred to a single title for exposure characterization.

The international research effort on EMF includes exposure assessment as well as laboratory and epidemiologic studies.

OUTSTANDING ISSUES

Exposure Metric

Because scientists do not agree on a mechanism for the effects of EMF fields, the choice of the specific agent for exposure assessment remains somewhat arbitrary. Recent epidemiologic studies seem to indicate the importance of magnetic rather than electric fields. However, magnetic and electric fields are correlated and some of the interactions with biological systems are similar, making a distinction between the two difficult. Laboratory research also indicates that effects may be frequency related. Further elucidation of mechanisms is needed before the appropriate choice of agent and, possibly, frequency is clear.

In order to perform an exposure assessment for an environmental agent, an operational definition for measuring the presence of the agent and exposure metric is required. To the extent practical, the exposure metric should be relevant to the effect of the agent on the receptor. For example, the concentration of lead in children's blood would be a better exposure metric for childhood lead poisoning than the presence of lead paint in their homes. There are several possible exposure metrics for EMF exposure. Perhaps the most commonly used has been time-integrated field exposure expressed in terms of kV-hr/m or mG-hr or, equivalently, as an average field in kV/m or mG. However, because there has not been clear evidence of effects related to time integrated exposure, this metric may not be the most appropriate. Numerous other metrics are possible (35).

Determination of an appropriate metric requires additional information from research studies on the effects and interaction mechanisms of ELF fields. However, until direction is available from such research, sufficient exposure data must be obtained to allow characterization in terms of several possible metrics. Identification of a comprehensive set of exposure metrics remains an issue for power frequencies and has not been addressed for other frequencies.

Exposure Indices and Summary Measures

Even without research supporting an exposure metric coupled to effects, it is still possible to develop and investigate exposure indices in the form of summary measures of exposure data or categorical parameters. The choice of exposure index can affect data collection, analyses and interpretation of results. The lack of an accepted mechanism for effects and the nature of EMF fields both argue that the selection of a single summary statistic for characterizing exposure may not be appropriate. Ongoing projects are beginning to investigate the relationship between various summary statistics and non-parametric indices as indicators of exposure (21).

The vast majority of occupational exposures, even among "exposed" groups, occurs at low field levels with relatively little time spent in high fields. In such distributions a few observations in the upper tail of the distribution can be very influential on the time-weighted (arithmetic) mean exposure. Thus, the arithmetic mean may not be a good indicator of central tendency for EMF exposures. Some research suggests that peak, rather than cumulative, exposures are of importance. If this is the case, time above a certain threshold might be a more appropriate summary measure. Obviously, choice of the threshold value would be crucial. Other hypothesized mechanisms could suggest other summary measures.

The uncertainty in identifying meaningful exposures and the skewness of the distributions of measurements argue strongly for utilizing, or at least exploring, more than one parameter to characterize exposure. Establishing relationships between these measures and selecting an optimum set of parameters will require additional research.

Common Protocols

There are numerous reports regarding occupational electric and magnetic field exposure measurements. In addition there are several on-going exposure assessment projects or epidemiologic studies that include exposure assessment. Unfortunately, no minimal set of common protocols has been established to facilitate comparison between studies or allow consolidation of their data. In an area with as much uncertainty as EMF exposure assessment, it is not desirable to establish a fixed exposure assessment protocol that would stifle research. On the other hand, there is a need for a basic set of measurements, analyses, and reports that could be used to link various investigations and facilitate comparison of levels and exposures at various locations.

Historical Exposure Models

Given the uncertainties in ELF exposure assessment and measurements, the extrapolation of contemporary measurements to historical exposures is difficult. Work is in progress to relate electric and magnetic field exposure to job category for electrical workers (36) and to establish the expert panel assessment as a means of determining EMF exposures (31). The results of these efforts should increase confidence in assigning historical exposures, especially among utility workers. However, identifying, quantifying and/or modeling historical exposures for other occupations will remain difficult until considerably more data are gained on non-utility occupational environments.

Database for Non-utility Environments

Several large studies have recently been completed or are currently in progress which will provide extensive data on electric and magnetic fields in utility environments at power frequencies and some harmonics. However, with the possible exception of video display terminals, no other occupational environments have been characterized sufficiently to provide baseline electric and magnetic field data at the frequencies of interest. Given the highly variable nature of ELF exposures, a carefully planned data collection effort will be required for a credible and cost-effective characterization of non-utility environments.

Scaling and Dose

Although exposure refers to the joint occurrence in space and time of a person and an environmental agent, it is important to recognize that exposure assessment, as defined here, is related to *in vivo* and *in vitro* studies. Not only must the exposure in such studies be quantified, but it must also be linked with practical human exposures for the purpose of risk assessment. However, without an accepted mechanism for biological and/or health effects, it is difficult to relate the dose, i.e. the actual amount of the agent that is acting on a biological system, to the exposure that is encountered. Thus, the scaling of exposures from the workplace to the laboratory and vice versa remains an issue for EMF research. Coupled directly to this is the development of dose concepts and models.

Health Effects and Risk Management

Although determination of health effects is outside the realm of exposure assessment, uncertainty about the risk from ELF fields remains the most prominent outstanding issue for exposure assessment. Determination of a mechanism or discovery of a threshold for effects would resolve many of the other issues and allow exposure assessment to more effectively support basic science and epidemiologic research.

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