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Magnetic Field Exposures in an Automobile Transmission Plant

Thurman B. Wenzl , David Kriebel , Ellen A. Eisen , Paige Tolbert & Marilyn Hallock

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THURMAN B. WENZL*
DAVID KRIEBEL
ELLEN A. EISEN
Department of Work Environment
University of Massachusetts
Lowell, Massachusetts

PAIGE TOLBERT
Emory University
School of Public Health
Atlanta, Georgia
MARILYN HALLOCK
Environmental Medical Services
Massachusetts Institute of Technology
Cambridge, Massachusetts

ABSTRACT. Inconsistent findings from recent mortality studies of workers exposed to magnetic fields have led to calls for more detailed understanding of exposure distributions and metrics in various industries. The authors undertook personal monitoring at an automobile transmission plant to (a) learn if magnetic field exposure differences were present, (b) make assignments for a brain cancer study, and (c) compare two exposure indices. A wide range of average exposures occurred (i.e., 0.016–4.6 microtesla). Within-day variability was also large, and it reached 4 orders of magnitude for some workers. Unexpectedly, demagnetizers were found among the strong sources that contributed to elevated exposures. The authors used conventional summary measures to assign job groups to exposure categories, and they used a new index of exposure irregularity to make alternative assignments. These new assignments appeared to differ from the original ones with respect to work time in each exposure group (i.e., 54% of the work time fell into different exposure categories).

RECENT STUDIES of the possible association between workplace exposure to magnetic fields (MFs) and certain cancers are superior to earlier studies because workplace measurements were used as the basis for exposure assignment in the recent studies. Investigations among large cohorts of electric utility workers have occurred in Canada and the United States,[1,2] but an association between brain cancer and MF exposure was found only in the United States. Investigators reported a relationship between MF exposures and chronic lymphocytic leukemia in a large Swedish case-control study conducted across many occupations, but no association with brain cancer was found.[3]

The results of early case-control studies suggested that there was some characteristic of electrical work that contributed to excess brain cancer,[4,5] and investigators hypothesized that this characteristic might have been exposure to MFs. Overall, both occupational and childhood study results have been inconsistent, and in some studies, no effects have been reported.[6] Given that it is not clear whether the time-weighted average exposure to MFs is the appropriate exposure index, some researchers have explored several choices of indexes.[3]

The current assessment of MF exposures was part of a case-control study of brain cancer at an automobile transmission-manufacturing plant. Our objective was to learn if a sufficiently wide range of MF exposures was present and to determine if there were groups of jobs that could be clearly differentiated by exposures. Furthermore, we compared different choices of exposure indices to learn if they identified the same groups as being "highly" exposed.

Dr. Wenzl is currently affiliated with the National Institute for Occupational Safety and Health, Cincinnati, Ohio 45226.

Method

For each of the 29 cases of primary brain cancer, we chose 5 controls from the cohort, matched for sex, race, and age at risk. Investigators abstracted work records of these study subjects, and they were provided approximately 2 800 work-years of job records for exposure assignment. Records took the form of a list of job title/department combinations, and they contained the dates that the study subjects had worked there. We set measurement priorities by determining fractions of the entire work time in each of the several broad job groups, and we allocated actual MF measurement times to correspond to these fractions (Table 1).

For monitoring purposes, we selected workers who spent most of their workday doing the most common jobs, based on their percentage of work time. We monitored a total of 81 workers who were selected from the same pool of employees that contained the study subjects. Exposure assessment was carried out in the absence of information about the disease status that corresponded to each job-history record.

We chose workers from departments that housed older machines to estimate past and present exposure patterns. In most cases, workers chosen for measurement had no knowledge of the expected exposures in their departments. As the measurement campaign progressed, unexpectedly strong field sources (e.g., demagnetizers) were discovered. These devices were used in several operations, and they removed permanent magnetism that parts acquired from the friction of a grinding operation. To investigate the impact of the demagnetizers, we selected a few workers for measurement from three departments known to have these sources. We used influence analysis to investigate the possibility of bias from the measurements for the 8 workers chosen from these three departments; 4 of the 8 workers were actually exposed to the strong fields from the demagnetizers.

Personal measurements of MF exposure were made with a 3-axis data-logging dosimeter, the Emdex C (EFM [W. Stockbridge, Massachusetts)], which was worn by the selected workers during a 1/2-h shift during which they completed their normal tasks. This device, which combines the 3-axis readings into a resultant, records a detailed MF exposure profile by taking a measurement every 4 s. At the end of each day, the data were downloaded to a portable computer. The patterns of use of certain strong MF sources were gleaned via interviews and observation.

