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Assessment of Magnetic Field Exposures for a Mortality Study at a Uranium Enrichment Plant

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A survey of workplace exposures to 60-Hz magnetic fields was carried out at a large uranium enrichment facility to assign exposures for an updated mortality study. Stratified random selection was used to choose workers for measurement in all jobs and areas, to determine whether consistent distinctions could be made between job groups based on average magnetic field exposures. A total of 252 workdays was measured with a personal monitor, and individual average magnetic field exposures ranged from 0.20 to 82.6 mG. A priori job groups showed significant differences between geometric mean exposures, which ranged from 0.80 to 3.51 mG. Most of these groups showed widely ranging exposures, so they were subdivided based on location and job title to improve the precision of the exposure assignments for the mortality study. These final assignments were made up of 26 groups having arithmetic means ranging from 0.43 to 24.9 mG, with most groups defined by location in addition to job title. In general, electrical maintenance workers did not have elevated magnetic field exposures (>3 mG), but the exposures of the electricians in switchyard (substation) jobs were elevated. Available employment records did not allow most electricians to be distinguished based on location, so they were assigned exposures based on their plantwide average (above 7 mG). An estimated 9% of the work time of this cohort was spent at daily average exposures above 3 mG, despite the very large electric power consumption at this plant.

Keywords: bimodality, exposure assessment for epidemiology, magnetic field exposures, uranium workers

An unpublished mortality study by the National Institute for Occupational Safety and Health (NIOSH), covering the period from 1954 through 1982, found a nonsignificant excess of lymphatic and hematopoietic cancer among workers at the Portsmouth (Ohio) uranium enrichment plant.[1] To take advantage of additional years of follow-up, an updated study was undertaken to include a more detailed assessment of airborne uranium exposures, the agent of most concern for chronic disease outcomes. Because of the very large consumption of electric power at this plant, it was hypothesized that many workers would also be highly exposed to magnetic fields. Up to 1750 megawatts is used daily, nearly as much as is used by a metropolitan area of one million people.

Slightly increased risks of leukemia and brain cancer from magnetic field exposure have been reported, based on utility worker studies that have relied on personal exposure monitoring.[2,3] A regional case-control study of adults in central Sweden found an apparent association between chronic lymphocytic leukemia and measured exposure to power-frequency magnetic fields.[4] Other studies have found no such association.[5]

This article presents the strategy used to survey workers' personal exposure to magnetic fields, and to summarize those results in making exposure assignments for the epidemiologic study. One goal was to use personal measurements to learn whether there were consistent exposure differences between groups of current workers, and to determine whether a large percentage of the work force was exposed to high

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magnetic fields. Another goal was to learn whether electrical workers in general were highly exposed at this plant. Finally, a strategy was developed to assign exposures to work groups identified from historic employment records, based on recent measurements of workers' magnetic field exposures.

Natural uranium consists of U-238 (99%), U-235 (0.7%), and U-234 (0.006%). The proportion of U-235 must be "enriched" to support nuclear fission of the energy released by the nuclear breakdown, whether for weapons or for peaceful uses. This proportion must be increased to at least 2.5% for power generation, and to 97% for military uses. In this plant uranium hexafluoride is heated to become gaseous and the gas is repeatedly driven through porous diffusion barriers. Because the U-235 isotope has slightly less mass, it preferentially passes through the barriers, and gradually has its proportion enriched. This series of diffusion stages is referred to as a "cascade." The gaseous diffusion process uses large amounts of electric power to compress and force the uranium hexafluoride repeatedly through these barriers. Each of the two operating enrichment plants in the United States are made up of thousands of motor-compressor-barrier stages. In some other countries gas centrifuges are used to separate the lighter from the heavier isotopes of uranium.

