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COMPARISONS BETWEEN MAGNETIC FIELD EXPOSURE INDICES IN AN AUTOMOBILE TRANSMISSION PLANT

Thurman B. Wenzl^a
David Kriebel
Ellen A. Eisen
Michael J. Ellenbecker

Department of Work Environment, University of Massachusetts Lowell,
 Lowell, MA 01854; ^aCurrent address: National Institute for Occupational
 Safety and Health, 4676 Columbia Parkway, R-44, Cincinnati, OH 45226

Personal monitoring of extremely low frequency magnetic fields was conducted at a large automatic transmission plant for a case-control study of primary brain cancer. Current workers were selected to represent the jobs most commonly held by study subjects. Several exposure indices, corresponding to different plausible biological mechanisms, were computed for each of 81 workers who wore the monitoring instrument for one-half shift. Average exposures covered a range from 0.16 to 46 mG; median exposure was 1.3 mG. Nonparametric correlations were estimated to learn whether all of these indices rise and fall together. Results were mixed, in that indices sensitive to high values showed correlations above 0.7, but other correlations were between 0.4 and 0.6. Different indices may thus identify different groups as "highly" exposed. The authors also tested whether indices based on the fraction of time spent above hypothesized thresholds were accurately predicted by a lognormal model. For 47% of the workers, the observed indices significantly exceeded those predicted by such a model, suggesting that lognormality is not a good model for distributions of individuals' short-term exposures.

Evaluation of possible associations between brain cancer and extremely low frequency magnetic fields (MF) is hampered by the limited biological guidance on which aspect of these low energy fields might contribute to excess risk.⁽¹⁾ This article presents an exposure survey and data analysis comparing different ways of summarizing magnetic field exposure for a case-control study of brain cancer at a large industrial plant. This is one of the first surveys to utilize personal monitoring of MF exposure outside the electrical utility industry.

Both occupational and residential studies of magnetic fields have suggested a cancer promotion effect for these fields, but

most have relied on exposure surrogates thought to correlate with magnetic field exposure.^(2,3) In residential studies of childhood leukemia the health effects appear to be associated more closely with the surrogate—an indicator of proximity to high-current neighborhood wiring—than with the measured average MF exposure.^(4,5) One possible explanation of this result is that some aspects of the MF are carcinogenic, but the wire code better represents the "true" exposure index than does average exposure as estimated by the household measurements.

It is important that any exposure index used in an epidemiological study be consistent with what is known of the mechanisms of harm.⁽⁶⁾ Such an exposure index is a biologically relevant summary of an individual's exposure pattern over time. For example, to assess hazards of dusts that cause damage to the deep lung, the relatively small respirable fraction of the total airborne particulate is collected and used to estimate cumulative exposure.

New instruments allow us to record real-time profiles of personal exposure to MF. For this work, half-shift exposure profiles were recorded for a representative group of workers in an automobile transmission plant as part of an epidemiological investigation of brain cancer. From these profiles examples from several types of plausible exposure indices were derived. If these indices are highly correlated with one another, and if one of them is biologically appropriate, we will then have more confidence in the interpretation of an epidemiological result based on any one of them. But if they are not highly correlated, then exposure assignments may differ depending on the index chosen, and exposure assessment strategies will have to be designed to capture each of the characteristics that may be biologically relevant.

In the absence of clear guidance at this time on the biological mechanisms of cancer promotion from these fields, we cannot say which exposure index is physiologically appropriate. But we can compare several reasonable indices with one another. Two of the indices used here are measures of the central tendency of the distribution of magnetic field exposure over time, others of percent time spent above possible threshold exposures ("exceedance fractions"), and yet others of exposure variability. To estimate the degree of association between each pair of indices, the Spearman correlation coefficient has been used, since the distributions of the indices are not normal but skewed to the right.

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Distributions of short-term mean exposures generally are skewed toward higher values and sometimes are regarded as log-normally distributed for each individual worker. With their data the authors have compared the measured exceedance fractions (for the one minute mean exposures) with those for the corresponding lognormal distributions to test whether these indices are predicted accurately by such an assumption.