Table 1.—Distribution of Work Time for Brain Cancer Cases and Controls among Job Categories

Category	Work time (%)*
Production machining	43
Nonproduction machining	8
Assembly	15
Maintenance	18
Other plantwide workers	16

*Percentage of the total of 2 800 work years spent in each job category at the plant, by study subjects.

We reduced exposure records to a series of 1-min averages for further analysis. In an effort to summarize exposures, we accounted for both within-worker and between-worker variability. The choice of a within-worker exposure index to be used in an epidemiologic study should be based on what is known about biologic mechanisms of harm (e.g., whether short-term peak exposures contribute to the effect being studied).[7]

In our study, the initial exposure evaluation included the usual within-worker summary—the arithmetic mean (*AM*) of the sequential measurements—which is equivalent to the time-weighted average (TWA) exposure. To summarize between-worker variability for each group, we used the geometric mean (*GM*) of the individual TWAs because the median of a log-normal distribution of exposures can be estimated by this statistic.

We identified jobs that involved similar tasks and exposures, and all job titles were collapsed into 13 groups. We ordered these groups by the exposure summary statistic chosen (i.e., the group geometric mean of the within-worker arithmetic mean). Exposure assignment, which we made for the epidemiologic study by assigning each job group to one of three exposure categories (i.e., high, medium, or low), were based on the group geometric means. There was poor precision in some groups that resulted from the small numbers of measurements with a wide range; therefore, we decided to place jobs into three exposure categories.

As described earlier, a few workers had very high exposures because they worked near demagnetizers and other strong and uncommon MF sources. We based some assignments of jobs to exposure categories on judgments about the prevalence of nonrepresentative sources among the measured workers in a job group.

There was a wide range of exposures in each category; therefore, we used analysis of variance (ANOVA) to compare the between-category with the within-category differences. Exposure distributions were tested for log-normality, using the Shapiro-Wilk's statistic.[8]

To learn whether the category geometric means differed from one another, we also performed multiple-comparison tests. We initially performed these tests on the entire data set, after which we used two types of exclusions to further evaluate the influence of the demagnetizers on the results. First, we excluded all 8 demagnetizer-exposed workers. We then excluded another group of 8 because they were from departments in which employees had advance knowledge of the presence of demagnetizers. This "influence analysis" allowed us to determine whether the observed differences between categories were driven solely by the exposures of a few workers who may have had nonrepresentative exposures.[9]

We used the geometric mean exposures of each of the three categories to make quantitative exposure assignments (in milligauss) to all job titles. Given the sensitivity of some category geometric means to the exposures of a few workers exposed to peaks from demagnetizers, we compared the percentage of demagnetizers in our measured sample with an estimate of the percentage plant-wide. We used this estimate to interpolate an exposure value between the geometric mean exposure of the slightly biased sampled population and the geometric mean of the workers uninfluenced by demagnetizers.

The initial exposure index (or metric) was not the only one possible. The arithmetic mean (or TWA) for individuals has been used, but it is possible that the active biological mechanism may be consistent with other summary measures of exposure. There is some evidence that variability in exposure may be a biologically active property[10]; therefore, we created a robust index of variability to make alternate exposure assignments. These new assignments were then compared with the original assignments.

We defined this variability statistic (i.e., jag5) as the percentage of adjacent minutes during the measured period for which the 1-min average exposures differed by more than 0.5 microtesla (μT). This definition reflected variability throughout the day—not just isolated peak exposures. We computed the median of this jaggedness statistic for each group, and the 13 job groups were rank ordered, based on these medians. We made alternate assignments to high, medium, and low degrees of jaggedness.

To test whether this alternate exposure scheme caused jaggedness categories to differ significantly from one another, we used a nonparametric test.[11] We assessed agreement between these alternate assignments and the original ones (i.e., based on the geometric mean of the TWAs) with a 3 × 3 table, with entries reflecting the percentage of time study subjects spent in each job group (Table 2).

Results

Within-day variability of exposures for some workers was very large (i.e., 1-min average MF exposures ranged over 4 orders of magnitude, from 0.01 to 130 μT [1 μT = 10 milligauss]). An example of this temporal variability in exposure is shown in Figure 1. Arithmetic means of the 200 1-min average exposures—equivalent to the usual TWA exposure—varied from 0.016 to 4.6 μT.

We expected that motors and wiring would be principal sources of MFs, but an unexpected variety of other strong sources emerged. Unexpectedly, we found that demagnetizers were quite important: they influenced exposures of 10% of the workers sampled. These devices, which are used in grinding operations, remove permanent magnetism induced in the metal part by the friction of the grinding wheel. In the plant, we identified a total of 21 demagnetizers, of which 10 were in production departments. Other MF sources included power panels, motors, and fluorescent light ballasts.