Electromagnetic fields (EMF) in general are made up of a range of frequencies, including visible light, radio waves, and some ionizing radiation above the ultraviolet frequencies. Because childhood leukemia studies have suggested an effect from living close to high-current neighborhood wiring, workplace and residential studies have primarily focused on power-frequency EMF.[6,7] At these extremely low frequencies the electric and magnetic fields are not coupled and can rise and fall independently of one another. Magnetic fields are generated by flowing current, whereas electric fields are generated by voltage differences. At home, for example, a plugged in but not operating appliance may generate electric fields but not magnetic fields, since current is not flowing. Electric fields, as opposed to magnetic fields, are distorted by all conducting objects, including the human body and any measuring device. Thus, it is not clear how to measure personal exposure to electric fields accurately, since any personal monitor would distort such fields.

Research interest has thus focused primarily on the possible effects of magnetic field exposures, since they would be expected to be high inside homes close to high current conductors, such as those near neighborhood step-down transformers. These magnetic fields are very different from most industrial hazards for which exposures are measured, in that exposures can be just as high at home as at work. The median of both household and workplace daily average exposures is about 0.8 milligauss (mG), so this can be thought of as a typical exposure.[8] A daily average of 3 mG is considered unusual, since it is the approximate 90th percentile of daily average exposures at work.[9] In this article a daily average exposure above this level is considered elevated. There is a threshold limit value (of 10,000 mG) from the American Conference of Governmental Industrial Hygienists for these 60-Hz magnetic fields, but it is not based on the suspicion of carcinogenicity. Instead, it is based on limiting the density of the electrical current induced in the body by the time-varying fields.[10]

In the process of developing a measurement strategy for this proposed study, important decisions needed to be made that were consistent with both feasibility and scientific considerations about possible effects. These decisions included choices of whether to measure electric and magnetic fields, what frequency ranges to measure, how to summarize the between-worker component of exposure variability, and how to choose the workers to be measured in the plant. Some of these decisions were made prior to the start of the range-finding exposure survey; others were made as a result of the experience gained during the survey.

METHODS

To record magnetic field profiles, EMDEX personal dosimeters (Enertech Inc., Campbell, Calif.) were chosen to capture details of the expected variability in personal exposures during the normal workday. Based on earlier workplace measurements, this variability was expected to range up to four orders of magnitude from minute to minute.[11] These instruments, originally developed for the electric utility industry, are small computer controlled 3-axis magnetic field measuring devices with datalogging capacity. They measure the fields repeatedly throughout the work shift and store the data, which were downloaded each day to a personal computer for processing. The EMDEX II model measured simultaneously in the 40–800 Hz and 100–800 Hz bands, which made it possible to deduce whether significant magnetic field exposures lay in the harmonic frequencies (integer multiples of the 60-Hz power frequency).

The term "magnetic fields" will be used here to refer to fields in the frequency range from 40 to 800 Hz, since this is the range that has been measured in other occupational and residential studies. This will allow the results to be compared with other investigators' exposure estimates.

A measurement strategy was developed with several combined goals. These included measuring sufficient workers to detect magnetic field exposure differences between groups, if such differences were present. Job titles were initially gathered into six *a priori* groups thought to have similar exposures to magnetic fields. These groups were ranked by the percentage of total cohort work time, and these percentages formed the basis for the proportional allocation of measurement resources. For example, "other maintenance" jobs made up about 30% of the work time and formed the largest such group, thus workers in these jobs received a commensurate number of personal monitors.

Later, to increase the precision of the estimates for the more highly exposed groups, additional workers were measured. Those groups included electrical maintenance, power operations, and welders. Expected exposure differences were estimated from a review of other workplace measurements of personal exposures to magnetic fields.[11,12]

Whenever possible, workers were selected randomly for measurement from supervisors' lists of workers in the jobs and locations where exposure estimates were needed. To avoid possible bias, two precautions were taken. First, in most cases workers were not allowed to volunteer for measurement. In the author's experience workers tend to volunteer for measurement if they are doing some "interesting" task or think they will be near a field source. Second, the instrument's readout window was inactivated to eliminate "curiosity measurements" by workers. These might include using the instrument to measure magnetic field strength at a location closer to a source than the worker would usually work. Measurement of suspected worst-case exposures was discouraged, since one objective was to estimate the mean of the daily average exposures.