The overall goal of this work was to survey MF exposures across a large nonelectrical plant, and to compare with one another a collection of exposure indices corresponding to several different biological models. Secondly, whether exposure indices based on percent time above a possible threshold are well predicted by assuming a lognormal distribution of short-term exposures for each worker was investigated. Exposure assignments for the epidemiological investigation of brain cancer have been developed elsewhere.⁽⁷⁾

METHODS

This exposure evaluation took place in a large metal machining plant in the midwestern United States that manufactures automobile transmissions. Exposure data were collected for use in a case-control study of brain cancer, nested inside a cohort study of all subjects who had worked for at least three years at this facility during the period 1941 to 1985. Approximately 8000 persons now work at this plant in a variety of machining, assembly, and maintenance tasks. Steel parts are machined and assembled into transmissions, which are then sent to auto assembly plants. The plant has been operating at this location since 1954, with gradual reductions in the workforce from the introduction of more automated machines.

Measurement Strategy

Workers were selected for MF measurement from job titles chosen to be representative of the jobs held by the subjects in the case-control study. Total work-time for these subjects was computed from work histories and, for example, 20% of this time was made up of machine repair and maintenance jobs. Thus about 20% of the total of 81 workers measured were chosen from these jobs (Table I). Similarly, about 60% of the work time was in machining jobs and 15% in assembly jobs. The total number of workers measured was based on the resources available for four weeks of field measurements. Within these broad categories the most common job titles were determined and departments having both these jobs and older machines were identified. Then, with the cooperation of supervisors and union representatives, volunteers were sought for measurement in these jobs. The industrial hygienist selecting jobs for measurement was provided with a list of jobs held by either cases or controls and the amount of work time in each job, but was unaware of which jobs were held by cases versus controls.

Each worker selected for measurement was asked to wear a magnetic field measuring instrument for about 3.5 hours. This measurement duration was chosen, rather than a full shift, to allow monitoring of sufficient workers, as a balance between

feasibility and numbers. One-half shift was believed to be adequate to capture most of the normal within-day exposure variability for each worker.

The measuring device used, the EmdexC (EFM Inc., W. Stockbridge, Mass.), is a small computer-controlled field measurement and recording instrument, sensing magnetic flux density with three mutually perpendicular coils. The principle of operation is that a time-varying magnetic field induces a current in a wire coil having its plane perpendicular to the field. Raw data from each of these coils is combined onboard into a resultant value by taking the square root of the sum of the squares of the three components. These data were downloaded each day into a portable computer for further processing. The internal circuitry has a relatively flat frequency response from 40 to 400 Hz, and so, while 60 Hz fields are the principal target of this study, it will detect those in a limited range of other frequencies. An independent check showed that the accuracy of this instrument is approximately $\pm 7\%$ of the indicated reading.⁽⁸⁾ Before and after each measurement campaign, the calibration of the meters was checked by placing them in known magnetic fields up to 25 mG generated by a Helmholtz coil (Model 117, EFM Inc.) Calibration results varied by approximately 5% over time. Background field strength at the location of the calibration was 0.4 mG.

The instrument was set to measure and record readings every four seconds, which were then reduced to one-min (arithmetic) means for further analysis. The within-worker exposure indices were then computed from these sample distributions of one-min means. This type of data smoothing implies that the biological mechanism (if any) is insensitive to brief changes, but that minute-long changes in MF strength may cause an effect.

In general, workers were chosen without any knowledge of exposure levels or sources that might have been present. Older departments were chosen to estimate past exposures at the plant for the epidemiological study. As the measurement campaign progressed, unexpectedly strong sources such as demagnetizers (see below) were identified, and in a few cases persons were selected for measurement because they worked in a department having a demagnetizer. The potential effect of this selective sampling on the comparisons between exposure indices was examined by comparing the correlation coefficients computed with and without these eight workers included.

Choice of Exposure Indices

Exposure indices to summarize the single half-day's experience of each worker were chosen from among several categories, including measures of central tendency of the distribution of one-min means, skewness (or right-tail size), and variability over time (Table II).