We ranked the geometric mean exposures for the 13 job groups, and assembly workers and material handlers had consistently lower MF exposures than machining and maintenance workers. Similarly, nonproduction grinders and electricians experienced higher exposures than other production machining and maintenance workers. We therefore assigned nonproduction grinders and electricians to a high-exposure category, assembly and material-handling workers to a low-exposure category, and all other remaining jobs to a medium-exposure category.

We used professional judgment and robustness considerations to place borderline-exposure job groups. One factor we considered was the presence among the measured sample of several workers for whom exposures were influenced greatly by demagnetizers. We compared the proportion of sampled workers in each category affected by these sources with the estimated true proportion in each category. For example, 40% of the measured jobsetters worked near demagnetizers, but this source was overrepresented in our measured population because every department had a job setter, but less than 40% of departments had demagnetizers. Thus, we down weighted the geometric mean for this group, and we assigned the job setters to the medium-exposure category. We made similar judgments to distinguish assembly testers from other production machinists (Table 3).

The exposure distributions were more log-normal and normal, and the variances of log-transformed exposures were approximately equal for each of the exposure categories. We applied an ANOVA model to the three categories of log-transformed within-worker arithmetic means, and some pairs of geometric means differed significantly for these categories ($p < .001$). Assuming log-normality and using the pooled sample variance, we estimated 95% confidence intervals for each of these category geometric means (Fig. 2).

We used multiple-comparison tests with influence analysis to evaluate whether the exposure differences between categories were driven solely by a few highly exposed workers. The ANOVA result remained significant when we excluded two different groups of potentially influential exposures. One excluded group was all

Table 2.—Comparison of Two Methods of Exposure Assignment: One Based on the Geometric Mean (*GM*) of Arithmetic Means (*AMs*) and the Other Based on the Medians of jag5[2] (0.5-μT Jaggedness Statistic)

	GM of *AMs*			
	Low	Medium	High	Total
Median jag5:				
Low	7.6	20.1	0	27.7
Medium	13.6	35.2	4.7	53.5
High	0	15.9	2.9	18.8
Total	21.2	71.2	7.6	

Notes: Entries are percentages of study subjects' work time spent in each exposure assignment category. *GM* of *AM* = the geometric mean across workers of the individual worker's arithmetic means. Median jag5 = the median across persons of the individual worker's index of jagged exposure.

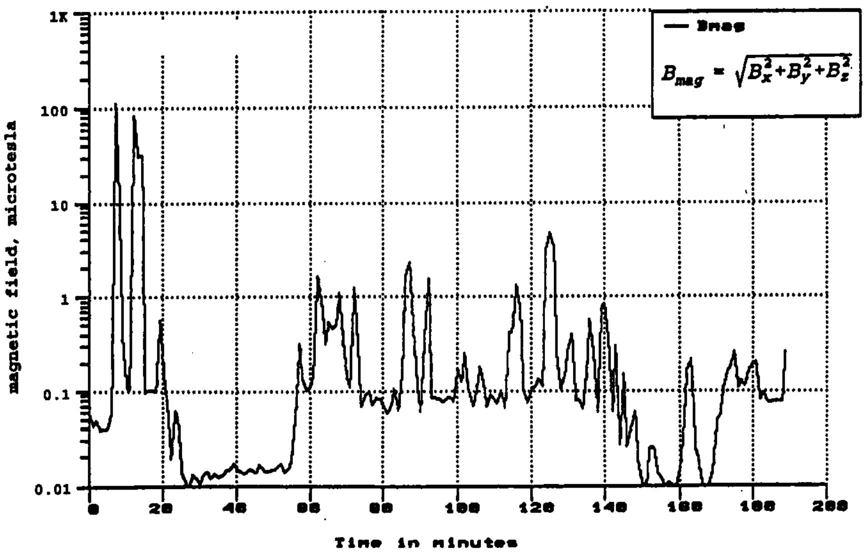

Fig. 1. Magnetic flux density (1-min averages) versus time. Shown is an example of a worker's large minute-to-minute variability in personal exposure.

workers exposed to demagnetizers, and the second group comprised 8 individuals who worked in departments and for whom there was an awareness that high exposures were possible.

We used several multiple-comparison tests on the entire data set, with the same exclusions. Each of the category geometric means differed from one another, even when we excluded possibly nonrepresentative workers. Therefore, the exposure distinctions between the categories chosen appear to be robust.