Workers in all jobs and areas, including managers, office, and security workers were measured. Since these magnetic fields are generated by ordinary 60 Hz current, one cannot assume that certain groups of workers are not exposed to these fields.

To create confidence in estimating group mean exposures, it was also important to be able to estimate the between-worker variability of exposure in similar jobs. This variability in daily average exposures was expected to be quite large for maintenance workers, based on other surveys of magnetic field exposure in electrical and other industries. In one large survey of electric utility workers, the distribution of time-weighted average (TWA) exposures for shop workers was very skewed, with a geometric standard deviation (GSD) greater than 3.0.[8] Magnetic field distributions also have been found to be very skewed for other jobs, such as toolmakers and machine repairers.[12]

A two-stage analysis of variance (ANOVA) model was used to evaluate whether to repeat measurements on individual workers. The overall variance of a group mean can be written in terms of the between-worker and within-worker components.[13] If n_1, n_2 are the numbers of workers and of repeat measurements per worker, respectively, and σ_1^2, σ_2^2 are the variances between- and within-workers in each group, then the variance of the group mean exposure can be expressed by the following formula:

$$\sigma_{\bar{x}}^2 = \frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_1 n_2}.$$

If we assume that σ_1^2 and σ_2^2 are approximately equal, it can be seen that increasing n_1 (the number of workers) will serve to minimize this expression more effectively than increasing n_2 (the number of repeats). Such an assumption was found to be reasonable based on magnetic field measurements among utility workers.[14] Thus, for practical convenience and to gain the most precise estimates of the group mean exposures with fixed resources, it was decided not to attempt repeat measurements.

Since between-worker exposure distributions are typically skewed to the right, the geometric mean (GM) is close to the median if the exposure distribution is approximately lognormal. To estimate the sample sizes needed to detect whether two groups of workers have distinct exposures, lognormality of the between-worker distributions was assumed and a standard sample size formula was used on the log-transformed daily averages. With such an assumption, the GM is used as a measure of central tendency, and the quotient of the GMs (rather than their difference) is used to indicate separation. The derivation of these results for a range of between-worker GSDs and a range of quotients of GMs is shown in the Appendix. To detect whether the GM exposures of two groups differ by at least a factor of 2, if the GSD of each group is 2.5, then at least 22 workers must be measured in each group to detect such a difference with 80% power. With these estimates for guidance, plans were made to measure an adequate number of workers to detect 1.5 to 2-fold differences in group GMs.

The measurement campaign began with half-shift sampling to maximize the number of workers. This strategy assumed that the first and second halves of each work shift have similar exposures. As the campaign progressed, doubts arose concerning whether cascade operators might have higher exposures during the first half of their shifts. It was suggested that they might prefer to leave their control rooms to visit less pleasant areas early in the shift, and those areas might result in higher exposures if they had more magnetic field sources. This possibility was investigated following the first part of the data collection, and the data did not support the presence of any such bias.

To evaluate whether the *a priori* job groups had distinct exposures, the observed exposure distributions were examined for symmetry and homogeneity of variance. Since most of these were skewed to the right, ANOVA methods were used on log-transformed data. Effectively this tests whether the GM exposures of the groups are significantly different from one another.

Inspection of the exposure distribution histograms for some of these groups revealed possibly bimodal distributions. This suggested that the *a priori* groups (based only on job titles) were mixtures of workers having different exposure patterns. A statistical test based on bootstrap methods was used to test these distributions for multimodality.[15] This test uses multiple resampling (similar to Monte Carlo methods) based on the idea that the number of modes for a histogram of a distribution decreases as the bin width increases.

To make exposure assignments to workers' job histories for the mortality study, the a priori groups were subdivided into smaller groups having similar exposures. Each of these groups had to be identifiable from the work histories. The available work histories did not directly identify the worker's location but did contain a department number. In most cases it was possible to relate this number to a plant location based on other historic records. Similarity of exposure for these smaller assignment groups was evaluated by comparing their GSDs with the GSDs of the a priori groups.