The measures of central tendency considered were the arithmetic mean (AM) and geometric mean (GM) of the one-min averages. The AM is the equivalent of the traditional TWA, or the area under the exposure curve divided by the time elapsed. This index is consistent with a cumulative exposure model, appropriate when risk is believed to increase linearly with increasing total dose.⁽⁹⁾ The GM, on the other hand, deemphasizes the influence of brief high exposures, since the average is computed on the log-transformed data. Biologically this index might

TABLE I. Magnetic Field Exposure Averages by Job Category (in milliGauss)

Job Category	n	GM ^A of AMs ^B	Range of AMs
All Measured Workers	81	1.6	0.16–46
Machining	49	1.9	0.41–46
Plantwide Maintenance	15	1.5	0.70–9.9
Assembly	12	0.65	0.16–4.9
Demagnetizer-Influenced Workers	8	13	4.4–46

^A Geometric mean—this is the exponentiated mean (across-workers) of the log-transformed within-worker AMs, chosen to represent the central tendency of the skewed distribution across workers.

^B Arithmetic mean—this within-worker average is the sample mean of the approximately 200 one-minute average exposures, each of which is an average of 15 instantaneous datalogger readings; there is one of these AMs for each person. This AM is equivalent to the usual TWA exposure.

correspond to a mechanism that is insensitive to brief peak exposures.

Another possible model for the mechanism of action is the existence of a threshold below which repair mechanisms are effective. Risk in this case would only be associated with exposures in excess of this threshold. If the dose-response curve were relatively flat above this point, then one possible exposure index would be an estimate of the percent time spent above this threshold. (If it were not flat, an appropriate index might be a TWA for only those periods when the threshold was exceeded.)

For estimating such a right-tail probability (of an exposure distribution), two of the indices chosen were exceedance fractions. The percent time spent above 3 and 10 mG were computed (and will be referred to as ex3 and ex10). The 3 mG point was chosen as a possible threshold because two independent groups of investigators have determined that about 95% of U.S. homes have magnetic field exposures below this level.^(10,11) The 10 mG level was chosen as an exposure level unlikely to be found at home, which might identify high industrial exposures. The 95th percentile of each worker's exposure distribution (of one-min mean exposures) also was computed as another index that would distinguish a skewed distribution by its right-tail probability.

Recent investigations suggest that exposure to MF intermittents, or "jagged" exposure profiles, may be the biologically active property. One recent study suggests that 5 mG exposure spikes (from certain types of electric blankets) are associated with diminished night-time melatonin production by the pineal gland.⁽¹²⁾ Since melatonin is known to hinder cancer growth,⁽¹³⁾ this may be the biological link between magnetic fields and cancer promotion. Other studies show a possible biological effect to the heart from sudden changes in magnetic field exposure intensity, rather than from its average intensity.⁽¹⁴⁾

Based on these reports a measure of the "jaggedness" of the exposure pattern also was computed. This new index was defined as the percent of consecutive minutes for which the exposure differed by more than 5 mG (referred to as jag5), giving a relative frequency of exposure jumps of at least 5 mG.

The standard measure of spread for a lognormal distribution, the geometric standard deviation (GSD), also was computed for

each worker. Since the GSD is the exponentiated standard deviation of the log-transformed data, it also can be thought of as a measure of variability in the exposure profile. It is also an indicator of the degree of skewness of an exposure distribution; that is, how far it differs from a symmetric normal distribution. In summary, a total of seven exposure indices were computed for each measured worker.

Correlations Between Exposure Indices

To evaluate the degree of association between exposure indices, nonparametric Spearman correlation coefficients⁽¹⁵⁾ were computed. This statistic was used to measure the degree of association because each index had a non-normal distribution, skewed to the right. Pairwise correlations of six indices of central tendency, exceedance, and exposure variability thus were calculated. (One exceedance index, ex10, was excluded from these comparisons because half the measured workers' exposures never exceeded 10 mG.)

Because of the potential importance of demagnetizers and other strong sources on a few workers' exposure patterns (described below), each of the correlations was calculated on the entire data set and on a restricted data set. The restricted data set excluded the eight workers measured in departments chosen with advance knowledge of high-intensity sources being present. Such an influence analysis indicates whether the findings are robust with respect to possible biases introduced by the measurement strategy chosen and by the presence of demagnetizers in certain departments.