To accumulate exposure for the epidemiologic analysis, we estimated magnetic field intensity levels for the jobs in each of the exposure categories. The demagnetizer-influenced workers were overrepresented slightly among the workers measured; therefore, we estimated field levels for each exposure category by interpolating between the geometric mean values for the population sampled and the slightly slower geometric means for the 73 workers uninfluenced by demagnetizers.

We estimated the true fraction of demagnetizer-influenced workers by comparing the fraction influenced on the first 2-wk measurement visit (i.e., when departments were chosen for measurements and when there was no awareness of demagnetizer presence) with the overall sample fraction. The latter fraction was influenced by our subsequent choice, based on the expected presence of demagnetizers, of three departments for measurements. The overall sample fraction of demagnetizer influence was 10%, whereas the sample fraction determined for the first visit was 7.5%. Based on advance knowledge, we excluded from the measured sample the 8 workers in the three departments chosen for measurements, and the sample fraction for demagnetizers was 5.5%. Given that the number of departments with demagnetizers was small, relative to the plant as a whole, the true fraction having this influence was estimated at 6%. We used this figure to adjust by interpolation the exposures of the high- and medium-exposure groups.

In addition to the TWA, we calculated the new index of irregularity (jag5) from each worker's exposure profile. To use this index for alternate exposure assignments, we ranked the 13 job groups by the median of the worker's jag5 index. We then divided ranked groups into high-, medium-, and low-exposure categories. Several such divisions were possible, each based on professional judgment. One such assignment placed maintenance electricians, production grinders, job setters, and nonproduction machinists in the high-exposure group (median jaggedness: 3%–8%). We used a median jaggedness equal to 0 to place nonelectrical maintenance workers, bore and face machinists, and hand-assembly workers in the low-exposure category. We assigned the remaining job groups to the medium-exposure category.

A nonparametric Kruskal-Wallis test, performed across these three (new) exposure categories, showed that there were significant differences between the categories ($p < .0001$). The time at work in each exposure group was compared with the original assignments in a 3×3 table (Table 2); the study subjects spent 54% of their time completing tasks in job categories for which the two assignments did not agree. This result suggests that an epidemiologic analysis based on these alternate assignments may have different results than one based on the initial (i.e., TWA-based) choice of exposure index.

Discussion

We detected exposure differences between grouped jobs in an automobile transmission plant. The results of influence analyses showed that these differences were not artifacts that depended on the presence of very strong sources or on a few departments selected nonrandomly during the survey.

Table 3.—Job Group Exposure Summaries with Assignments to Categories (in microtesla)

Job group	*N*	*GM* of *AM**	No. influenced by demagnetizers†	Category *GM*	Assignment category
Nonproduction grinders	4	0.39	1	0.39	High
Maintenance electricians	4	0.38	1		
Jobsetters	5	0.37	2	0.18	Medium
Production grinders	6	0.26	2		
Other nonproduction machinists	4	0.23	0		
Inspectors	4	0.20	0		
Drill	7	0.19	1		
Bore and face	5	0.14	0		
Nonelectrical maintenance	9	0.14	0		
Other production machinists	18	0.13	1		
Assembly, utility, and test	4	0.13	0	0.06	Low
Material handlers	3	0.05	0		
Assemblers (hand)	8	0.05	0		

*The geometric mean (*GM*) of the arithmetic means (*AMs*) is the *GM* across workers of the individual worker's measured AM exposure (i.e., time-weighted average).
†The number of workers in each group whose exposures included a component from the demagnetizers.

Some investigators have suggested that most other exposure indices correlated reasonably well with the individual arithmetic mean.[12] Use of another type of comparison, based on fractions of cohort work time in our analysis, enabled us to suggest that one other index (i.e., exposure irregularity) may yield different results; in this analysis, we placed different workers' jobs in the high-exposure category.

The range of exposures at this plant was similar to that of electric utility workers (group geometric mean exposures: 0.06–0.39 μT). Our plant, however, likely contained a smaller fraction of the workforce exposed at high levels. In our study, approximately 7% of the workers had elevated average exposures (i.e., > 0.3 μT); this percentage was based on the time that cases and controls spent in the high-exposure jobs. In one of the few exposure surveys conducted across many nonutility workplaces, Floderus found personal exposures that are in agreement with our results.[13] In her survey, geometric means of daily averages for mechanics, repair workers, and machine operators ranged from 0.16 to 0.31 μT.

