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Refinements in Magnetic Field Exposure Assignment for a Case-cohort Study of Electrical Utility Workers

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This study examined the effect of refinements in exposure assignment on annual and career exposure to 60 Hz magnetic fields, using all deaths from brain cancer (145) and leukemia (164) and a random sample of 800 workers from a cohort of 138 905 men. Reassessment of 1060 job titles in the measurement database generated 20 subcategories in addition to 28 occupational categories used in the original cohort mortality study. Furthermore, previously misclassified jobs were corrected. The complete work history of each sub-cohort member was re-examined. Original and refined average annual exposures were 0.086 and 0.088 μT, respectively. The average career cumulative exposures were 1.40 and 1.44 μT-years, respectively. Spearman correlation coefficients between the original and refined methods across the companies were 0.81 for annual exposure and 0.93 for career cumulative exposure. 23% of the workers were assigned to another exposure ranking after refinement, but 85% of these moved to an adjacent group, suggesting that the differences in exposure ranking are small. The results of this study indicate that refinements have modest influence on the average annual and career exposures. However, the refinements may only change a very rough exposure assessment into one that is slightly less crude. The proportion of workers assigned to another exposure ranking indicated that nondifferential exposure misclassification in the original cohort mortality study may have occurred. Implications of these changes for the risk estimates of brain cancer and leukemia cases will to be examined.

Keywords: exposure assessment; electromagnetic fields; exposure classification

INTRODUCTION

Over the past 20 years, considerable concern has been raised about potential health effects of exposure to extremely low-frequency electric and magnetic fields. Overall the risks to health appear to be small or non-existent but a more accurate exposure assessment technique would help to evaluate the true extent of any health effects (Semple and Cherrie, 1998). Occupational classification schemes for categorizing workers use a variety of characteristics; job, work area, and employer are among the most common. Grouping of workers with similar exposures for epidemiological analysis is an important determinant of validity (Kromhout *et al*., 1995, 1997; Loomis *et al*., 1998). It is necessary to find a balance between minimizing misclassification and the practical limitations of handling many categories, each of which may contain few workers and provide low statistical precision (Loomis *et al*., 1994a).

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Among epidemiologic studies of occupational electric and magnetic fields, Savitz and Loomis (1995) had a unique exposure assessment because they monitored magnetic fields on an exceptionally large number of workers selected randomly from the cohort. In the analysis reported here, on-site magnetic field monitoring data were linked with work history data in order to estimate annual and career magnetic field exposure for a case-cohort study. For the full cohort of 138 905 men, close to 25 000 raw job titles held over several decades at five electric power companies were collapsed into a total of 28 occupational categories in order to assess and assign exposures (Kromhout *et al*., 1995) and conduct the epidemiological analysis (Savitz and Loomis, 1995). A better understanding of the sources of magnetic field exposure and the availability of a large number of magnetic field measurements made it possible to generate 20 new occupational subcategories by reassessing of job titles monitored during the exposure assessment phase of the original cohort mortality study. Case-cohort sampling resulted in a sub-cohort containing fewer than 2000 raw job titles, permitting a more detailed examination of individual workers and jobs than was feasible for the full cohort. The changes in exposure assignment resulting from these refinements were examined and quantified. Although specifically designed for this study, the methodology of exposure reassessment should be of interest for other electric utility industries, and hopefully for other occupational settings as well.

MATERIALS AND METHODS

Sub-cohort identification

Case-cohort sampling included all deaths from brain cancer and leukemia as well as a sample of the original cohort of 138 905 men. Eligible workers were employed full-time at any of five electric power companies in the United States at any time between 1 January, 1950 and 31 December, 1986, with a total of at least 6 months of continuous employment. Women were excluded because they rarely worked in jobs with the exposures of interest. Detailed information on the design of the original retrospective cohort mortality study can be found elsewhere (Savitz and Loomis, 1995). All leukemia (164) and brain cancer (145) deaths were identified from the entire study cohort. In addition, a sample of 800 workers (0.6%) was randomly selected from the total population of electric utility workers in the original study. No cases of leukemia or brain cancer were randomly selected, although the sampling strategy did not preclude the selection of cases in the sub-cohort sample. Identification numbers were assigned to each worker in order to mask the identity of cases during the exposure assessment phase of the study. Complete job histories were compiled for all selected workers.