Prediction of Exceedance Fractions—Lognormality

Lognormality is widely used to describe various right-skewed distributions in occupational health, and this distributional form sometimes has been assumed to evaluate compliance questions for short-term mean exposures.⁽¹⁶⁾ Since the exceedance indices are areas under the right-tail of the observed distributions of one-min mean exposures, one might wish to estimate the actual exceedances by their lognormal equivalents. Here the observed exceedances for each worker are compared to those that would be predicted under the lognormal assumption, to test

TABLE II. Definitions of Exposure Indices Derived from Magnetic Field Datalogger Record for Each Worker Measured

AM:	Arithmetic mean of the one-min average exposures (n ≈ 200), equal to the TWA
GM:	Geometric mean of the same one-min averages
ex3:	Percent of one-min average exposures exceeding 3 mG
ex10:	Percent of these exposures exceeding 10 mG
ni5:	95th percentile of the (n = 200) one-min average exposures
jag5:	Percent of adjacent minutes with exposures differing by greater than 5 mG
gsd:	Geometric standard deviation of the individual workers' exposure distribution

TABLE III. Summary Statistics for Each of the Magnetic Field Exposure Indices (n = 81)

Exposure Indices	Summary Statistics:							
	min.	25th	50th	75th	max	AM	GM	GSD ^A
AM (mG)	0.16	0.82	1.3	2.5	46	3.1	1.6	2.8
GM (mG)	0.14	0.51	0.85	1.3	17	1.4	0.88	2.2
ex3 (%)	0	1.1	5.2	15	82	13	■	■
ex10 (%)	0	0	0.5	2.4	71	4.0	■	■
ni5 (mG)	0.28	1.7	3.0	5.2	140	7.8	3.5	3.1
jag5 (%)	0	0	1.2	3.9	42	3.8	■	■
gsd ^A	1.2	1.8	2.4	2.8	5.6	2.5	2.3	1.4

^A GSD and gsd are unitless measures of spread.

^B The GM and GSD cannot be computed on an index for which some values are equal to 0.

whether this model accurately estimates the proportion of time the worker spends above the possible thresholds. This comparison was carried out in the following way.

For each worker's measured exposure distribution, the sample GM and GSD were computed and an "expected" lognormal distribution constructed having these specific parameter values. The exceedances (beyond 3 and 10 mG) of each observed distribution then were compared with those of the theoretical lognormal distribution having the same GM and GSD. In this way the observed fraction of measurements above the hypothesized threshold was compared with the fraction expected from the "theoretical" lognormal distribution.

For each lognormal distribution generated from the observed GM and GSD, the standard normal deviates or "z-scores"⁽¹⁵⁾ for the 3 and 10 mG points were computed for the log-transformed data. For example, $z = \{\ln(3) - \ln(\text{GM})\} / \ln(\text{GSD})$ gives the z-score for the ln(3 mG) cutoff on the normal distribution that corresponds to a lognormal exposure distribution having a given GM and GSD. This was then converted into a probability for each worker, which was compared to the observed probability, namely the fraction of total minutes actually measured whose mean exposure exceeded 3 mG.

In order to place approximate 95% confidence intervals (CIs) around the exceedance fraction expected under lognormality, Monte Carlo simulations, sampling repeatedly from the lognormal distribution having the desired parameters, were used. Since each worker was represented by approximately 200 one-min average exposures, a 200-point random sample was drawn 100 times from each of the theoretical lognormal distributions and the exceedance was calculated for each. A 95% CI then was

estimated by taking the 2.5 and 97.5 percentiles of this sequence of exceedance fractions. An observed exceedance fraction then was said to be higher than expected if it lay outside this 95% CI placed around the exceedance fraction expected under lognormality. In this way the authors tested whether lognormality accurately predicts observed exceedance fractions for each individual worker. This could be a potentially important characteristic if a biological mechanism of harm having a threshold becomes important for MF.