Despite the presence of hundreds of electrically powered machine tools, background exposure at our plant was only about 0.015 μT. This can be compared with a large survey of electric utility workers (i.e., 24-h monitoring), in which only approximately 5% of average exposures at home were less than 0.02 μT.[14] This low background exposure at the plant may have resulted from the 440-V electrical-distribution network in the plant, thus causing a lower current flow than a 100- or 220-V system.

The least-exposed group of workers in this plant had median exposures (0.06 μT) in the same range as most persons' daily exposures. The median of home and office average exposures was approximately 0.07 μT.[14]

The contribution of demagnetizers to high personal exposures at this plant was totally unexpected. Smaller demagnetizers are used in some library and retail security devices, but it is not known if their contribution to worker exposure has ever been evaluated.

One initial hypothesis was that maintenance workers would have lower exposures than machining workers. This hypothesis was based on the fact that safety rules required electricity to be turned off to any machine before repairs could be made. The exposure patterns of the maintenance workers and observations of their work practices demonstrated that workers must get close to energized equipment during the diagnosing of problems. These workers experienced exposures in the medium to high range. Based on the measurements conducted, we placed electricians in the high-exposure category and other maintenance workers in the medium-exposure group.

Some exposure misclassification likely occurred in this study, and this would tend to obscure a disease association if one were present, given that misclassification would have affected both cases and controls equally. One area of possible misclassification was the lack of certainty regarding how the magnetic field exposure may have changed over time at this plant. Measurement at machines of different ages revealed no clear patterns, but this result was uncertain because there existed a

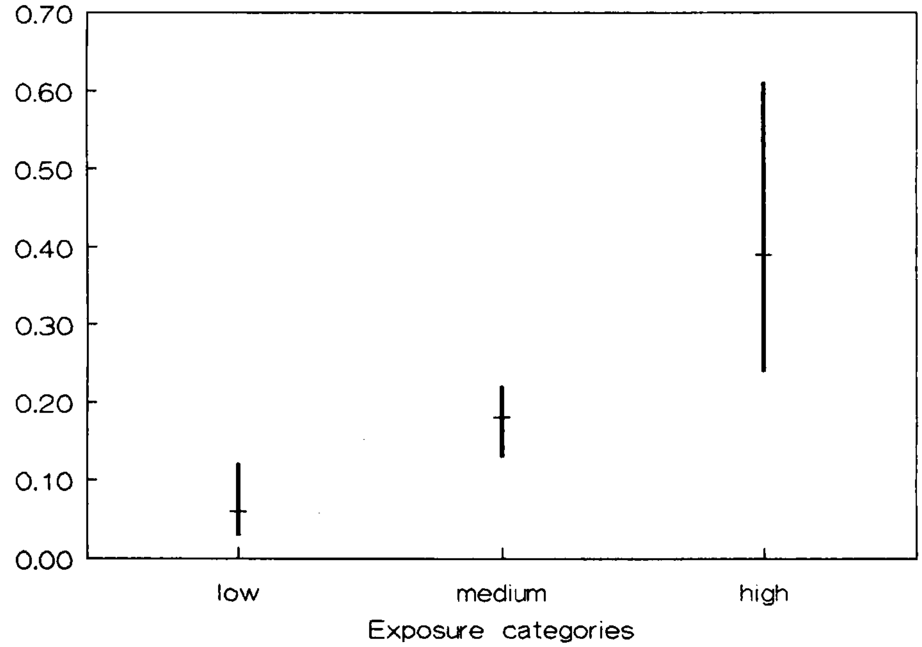

Fig. 2. Geometric means of exposure categories and 95% confidence intervals.

dearth of machines of very different ages. We used a strategy to seek out older departments, but most machines had been acquired after the 1970s.

We did not measure within-worker variability (i.e., from day to day) in our strategy. If one were to assume that this variability could be approximated by the variability between workers in the same job group, then the arithmetic mean of the individual arithmetic means may have been appropriate. A between-worker summary (i.e., arithmetic mean of the arithmetic means), however, has the disadvantage of having great sensitivity to a few high values, especially in the presence of small sample sizes. We used the geometric mean here to summarize group exposures because, in our situation, it had greater stability.

Any exposure-assessment team that undertakes estimation of long-term exposure patterns should evaluate possible sampling biases and, when possible, adjust for them. This can be important when historical data are compared with more recent exposure measurements, if it is suspected that past exposures were measured often in response to problems. The researcher may use both professional judgment and influence analysis to evaluate such uncertainties and possible biases.

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Requests for reprints should be sent to Thurman B. Wenzl, Sc.D., C.I.H., National Institute for Occupational Safety and Health, Mail Stop R-44, Columbia Parkway, Cincinnati, OH 45226.

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