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Sensitivity of the Relation between Cumulative Magnetic Field Exposure and Brain Cancer Mortality to Choice of Monitoring Data Grouping Scheme

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We examined the effectiveness of alternative grouping strategies with respect to cumulative exposure to magnetic fields and brain cancer mortality among electric utility workers. We applied a statistically optimal job-exposure matrix to calculate cumulative exposure over full work histories. We studied the sensitivity of the exposure-disease relation by assigning an array of different quantitative exposure estimates based on six schemes for grouping exposure measurements. The quantitative relation between cumulative magnetic field exposure and brain cancer mortality appeared to be sensitive to the choice of grouping scheme, with the optimized grouping scheme indicating stronger relations than standard schemes. (Epidemiology 1997;8:442–445)

Keywords: EMF, sensitivity, exposure-response relation, exposure assessment, brain cancer, workers.

Currently, two approaches are available to develop estimates of individual workers' quantitative exposure.[1–4] The first is comparable with approaches generally employed in nutritional epidemiology and utilizes personal estimates of historical exposure. The best example of this approach in occupational epidemiology is in studies of ionizing radiation exposure, in which each worker's exposure is monitored continuously during the entire period of employment. In most occupational studies, however, large temporal variation in exposure intensity, lack of historical data, and complicated logistics of data collection discourage application of the individual approach. More common is a group-based approach, in which monitoring data are used to assign exposure scores to workers who share the same environment, for example, department, job, function, or occupation.

Until recently, there was no formal method available to determine the optimal scheme for grouping workers when using the latter approach. A default grouping by job title was therefore typically applied. A simple ratio of the between-worker variance component and the sum of the between- and within-worker components has been proposed as a measure of between-group contrast in average exposure.[4] Estimating this ratio for different grouping schemes provides an opportunity to choose objectively the best-performing option for exposure assessment, using statistical criteria. The optimal grouping scheme can differ between industries, and even between agents within an industry.[1] Moreover, analyses to identify the optimal grouping strategy can be done independently of the assignment of individual exposure scores and analysis of the exposure-response relation.

Despite the theoretical advantages of using objective methods to aggregate workers in a group-based exposure, the effects of these procedures have not been empirically evaluated in studies with cumulative exposure data. Here, we examine the sensitivity of a previously observed exposure-disease relation to the choice of schemes for grouping exposure measurements. We reassigned exposure scores using an array of different quantitative exposure estimates based on different occupational grouping schemes, and we present the effect on the observed cumulative exposure-response relation.

Methods

In an earlier paper,[5] we observed a relative risk for brain cancer of 1.07 [95% confidence interval (CI) = 1.01–1.14] per μT-year of exposure to magnetic fields, using a company-specific job-exposure matrix optimized by methods described above to calculate cumulative magnetic field exposure over the work histories of 138,905 men employed at five electric power companies in the United States.[6] Detailed information on the design of the retrospective cohort mortality study can be found elsewhere.[5–8] Only the measurement strategy used to estimate exposure to magnetic fields, the different group-

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TABLE 1. Characteristics of Six Job-Exposure Matrices (JEMs) Used to Assign Magnetic Exposure Estimates to Workers from Magnetic Field Monitoring Data

JEM and Definition	Number of Groups	Contrast	Precision	Exposure Range (μT)
1. OC Measurements grouped by occupational category only	28	0.49	9.9	0.11–1.50
2. Company Measurements grouped by company only	5	0.02	19.2	0.41–0.69
3. OC/Company Measurements grouped by occupational category combined with company	120	0.56	5.0	0.05–1.95
4. Level Measurements grouped by level of exposure (High/Medium/Low) assessed by judgment of OCs	3	0.29	27.8	0.24–1.03
5. Optimal AM Measurements grouped by categorization of occupational category/company combinations producing maximal contrast and precision	5	0.59	25.5	0.12–1.27
6. Optimal GM Same as 5 for geometric mean magnetic field exposure	5	0.59	25.5	0.10–0.47

ing schemes, and the data analysis methods will be described here.

Measurement Strategy

We constructed 28 occupational categories to consolidate thousands of job titles at the five participating companies. Judgment and experience gained from two preliminary surveys were used to aggregate the 28 occupational categories into three ordinal levels of presumed magnetic field exposure. We set a goal of 4,000 full-shift magnetic field measurements, based on considerations of time, cost, and tolerance of the participating companies. The number of measurements to be made in each occupational category was a function of the total number of measurements projected, arbitrary weights of one, three, or five for the three exposure levels, and a second set of weights proportional to person-years of employed experience contributed by each of the five companies.

Randomly selected workers wore a personal dosimeter that recorded the time-integrated average magnetic field exposure over the work shift. To characterize temporal variability in exposure, each worker selected in the "medium" and "high" exposure groups was measured on 2 randomly selected days. The temporal variability in exposure in the "low" exposure group was expected to be small, so study resources were conserved by measuring workers in these occupational categories only once.