RESULTS

Measurement Summary

Eighty-one workers from jobs in departments having older machines were selected to wear the magnetic field dosimeter for approximately one-half shift. Workers were selected with the cooperation of union stewards and line managers, and included metal-cutting machine operators, assemblers, and various maintenance workers (Table I).

At the outset the principal sources of MF were anticipated to be the electric motors powering the machine tools in the plant. In addition to these, the measurement survey identified unexpected sources of very strong magnetic fields in several departments. One of these was demagnetizers, which are used in production and nonproduction departments to remove permanent magnetism induced in some parts by grinding operations. These were primarily AC coil demagnetizers that produced a continuously reversing magnetic field through which a conveyor stream of parts was passed to remove the permanent magnetism. A total

TABLE IV. Summary Statistics for Demagnetizer-Exposed Workers, for Each of the Exposure Indices (n = 8)

Exposure Indices	Summary Statistics:							
	min.	25th	50th	75th	max	AM	GM	GSD ^A
AM (mG)	4.4	7.1	10	33	46	18	13	2.3
GM (mG)	.44	1.1	1.9	7.8	17	4.6	2.5	3.3
ex3 (%)	3.6	6.5	24	73	82	35	20	3.4
ex10 (%)	1	2.6	17	47	71	25	11	5.0
ni5 (mG)	2.7	7.7	29	79	140	44	23	3.9
jag5 (%)	1.7	4.0	18	35	42	19	12	3.3
gsd ^A	1.9	3.2	4.1	4.6	5.6	3.9	3.7	1.4

^A GSD and gsd are unitless measures of spread.

of 23 demagnetizers were identified, 10 of which were in production departments. Of the 81 measured workers, eight had very high exposures due to work near these devices, with (half-shift) average exposures above 4.4 mG and one-min averages reaching 1300 mG. Another important source was electrical distribution panels near the workstations.

Full-period (one-half shift) measures of central tendency for individual workers varied over more than two orders of magnitude (Table III). The arithmetic mean (AM) exposure varied across workers from 0.16 to 46 mG, with median of 1.3 mG. The geometric mean (GM) also showed a wide range, from 0.14 to 17 mG. A consistently high exposure will result in both the AM and GM being high, but for an exposure profile with brief peaks the AM will be much larger than the GM. For example, this is illustrated in the data with one worker having AM = 4.4 and GM = 0.44 mG.

Measures of exceedance and jaggedness also showed a wide range of values (Table III). About half the workers exceeded the 3 mG threshold (ex3) more than 5% of the time. This particular statistic fails, however, to distinguish between exposures slightly higher and much higher than 3 mG; e.g., between exposures clustered around 4 or 40 mG. There is more information in the 95th percentile (ni5), since it describes more clearly how far above 3 mG most of the exposure lies. Looking at the interquartile range of ni5, we can see that about 25% of the measured workers had their 95th percentile above 5.1 mG. In most cases the highest exposures for each index were among the subset of workers exposed near the demagnetizers (Table IV).

Of the 81 workers measured, 30 (37%) never had a 5 mG jump or fall in exposure from one minute to the next; i.e., their jaggedness statistic (jag5) was equal to zero. Most workers with high jag5, that is having 5 mG exposure transients at more than 10% of their consecutive minutes, worked in departments with demagnetizers.

Correlations Between Indices

Nonparametric correlation coefficients were computed between each pair of exposure indices to estimate their degree of association. These coefficients show only a moderate relationship between the chosen indices of central tendency and right-tail size (Table V), with correlations ranging from 0.6 to 0.9. Correlations were lower between the GM and the indices of variability, jag5 and gsd.

As expected, stronger correlations were found between indices sensitive to the right-tail size—e.g., between the AM and ex3—than between the GM and ex3, since the GM deemphasizes the right-tail. Comparing the AM-jag5 with the GM-jag5 coefficients, we again can see the closer agreement between the first pair of indices, which are both sensitive to peaks.

The eight persons measured in departments chosen with advance knowledge of high-exposure sources were excluded and the correlation coefficients recalculated to learn whether the associations were strongly influenced by these few measurements. The Spearman (nonparametric) coefficients changed very little.