Exposure assessment

Original cohort mortality study exposure assignment. Complete work histories of cohort members were abstracted and computerized. To consolidate thousands of job titles at the five participating companies, 28 occupational categories were constructed (Loomis *et al*., 1994a). Some occupational categories were not represented at all five companies, which yielded data on 134 out of 140 possible company-occupational category cells. Within the occupational categories, 1060 distinct job titles were monitored during the exposure assessment phase of the study. Randomly selected workers wore a personal Average Magnetic Exposure (AMEX) meter (Enertech Consultants, Campbell, CA) that recorded the time-integrated average magnetic field exposure over the work shift (Loomis *et al*., 1994b). A total of 2842 usable measurements was obtained and used to compute time-weighted average (TWA) exposures and arithmetic means for each occupational category in the job-exposure matrix. No exposure data were obtained for 14 company-occupational category combinations (10%). Eight of these were groups with few workers, which were not selected in the random sample, and another six were historical groups no longer present. Average exposure levels for the 14 combinations lacking measurements were estimated according to a linear model. Occupational category and company were predictors, which explained only 7% of the total exposure variance due to the large day-to-day variability (Kromhout *et al*., 1995). Cells for magnetic field exposures were rank-ordered and collapsed into five groups in order to increase statistical precision. Grouping was based on the distribution of the arithmetic mean exposure of each occupational category measured successfully in each company ($N = 120$). The 25th, 50th, 75th, and 87.5th percentiles were chosen as arbitrary cutoff points to arrive at five exposure groups (Kromhout *et al*., 1997), with average exposures of 0.12, 0.21, 0.39, 0.62 and 1.27 μT ("original 5-level JEM"). The 134 company-occupational category combinations were placed in one of the five exposure groups according to their actual measured or estimated level of magnetic field exposure.

The average group exposures were assigned for each company-occupational category combination and summed over time for each worker. The average exposure in each calendar year of work (μT) was calculated for each subject in the cohort. All estimates over calendar year were summed and multiplied by the proportion of all hours spent at work, 0.23 (250 days $\times$ 8 h divided by 365 days $\times$ 24 h per day) to yield workday exposure expressed in

Table 1. Original occupational categories (**bold**)[a] and new subcategories (*italics*)

Occupational category	Occupational category (continued)
Senior managers and executives	**Electricians**
Engineers, professionals and specialists	*Power Plant*
Technical workers	*Substation*
Shop	*Shop*
Plant	**Linemen**
Gas	*Transmission & Distribution*
I&C, Telecom, Relay	**Instrument and control technicians**
Field/craft/trade supervisors	**Relay technicians**
Transmission & Distribution	**Telecommunication technicians**
Gas	**Cable splicers**
Power Plant	**Power plant operators**
Administrative supervisors	*Gas*
Administrative support/clerical workers	*Coal Yard*
Meter Reader	**Substation operators**
Sales, marketing and business workers	**Riggers**
Services	**Auto and truck mechanics**
Power Plant/substation	**Painters**
Mechanics	**Pipe coverers**
Plant/Substation—Power Plant	**Welders**
Plant/Substation—Gas	*Gas*
Machinists	**Heavy vehicle operators**
Power Plant & Shop	**Material handlers**
Boilermakers/steamfitters	**Labourers**
Power Plant	**Other craft workers**

[a]Not otherwise specified after refinement.

μT-days and divided by 365 to yield career exposure scores expressed in μT-years.

Case-cohort study exposure assignment. The case-cohort study exposure assignment consisted of two parts. First, reassessment of 1060 job titles, which were monitored during the exposure assessment phase of the original cohort mortality study, took place by further differentiation of distinct job groups, and generated 20 new occupational categories as distinct subcategories of the original 28 occupational categories (see Table 1). Furthermore, previously misclassified jobs were corrected. Second, the complete work history of each sub-cohort member was re-examined in order to better classify ambiguous job titles. Fewer than 2000 raw job titles were represented in the sub-cohort. Assignment of job titles into one of the 48 occupational categories was based on tasks performed and work environments, which were based on formal discussions with expert panels of experienced workers and on discussions during walkthrough surveys.

For the company-specific occupational categories, the average daily exposure to magnetic fields was determined. A total of 171 company-occupational category combinations and 2713 AMEX samples were represented in the sub-cohort. Of the 171 combinations, 23 (13%) had no exposure estimations. For any combination without exposure estimation, the average daily exposure was estimated using a linear regression model based on company and occupational category including all measurements (N = 2713). The model explained only 7% of the total exposure variance. In order to be consistent with the original exposure estimation scheme, cells for refined magnetic field exposures represented by the sub-cohort were rank-ordered and collapsed into five groups. Grouping was based on the distribution of the arithmetic mean exposure of each company-occupational category combination in the sub-cohort with measurements (N = 148). The lower three exposure groups correspond to the lower three quartiles of exposure; the highest quartile was halved to create the two highest groups. Average group exposures of 0.11, 0.19, 0.38, 0.60 and 1.21 μT were calculated using 2713 measurements represented in the 148 combinations ("refined 5-level JEM"). The 171 company-occupational category combinations were placed in one of the five exposure groups according to their actual measured or estimated level of magnetic field exposure. The average group exposures were assigned for each company-occupational category combination and summed over time for each worker. Worker's average exposure in each calendar year of work and career exposure were assessed as in the original cohort study (Kromhout *et al*., 1995).