Ultimately, 2,842 full-shift measurements were available, of which 662 were repeated measurements performed on average 120 days after the initial measurement (range = 1–649 days).

Grouping Schemes

We evaluated six job-exposure matrices (JEMs). Three were based on traditional groupings by factors that can be identified from company records: occupational category (OC JEM), company (Company JEM), and combination of occupational category and company (OC/Company JEM). A fourth JEM was defined by the three levels of presumed exposure assigned by judgment before the measurements were taken (Level JEM). Two other JEMs were developed by grouping the actual exposure measurements in each occupational category of the five companies. One of these (Optimal AM JEM) was the optimal JEM used in the original analysis of the retrospective cohort mortality study.[6] In this JEM, grouping was based on the distribution of the arithmetic mean exposure of each occupational category measured successfully in each company (N = 120). We chose the 25th, 50th, 75th, and 87.5th percentiles as arbitrary cutoff points to arrive at five groups. We also constructed a similar JEM based on the distribution of geometric mean exposure (Opti-

TABLE 2. Descriptive Statistics for Different Magnetic Field Exposure Metrics for All Members of the Cohort (K = 138,905)*

Metric	AM	GM	GSD	$_{BW}R_{.95}$	Range
Duration (days)	5157	3340	2.93	67	181–24662
Cumulative exposure OC JEM (μT-days)	473	260	3.36	114	0–5455
Cumulative exposure Company JEM (μT-days)	691	437	3.00	75	0–3743
Cumulative exposure OC/Company JEM (μT-days)	480	230	3.97	208	0–8789
Cumulative exposure Level JEM (μT-days)	527	291	3.37	116	0–4715
Cumulative exposure Optimal AM JEM (μT-days)	484	239	3.72	172	0–5770
Cumulative exposure Optimal GM JEM (μT-days)	228	130	3.27	104	0–2150

* Eighty-one cohort members had a cumulative exposure of 0 μT-days; calculations of GM and GSD were done by taking natural logarithm of (cumulative exposure + 1). N = number of observations; AM = arithmetic mean; GM = geometric mean; GSD = geometric standard deviation; $_{BW}R_{.95}$ = ratio of 97.5th and 2.5th percentiles of between-worker distribution.

TABLE 3. Correlation Matrix for Different Magnetic Field Exposure Metrics for All Members of the Cohort (K = 138,905)

Metric	Duration	OC	Company	OC/Company	Level	AM
OC JEM	0.73					
Company JEM	0.96	0.69				
OC/Company JEM	0.66	0.92	0.64			
Level JEM	0.75	0.91	0.72	0.85		
Optimal AM JEM	0.66	0.91	0.64	0.97	0.86	
Optimal GM JEM	0.79	0.90	0.76	0.92	0.88	0.94

mal GM JEM). We applied two-way random effects analysis of variance (ANOVA) models to estimate the contrast ratio and precision of the average exposure metrics for each grouping scheme. We defined optimal JEMs as the ones that simultaneously maximized contrast and precision (Table 1).

Estimation of Cumulative Exposure

We estimated cumulative exposure by applying each of the six JEMs to the job history of every worker. We calculated average exposure in each calendar year of work for each individual in the cohort (N = 138,905). We then summed all estimates over calendar time and multiplied by the proportion of all hours spent at work, 0.23 (250 days × 8 hours per day divided by 365 days × 24 hours per day), to yield total occupational exposure expressed in μT-days.

Exposure-Response Analysis

We estimated the relation between cumulative exposure to magnetic fields and risk of brain cancer on a continuous scale. For each JEM, we used the midpoints of deciles of the exposure distributions as exposure scores and then treated them as a continuous measure. The analyses assume a log-linear relation between exposure and mortality, estimating a common rate ratio across the range of exposure.

We estimated adjusted mortality rate ratios by Poisson regression,[9,10] with adjustment for age, calendar time (in decades), race (white, nonwhite), social class, and active *vs* inactive work status, as described elsewhere.[5] We conducted analyses for cumulative career exposure and for cumulative exposure over the time window 2–10 years before the current person-year of observation. Exposures in the latter period were most strongly related to brain cancer in the previous study.[5]

Results

Exposure Metrics

Table 2 gives descriptive statistics for duration of employment and cumulative exposure estimates at the end of follow-up. The OC/Company JEM, which had the largest number of cells, showed the highest range in cumulative exposures, as expected. Table 3 gives correlations between those exposure metrics. Correlation between cumulative exposure estimates at the end of follow-up was high (r = 0.85–0.97), except for those based on the Company JEM (r = 0.64–0.76). The latter was highly correlated with duration of exposure (r = 0.96).