Prediction of Exceedance Fractions—Lognormality

Comparisons of exceedance fractions between the actual measured distributions and the comparable lognormal ones

TABLE V. Spearman Correlation Coefficients Between Summary Exposure Indices Derived from Workers' Magnetic Field Exposure Records (n = 81)

	AM	GM	ex3	ni5	jag5	gsd
AM		.82	.79	.80	.74	.61
GM			.61	.60	.44	.21
ex3				.90	.72	.76
ni5					.74	.79
jag5						.69
gsd						

showed many of the measured exceedance fractions to be larger than expected under a lognormal model. An example of this comparison is shown in Figure 1.

At the 3 mG point, 20 of the 81 workers (25%) had observed exceedance fractions significantly larger than expected (based on lognormality). Using the simulated confidence intervals, the authors determined that the irregularities in the observed exceedances, as in Figure 1, were larger in each of these cases than could be accounted for by random variation within a lognormal model. A scatter plot of the observed vs. lognormal exceedances at 3 mG shows the prediction to be poor, with workers having exceedances either significantly larger or smaller than predicted (Figure 2). (Note that the straight line with confidence intervals in Figure 2 is not a regression line, but a line on which observed exceedances equal those expected under lognormality.) At 10 mG, 18 other workers (22%) had significantly larger exceedance fractions. Only one worker appeared in both groups, with exceedance fractions past both 3 and 10 mG significantly larger than expected. This total of 38 workers (47%) with either ex3 or ex10 larger than expected were not concentrated in any particular job category. Four of the workers near a demagnetizer had ex10 larger than predicted.

Since only 8 of the 81 workers had exposures influenced by demagnetizers, these larger-than-predicted exceedance fractions were apparently due to multiple MF sources, with the worker close enough to have an exposure contribution above the exceedance cutoff. These sources included fluorescent light ballasts and electric motors.

DISCUSSION

The authors' results at a nonelectrical industrial plant show a wide range of average exposures to power-frequency magnetic fields, but with many falling in the same range as typical exposures at home. Household average (AM) exposures have been reported to have a median of 0.8 mG, with an interquartile range from 0.4 to 1.3 mG.⁽¹⁷⁾ Approximately 50% of the sampled population had AM exposures below this 75th percentile (1.3 mG) of household exposures (Table III). Thus half the workers at this plant are estimated to have occupational exposures no higher than general population exposures at home.

The correlation coefficients found here between within-worker exposure indices were neither very high nor very low,