It was also possible to determine from these historical records that the production process and work practices had changed little over the 38 years of plant operation covered by the mortality study. This led to the assumption that the exposures measured in the 1990s give a reasonable estimate of exposures in earlier decades. There was no historical magnetic field measurement data available that might allow validation of this assumption. Therefore, the measured exposures were used to assign past exposures to worker histories from each decade of plant operation.

The cumulative exposure of any worker can be thought of as a sum of all the daily exposures over his or her work history. For each job this would be a sum of values from a skewed distribution of exposures for the group including that job. The central limit theorem implies that the distribution of sums (over days of exposure) from any skewed distribution will be normal.[13] Thus, for the exposure assignments for the mortality study, the arithmetic mean (AM) of each of these groups was used for each worker in that group.

RESULTS

A total of 252 workers was selected for measurement by stratified random sampling across all jobs at the plant. About half the workers wore the personal monitoring instrument for a full shift, while the other half wore it for a half shift. Half-shift averages were pooled with the full-shift averages, since no bias was found between measuring on the first or the second half of the work shift. Table I shows how the number of measured workers was distributed across the *a priori* job groups. Electrical maintenance workers were sampled more heavily than their work time alone would indicate in order to improve the precision of the exposure estimate for this group.

Daily average exposures of individual workers ranged from 0.20 to 82.6 mG. The highest values were observed among the welders. Within-shift exposure variability was especially large, sometimes reaching four orders of magnitude for workers who passed very close to field sources. The GM of all the average daily exposures was 1.38 mG. Individual group GMs ranged from 0.80 mG for the "other operators" to 3.51 mG for the electrical maintenance workers. These "other operators" worked at chemical cleaning or

TABLE I. Magnetic Field Exposures for *A Priori* Groups Based on Job Title Alone

Job Group	Estimated Percentage of Cohort Work Time[A]	Number of Workdays Measured	GM[B] (mG)	GSD	Range of TWA Exposures
Cascade operators	12	37	1.07	1.87	0.35–3.05
Other operators	15	22	0.80	1.76	0.29–2.69
Electrical maintenance (including power operators and welders)	8	49	3.51	4.69	0.20–82.6
Other maintenance	30	51	0.90	1.97	0.24–6.69
Technicians (including fire and security)	18	44	1.46	2.01	0.44–9.8
Managers, office workers	17	49	1.25	1.97	0.29–4.4
Total	100	252	1.38		0.20–82.6

[A]These are the percentages of total cohort work time (for the 38-year study period) in each group of jobs, based on departmental assignments in the work history file.
[B]This is the GM across workers of the TWA of each worker's sequentially measured daily exposure.

steam plant jobs, to distinguish them from the cascade operators who operated the production process. The distribution of average exposures was skewed to the right, with about 14% of the measured group of workers having averages above 3 mG.

ANOVA comparisons (on the log-transformed data) showed that the *a priori* job groups had distinct exposures, based on the group GM exposures. Pairwise comparisons, however, showed that the only statistically significant differences (at the 5% level) were between the electrical maintenance group and each of the other groups. For each of the other five groups, within-group variability exceeded that between the groups.

Inspection of the exposure distributions suggested that some groups appeared to be mixtures of several distinct distributions (Figure 1). Although the bootstrap statistical test failed to confirm this suggestion of bimodality, the exposure data were examined for characteristics that might predict the observed exposure differences.[15] Location was often found to be such a predictor. For example, it was observed that serving as a technician in a laboratory building dating from the 1950s predicted elevated exposure relative to similar technicians in newer buildings. The *a priori* exposure groups were thus subdivided to reduce spread and to be able to represent each with a single distribution.

The work history records being used for the cohort mortality analyses contained only job title and department information. Workers with the same job title were sometimes found to have quite different exposures, depending on location at the plant. Clerical workers in one older office building had more than three times the measured exposure of similar workers in a newer building. Past exposure assignments were thus made to cohort members based on their department number, since this usually identified their work location for some period of years. In a few cases the department number available was not specific and did not identify specific locations; in that case the assignment group had a fairly broad range of exposures.