Exposure-Response Relations

The results of the Poisson regression are summarized in Tables 4 and 5 for the unlagged exposure and exposure in the 2- to 10-year window, respectively. Table 4 shows that the two optimal JEMs resulted in the strongest exposure-response relations. The OC/Company JEM, on which both optimal JEMs were based, also showed a noteworthy relation. Other JEMs resulted in much lower or very imprecise regression coefficients.

The results were more consistent for analyses considering only the most recent exposure (2- to 10-year window) (Table 5). Nevertheless, the magnitude and precision of the regression coefficients varied extensively. The Optimal AM and GM JEM again showed the largest coefficients, and relative precision was highest for the AM JEM [β/SE(β) = 3.67]. The Company JEM led to high, but imprecise, regression coefficients.

Discussion

From exposure-response relations observed with six different job-exposure matrices, it is apparent that the way in which exposure levels are assigned to individual cohort members, and, consequently, the way cumulative exposure estimates are calculated, can have pronounced effects. The optimal JEM used in the previously published study[5] consistently indicated a strong exposure-response relation. That study, however, might have been described as nonsupportive of a relation between brain cancer and career cumulative magnetic field exposure if magnetic field monitoring data had been grouped only by occupational cate-

TABLE 4. Poisson Regression Results for Several Estimates of Cumulative Magnetic Field Exposures on Brain Cancer Mortality Adjusted for Age, Race, Calendar Year, Socioeconomic Status, and Work Status with No Exposure Lag Applied

Cumulative Exposure Metric	RR/μT-Year	95% CI	$\beta \cdot 10^5/\mu$T-Day	SE (β) $\cdot 10^5/\mu$T-Day	β/SE (β)
OC JEM	1.033	0.964–1.107	8.92	9.64	0.93
Company JEM	1.050	0.947–1.163	13.23	14.38	0.92
OC/Company JEM	1.046	1.005–1.089	12.36	5.58	2.22
Level JEM	1.029	0.951–1.112	7.78	10.91	0.71
Optimal AM JEM	1.071	1.011–1.135	18.91	8.11	2.33
Optimal GM JEM	1.212	1.039–1.413	52.58	21.53	2.44

TABLE 5. Poisson Regression Results for Several Estimates of Cumulative Magnetic Field Exposures on Brain Cancer Mortality Adjusted for Age, Race, Calendar Year, Socioeconomic Status, and Work Status for Exposure in 2- to 10-Year Window

Cumulative Exposure Metric	RR/μT-Year	95% CI	$\beta \cdot 10^5/\mu$T-Day	SE (β) $\cdot 10^5/\mu$T-Day	β/SE (β)
OC JEM	1.487	1.070–2.068	108.8	46.04	2.36
Company JEM	1.960	1.160–3.310	184.4	73.26	2.52
OC/Company JEM	1.388	1.089–1.769	89.86	33.90	2.65
Level JEM	1.458	0.955–2.225	103.2	59.09	1.75
Optimal AM JEM	1.959	1.370–2.801	184.2	49.98	3.67
Optimal GM JEM	3.561	1.402–9.046	347.9	130.3	2.67

gory, a commonly used approach. In contrast, JEMs based on company produced large regression coefficients in some analyses, as did JEMs based on the geometric (rather than arithmetic) mean of daily exposure.

The JEM in which contrast in exposure and precision of estimated average exposure level were quantitatively optimized[6] consistently performed well relative to JEMs based on traditional, general grouping factors like occupational category, company, occupational category plus company, and exposure level assessed by judgment.

The larger regression coefficients for the Optimal GM JEM are a predictable result of the smaller range of cumulative exposures estimated with this JEM, relative to others. Use of the GM JEM with no lag in exposure nevertheless yielded estimated rate ratios similar to those obtained by applying the Optimal AM JEM. The unexpectedly large regression coefficients for the Company JEM were most likely caused by lack of contrast in average exposure level between companies. In this case, cumulative exposure mainly reflects duration of employment within utilities and will again result in a limited range in cumulative exposure estimates. An artifact of the measurement scheme might also have played a role; more sampling effort was devoted to the occupational categories assumed to be highly exposed, biasing the average exposure estimates for each of the five companies upward.

Rate ratios in the relatively wide range of 1.2–3.2 can be estimated for workers in the highest decile of cumulative exposure (10th decile) by using different JEMs to assign exposure scores. All of these cumulative exposure estimates were based on the same job history information and monitoring results, differing only in the time window considered and the scheme used to group the monitoring data.

Our previous estimates of relative risk for brain cancer mortality in relation to cumulative exposure to magnetic fields[5] appear adequate, given the cohort and their job histories. Nevertheless, the quantitative relation between cumulative magnetic field exposure and brain cancer mortality can be sensitive to the strategy used to group monitoring data. Methods for constructing optimal exposure grouping schemes have been described recently.[1,2] The use of such approaches in occupational exposure assessment will prevent many pitfalls of *post hoc* judgment based on observed strength of exposure-response relations.

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