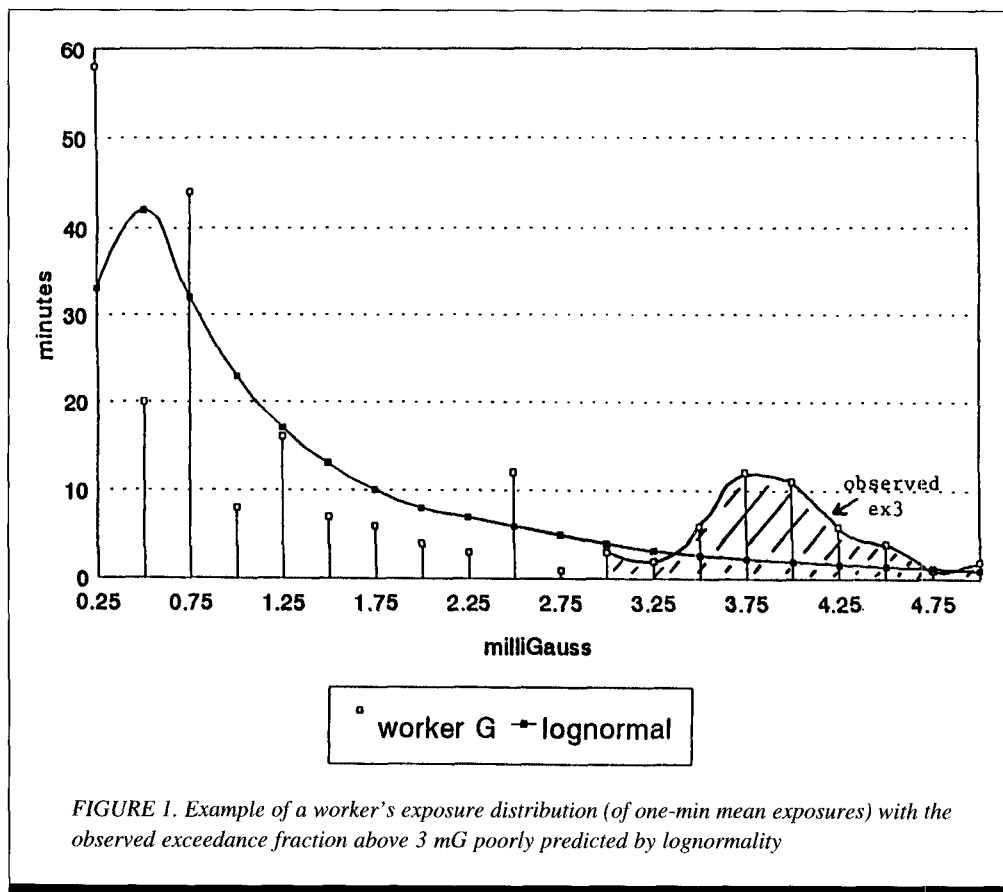


FIGURE 1. Example of a worker's exposure distribution (of one-min mean exposures) with the observed exceedance fraction above 3 mG poorly predicted by lognormality

those departments' results removed and showed only slight changes, suggesting that no major bias was introduced.

The results here are consistent with those of Armstrong,⁽¹⁹⁾ who computed correlation coefficients between several exposure indices for electrical utility and office workers and found similar degrees of association among indices of central tendency and right-tail size. In his case, using a "contrived" sample of utility and office workers that was not chosen with any attempt at representativeness, he was concerned about limits on generalizability. Now with a similar result from a more representative sample across a large workplace, the present authors can suggest that these correlations may hold more generally. Armstrong did not look at the measures of exposure variability, but did investigate several unusual "window" statistics, namely exposures that fell into certain ranges, bounded both above and below. He also looked at correlations between electric

and magnetic field indices, and found them to be poor.

making interpretation difficult. If we interpret the correlation coefficients using an important general finding on mismeasured explanatory variables,⁽¹⁸⁾ then we can say, for example, that if ex3 were the biologically appropriate measure of exposure, then the power of a study using the AM would be only 63% of that from using the ex3, since this is the square of the estimated correlation between these two indices. In the case of rare diseases such as brain cancer, which provided the impetus for this exposure survey, this loss of power could be significant in an effort to detect slightly increased risks.

One could ask whether the measurement campaign captured a typical collection of exposures at this workplace, or whether biases were introduced in the measurement strategy. The selection of measured jobs was based on the work time held by 29 cases and 145 matched controls. The workers chosen to wear dosimeters were selected from representative jobs found in departments in the older sections of this plant. Even if cases were concentrated in particular jobs or areas, 80% of the work time (which was the basis for the representative selection) was accounted for by the matched controls. Thus the measured workers can be expected to represent approximately the plant's entire historical work force, since the work time of study subjects was dominated by the disease-free controls.

The sampling strategy became slightly nonrepresentative as the authors sought measurements in a few departments where some workers were heavily exposed by unexpected magnetic field sources. Correlation coefficients were recomputed with