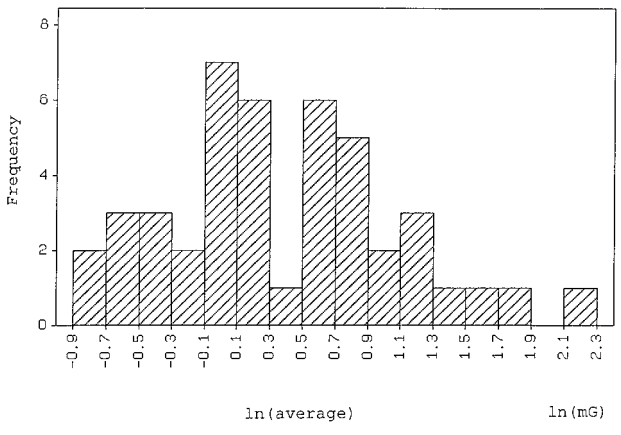

FIGURE 1. Possibly bimodal distribution of log-transformed average exposures of technicians (N=44)

To make an exposure assignment for cohort members in a given department, the largest measured group of workers was chosen whose location and jobs most closely matched that department. The AM exposure of that sampled group served as the exposure estimate for workers in that department. With more than 800 different departments over the 38-year study period, this process was done individually for each of the 200 largest departments, as defined by their contribution to the work time of the cohort. These 200 departments accounted for 93% of the total work time.

These final subdivisions of the six *a priori* groups into smaller exposure groups resulted in 26 subgroups, with average exposures ranging from 0.43 to 24.0 mG (Table II). These final assignment groups usually had smaller measures of spread (GSDs) than did the *a priori* groups. In some cases a department was defined broadly, so the assignment group had a slightly larger GSD. The leftmost column in Table II refers to jobs in departments from the work histories for which exposure assignments were made. The right column refers to the number of measured workers whose exposures best represent the departments in question.

In some cases these exposure assignment groups overlap, since the breadth of departments changed over the plant's history. For example, such overlap could occur if a broad department was subdivided into more specific ones at some other point in time. In that case, the exposure assignment group for the latter (more specific) department became a subgroup of another larger exposure group. As an example, only during certain years was the department for cascade electricians distinguished from that for all plantwide electricians in general. Thus, in the assignments the measured workers' exposures for the small group (cascade electricians) made up a subset of the larger group (all electricians).

Occasionally it was not possible to relate a past department to a group of measured workers. This happened for janitors, who could have worked anywhere in the plant. For these workers and for those assigned to the 600 smallest departments, it would not have been reasonable to assume no exposure, since in modern industrial society everyone is exposed to these magnetic fields.

TABLE II. Magnetic Field Exposure Summary by Subgroups (Ordered by Increasing AM Exposure (mG)

Department Description	AM	GM	GSD	n
Supply clerks	.43	.42	1.31	4
Raw material feed	.56	.52	1.54	5
Decontamination operators	.61	.61	1.06	3
Hi-enrichment cascade operators	.73	.66	1.60	15
Engineering	.75	.70	1.54	4
Maintenance repair shop	.80	.74	1.52	17
Electronic repair	.82	.79	1.36	6
Offices (new)	.84	.79	1.43	12
Mechanical maintenance	.93	.77	1.89	16
Cascade maintenance	1.08	.83	1.93	45
Police	1.17	1.06	1.63	12
Maintenance administration	1.19	.93	1.93	57
Cascade operators	1.28	1.07	1.87	37
Instrument maintenance	1.41	0.98	2.17	16
Computer operators	1.52	0.87	2.85	6
Other cascade operators	1.65	1.48	1.64	22
Garage	1.74	1.58	1.64	7
Air plant	1.84	1.72	1.50	22
Chemical laboratories	2.07	1.91	2.25	14
Medical	2.44	1.90	2.51	3
Cascade electricians	2.52	1.65	2.56	12
Offices (old)[A]	2.71	2.55	1.42	16
Fire protection	3.84	1.66	2.52	7
Plantwide electricians	7.46	2.62	4.37	29
Welders	14.2	5.31	4.60	10
Power operations	24.9	19.0	2.08	6

[A]Workers in these offices, in a building built in 1954, had somewhat elevated exposures that appeared to be due to stray ground return currents from the old wiring.