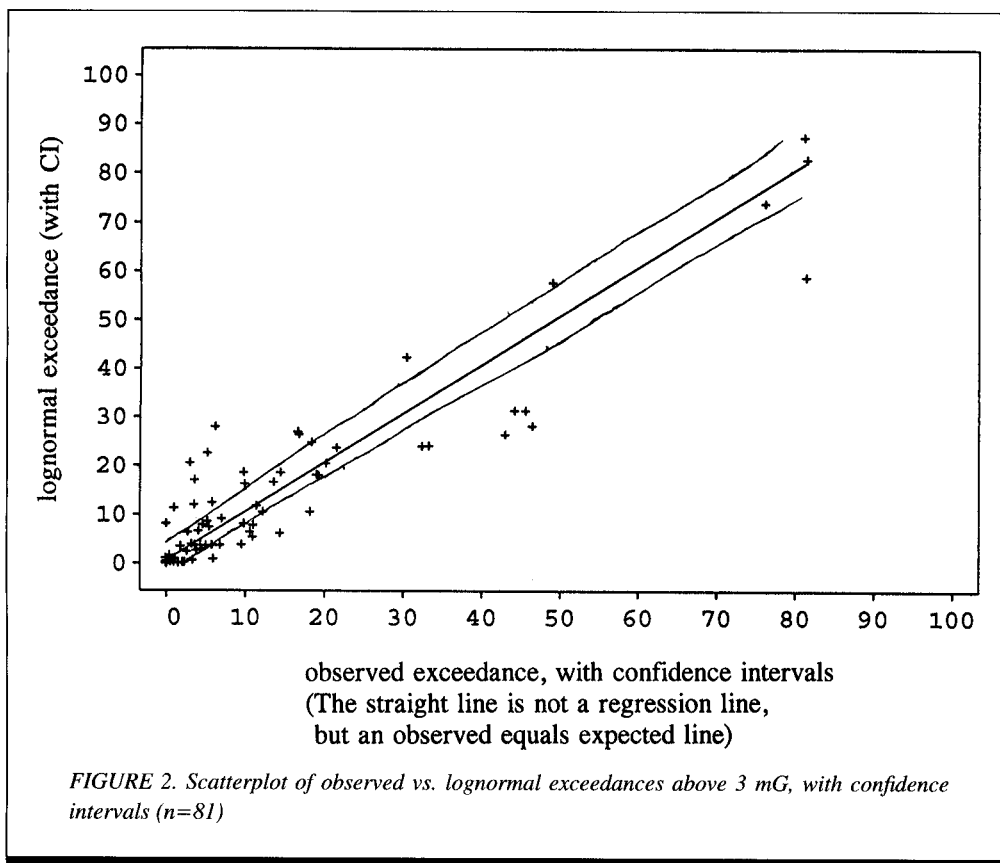
and magnetic field indices, and found them to be poor.

The authors have made specific choices with the data as to smoothing interval (one minute) and transient-height (5 mG). In some cases the indices may vary with different choices here. For example, the gsd as an index of variability would be larger if it had been computed on the original (every 4 sec) data. It also will be useful to learn "background" levels of the new jaggedness index, to learn how this workplace differs from household exposures.

Exceedance fractions for short-term magnetic field exposure were not reliably predicted by a lognormal model, as numerous workers had larger-than-expected exceedances above both 3 and 10 mG. For individual workers the authors showed via simulation that random variation from minute to minute within a lognormal model could not explain the variation in the observed tails. As far as variability across workers, the observed exceedances fell on both sides of those predicted by the lognormal model; some were underestimated while others were overestimated.

Such a lognormal assumption has been used to suggest that short-term exposure limits (STELs) for chemicals may be redundant.⁽¹⁶⁾ It has been argued mathematically that if short-term means are lognormally distributed, then eight-hour average sampling "can be used to limit the frequency of exposures in excess of a STEL."⁽¹⁶⁾ The authors' result may become important if a threshold mechanism turns out to be biologically significant, and an exceedance-type exposure index then becomes the

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appropriate choice for epidemiological analyses. If so, it will not be appropriate to estimate these indices from any assumption of lognormality, and they will have to be derived from the measurements.

This survey suggests that these fields are very different from most occupational chemical exposures, since home and work averages are often in the same range. For other exposure indices such as exceedance fractions and variability measures, it remains unknown whether there are significant differences between home and work exposure patterns. Additional surveys of personal exposure are needed to better characterize exposure patterns in a broader population of workplaces and homes.

CONCLUSION

While the interpretation of these associations between indices remains uncertain, the modest coefficients suggest that epidemiological analyses should be carried out with more than one type of exposure index, since they may not rise and fall together. Exposure variability may be the biologically important characteristic and the authors' indices of this characteristic might differ from the usual average exposure, so different indices may identify different groups as "highly" exposed. If so, epidemiological results would certainly depend on this choice of index. A recent conference report suggests that analyses with more than one index are feasible, as residential magnetic field exposure profiles from a childhood leukemia study are now being reworked in this way.⁽²⁰⁾

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