Since none of these workers would have spent very much time in the 3 most highly exposed jobs or locations, they were assigned the mean exposure (1.4 mG) of the 207 measured workers who remained when electricians, welders, and switchyards were excluded. This assumption was used to assign exposures to only 9% of the work time of the entire cohort.

In one department with a range of job titles having very different exposures, it was necessary to subdivide the departmental exposure assignment based on job title. Welders were distinguished from nonwelders for that department's assignment since they had very different exposures and both contributed substantially to the work time of that department.

Only some of the electricians at this plant were among those with elevated exposures. Those regularly near high-current conductors, such as in the switchyards where large transformers reduce transmission voltages, were highly exposed. Electricians not in the switchyards had a median exposure of 1.23 mG (n=26), only slightly above the normal background of about 0.8 mG.

Certain groups of office and professional workers had higher than expected exposures, with GMs above 1.9 mG. One office and one laboratory building were found to have above background magnetic field exposures, which were not specific to any particular source or job. Exposures in these buildings were not due to nearby high-current power lines, but appeared to be due to anomalies in the buildings' internal wiring that may have caused additional ground return currents.

DISCUSSION

At this workplace it has been possible to distinguish groups of workers from one another based on measured personal exposures to time-varying magnetic fields. Most of these distinctions have been based on combinations of location and job title. In some cases, job title alone did not predict exposures, as was illustrated for electricians and office workers.

Very high consumption of electrical power at this plant does not imply that a large fraction of the workers are highly exposed to magnetic fields. An initial hypothesis had been that since flowing current generates magnetic fields, and this plant uses as much electrical power as a large city (up to 1750 mW daily), then many workers would have high exposures. More measured workers had average exposures above 3 mG than in the employed population in general (14 versus 10%), but workers in these jobs represent only about 9% of the work time of the cohort. These high exposures were encountered by switchyard workers, welders, and some electricians. Magnetic fields lose strength rapidly with distance from the source, and it was found that relatively few workers at the plant were consistently very close to the magnetic field sources.

Some common assumptions about workplace chemical exposures do not apply to magnetic fields at this site. For example, large groups of professionals and office workers had higher magnetic field exposures than did production and maintenance workers. This was likely due to ground return currents from frequently modified internal wiring in one old office building, built in 1954. These slightly elevated exposures were not due to nearby high-voltage transmission lines, nor to office equipment. Most electricians outside the switchyards did not have elevated daily average exposures. Those working near high power conductors did have elevated exposures but those doing maintenance work in production areas did not.

Some misclassification was likely to have occurred in making these assignments, primarily because the groups were defined only with variables available in the work histories, which were not as specific as desired. For example, these histories were only partially informative on whether an electrician was assigned to general maintenance or to cascade maintenance. The former could have been in the switchyard (with high exposure), whereas the latter would not have been. Such misclassification would be unlikely to result in a spurious epidemiologic finding of an exposure effect, since it would likely to be nondifferential with respect to disease status.

The smaller AMEX personal monitor (Enertech Inc., Campbell, Calif.) was used by other investigators to sample electric utility workers randomly for magnetic field measurements.[2] Its use was considered but rejected here, because it offered a report of only average exposure and could not record an exposure profile. These profiles may become important in the future to compute and compare alternate exposure indices among this population.[16] Brief events can have a major impact on average exposure, and the Emdex instruments preserve a record of most of them. Later research may indicate that the TWA field strength is not an appropriate summary metric and that some measure of exposure irregularity is biologically active. In that case, such an metric can be computed and workers' relative exposures can be reassigned to learn whether the new metric may be associated with an increased risk of chronic disease.

A number of case-control studies have been carried out that use job title as the basis for making judgments about magnetic field exposures. Some of these studies have found increased risk of brain cancer or leukemia among electrical workers. Such studies have often been interpreted as magnetic field studies based on an assumption that most electrical workers have had elevated exposures.[17,18]

A few investigators have attempted to validate this widely held

belief that electrical workers, in general, are highly exposed to magnetic fields. London and Bowman sampled a variety of electrical occupations and used a task-based exposure reconstruction strategy.[19] They concluded that most of these occupations were more highly exposed than the overall population of workers. Their result seems to differ from the present study, in that most electrical maintenance workers (outside the switchyards) at this plant did not have elevated exposure. This difference may be due to the possibility that "curiosity" measurements by sampled workers might have biased some of their results by introducing spurious peak values. Workers may also have volunteered for measurement on the basis of doing especially "interesting" work that day, work that may have had higher exposure than typical tasks. The choice of task percentages may also have inadvertently introduced an upward bias in their exposure estimates.

The weakness of job title alone in predicting exposures has also been suggested in other exposure investigations. A French survey of the magnetic field exposures in electrical generating workers found that the type of plant (fossil fuel versus nuclear) was the most important characteristic to be included in an occupational exposure matrix.[20] In an exposure assessment across three large electric utilities in Canada and France, exposure differences also were found for the same job at different employers.[3] Given the possibility of these differences, future epidemiologic investigations of possible effects of magnetic field exposures may have to be more cautious in making presumptions of exposure similarity within jobs. On the other hand, when making exposure assignments for an entire study population based on personnel records, it may not always be possible to make fine distinctions based on location or task. In any case, careful exposure evaluation strategies can provide an improved understanding of the magnitude of the exposure misclassification that may be present.

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REFERENCES

1. **Brown, D., and T. Bloom:** "Mortality among Uranium Enrichment Workers. Report to the National Institute for Occupational Safety and Health." 1987. [Unpublished] National Institute for Occupational Safety and Health, 4676 Columbia Pkwy, R-14, Cincinnati, OH.
2. **Savitz, D., and D. Loomis:** Magnetic field exposure in relation to leukemia and brain cancer mortality among electric utility workers. *Am. J. Epidemiol. 141*:123–134 (1995).
3. **Theriault, G., M. Goldberg, and A. Miller:** Cancer risks associated with occupational exposure to magnetic fields among electric utility workers in Ontario and Quebec, Canada, and France: 1970–1989. *Am. J. Epidemiol. 139*:550–572 (1994).
4. **Floderus, B.P., T. Persson, and C. Stenlund:** Occupational exposure to electromagnetic fields in relation to leukemia and brain tumors: a case-control study in Sweden. *Cancer Causes Control 4*:465–476 (1993).
5. **Sahl, J., M. Kelsh, and S. Greenland:** Cohort and nested case-control studies of hematopoietic cancers and brain cancer among electric utility workers. *Epidemiology 4*:104–114 (1993).
6. **London, S., D. Thomas, J. Bowman, E. Sobel, T. Cheng, and J. Peters:** Exposure to residential electric and magnetic fields and risk of childhood leukemia. *Am. J. Epidemiol. 134*:923–937 (1991).
7. **Savitz, D., H. Wachtel, F. Barnes, E. John, and J. Tvrdik:** Case-control study of childhood cancer and exposure to 60-Hz magnetic fields. *Am. J. Epidemiol. 128*:21–38 (1988).
8. **Bracken, T.:** Exposure assessment for power frequency electric and magnetic fields. *Am. Ind. Hyg. Assoc. J. 54*:165–177 (1993).
9. **Bowman, J., D. Garabrant, E. Sobel, and J. Peters:** Exposures to extremely low frequency (ELF) electromagnetic fields in occupations with elevated leukemia rates. *Appl. Ind. Hyg. 3*:189–94 (1988).
10. **American Conference of Governmental Industrial Hygienists (ACGIH):** *Documentation of the Threshold Limit Values and Biological Exposure Indices,* 6th ed., vol. 3. Cincinnati, OH: ACGIH, 1991.
11. **Wenzl, T., D. Kriebel, E. Eisen, P. Tolbert, and M. Hallock:** Magnetic field exposures in an automobile transmission plant. *Arch. Environ. Health 52*:227–232 (1997).
12. **Floderus, B., T. Persson, and C. Stenlund:** Magnetic field exposures in the workplace: reference distribution and exposures in occupational groups. *Int. J. Occup. Environ. Health 2*:226–238 (1996).
13. **Snedecor, G., and W. Cochran:** *Statistical Methods.* Ames, IA: Iowa State University Press, 1967. p. 529.
14. **Kromhout, H., D.P. Loomis, G.J. Mihlan, L.A. Peipins, et al.:** Assessment and grouping of occupational magnetic field exposure at five electric utility companies. *Scand. J. Work Environ. Health 21*:43–50 (1995).
15. **Silverman, B.:** Using kernel density estimates to investigate multimodality. *J. Royal Stat. Soc. B 43*:97–99 (1981).
16. **Wenzl, T., D. Kriebel, E. Eisen, and E. Ellenbecker:** Comparisons between magnetic field exposure indices in an automobile transmission plant. *Am. Ind. Hyg. Assoc. J. 56*:341–348 (1995).
17. **Lin, R., P. Dischinger, J. Conde, and K. Farrell:** Occupational exposure to electromagnetic fields and the occurrence of brain tumors: an analysis of possible associations. *J. Occup. Med. 27*:413–419 (1985).
18. **Milham, S.:** Mortality in workers exposed to electromagnetic fields. *Environ. Health Perspect. 62*:297–300 (1985).
19. **London, S.J., J.D. Bowman, E. Sobel, D.C. Thomas, et al.:** Exposure to magnetic fields among electrical workers in relation to leukemia risk in Los Angeles county. *Am. J. Ind. Med. 26*:47–60 (1994).
20. **Guenel, P., J. Nicolau, E. Imbernon, G. Warret, and M. Goldberg:** Design of a job exposure matrix on electric and magnetic fields: Selection of an efficient job classification for workers in thermoelectric power production plants. *Int. J. Epidemiol. 22(suppl 2)*:S16–S21 (1993).
21. **Kleinbaum, D., L. Kupper, and K. Muller:** *Applied Regression Analysis and Other Multivariate Methods.* Boston: PWS-Kent Publishing Co., 1988. p. 31.

APPENDIX

In this context "statistical power" refers to the ability to detect differences between the magnetic field exposures of job groups, if such differences are truly present.

Using a classic sample size formula, it is possible to estimate the magnitude of an exposure difference between job groups that can be detected with a given level of confidence. This treatment assumes that the between-worker exposure distributions are approximately lognormal. Then a one-sided statistical test can be used on the log-transformed exposures to calculate the magnitude of the differences (quotients) in the group GM exposures that it will be possible to detect. For this application to magnetic fields, it will be assumed that each individual is assigned his or her individual AM exposure (equivalent to the traditional TWA) and that detection of differences in the group GMs is being attempted.

To test H_o: $GM_1 = GM_2$ versus H_a: $GM_1 < GM_2$, one formula reads:[21]

$$n > 2(Z_{1-a} + Z_{1-b})^2\sigma^2/\Delta^2$$

Applying this formula to the log-transformed (normal) exposure data:

- Δ = $\ln(GM_1)$-$\ln(GM_2)$ = $\ln(GM_1/GM_2)$, the difference to be detected
- σ = ln(GSD) for GSD = GSD of each between-worker distribution.
- a = probability of Type I error, namely finding a difference where none exists
- 1−b = power, where b = probability of Type II error, failing to detect a difference that is present
- n = number of measured workdays needed in each group
- Z_c = value of standard normal deviate with area to the left (under the standard normal curve) equal to c; for example, $Z_{.975} = 1.96$

For the range of GSDs expected, and for various quotients of group GM exposures, this formula gives required sample sizes for each group (for a=0.05 and b=0.20).

TABLE IA. Required Sample Sizes

	GM_1/GM_2		
	1.5	2	3
GSD			
1.5	13	5	2
2.0	37	13	5
2.5	65	22	9
3.0	93	31	13