Data analysis

The efficiency of different grouping strategies was assessed by applying a two-way nested random-effects ANOVA model. The purpose of this procedure was to compare the efficiency of grouping strategies using the original system (Kromhout *et al*., 1995) with the efficiency after the refinements. The contrast in exposure levels between the created

Table 2. Comparison of grouping efficiency[a]

Grouping	Original[b] ($N = 2842$)				Refined ($N = 2713$)[c]			
	Number of groups	$_{BG}R_{0.95}$[f]	ε	π	Number of groups	$_{BG}R_{0.95}$	ε	π
Occupational category	28	6.41	0.49	9.9	46[d]	6.94	0.50	7.2
Company	5	1.51	0.02	19.2	5	1.44	0.02	18.6
Occupational category-company	120	7.18	0.56	5.0	148[e]	7.41	0.54	4.2
5-level JEM	5	8.61	0.59	25.5	5	9.38	0.59	25.7

[a]Exposure measurements were log transformed.
[b]Kromhout *et al.* (1995).
[c]Represented in sub-cohort.
[d]No exposure estimations in 2 of 48 occupational categories.
[e]No exposure estimations in 23 of 171 combinations.
[f]$_{BG}R_{0.95}$ = ratio of 97.5th and 2.5th percentiles of the between-group distribution. ε = ratio of the between-group and the sum of the within-group and between-group variance components. π = median precision.

groups was indicated by the ratio ($_{BG}R_{0.95}$) of the 97.5th and 2.5th percentiles of the between-group distribution and the ratio (ε) of the between-group and the sum of the within-group and between-group variance components. The precision (π) of the average exposure level for each of the groups was estimated from the median of the reciprocal of the standard error of the average exposure for each group.

The changes in exposure assignment resulting from the refinements made to the original cohort job-exposure matrix were examined by comparing the original and refined 5-level JEM. Analyses were performed on two levels. The first level of analysis was focused on the average exposure in each calendar year of work (annual exposure), expressed in microtesla (μT). The annual exposures assigned using the original cohort job-exposure matrix were compared to the annual exposures assigned using the refined case-cohort job-exposure matrix. The second level of analysis focused on "career exposure" in microtesla-years (μT-years), which was the final accumulated exposure when the job history ended due to retirement, death, or the end of the study. The career exposures assigned using the original cohort job-exposure matrix were compared to the refined case-cohort career exposures. The frequency and direction of changes in assignment and the magnitude of correlation using the original and the refined system were examined. Furthermore, cut points for deciles of exposure were established. For both the original and refined system, the career exposure was separately derived for all decedents of brain cancer and leukemia, thereby ensuring an equitable distribution of cases across groups. Subjects below the 30th percentile of that distribution formed the referent category, with the other percentiles defined as 30– < 50, ≥50– < 70, ≥70– < 90, and ≥90. Comparison of the number of workers assigned to each of the five exposure rankings under each system was made in order to determine how many workers were classified differently after refinement. Finally, the average annual exposure within each refined occupational category was examined in order to determine whether refinement resulted in distinct exposure estimates across occupational subcategories.

RESULTS

Demographics of the sub-cohort were similar to the original cohort (Savitz and Loomis, 1995). Almost 90% of the men in the sub-cohort were white and most of them were blue-collar workers. Person-time experience was concentrated in men younger than 50, and in the 5–20-year employment duration. The average length of service among all employees in the sub-cohort was 16.4 years with a standard deviation of 11.3 years.

The results of analyses comparing the efficiency of three *a priori* exposure assignment schemes (occupational category, company, and occupational category and company combined) and one *a posteriori* scheme (measured exposure level) are presented in Table 2. The *a posteriori* grouping [with the 25th, 50th, 75th, and 87.5th percentiles of the distribution of average exposures (arithmetic means) of occupational category plus company groups as cut-off points] showed, as before, the greatest contrast (as indicated by ε and $_{BG}R_{0.95}$) and precision (π) in average exposure levels. For the *a priori* exposure assignment schemes, the refinement generally resulted in similar contrast but somewhat less precision. The overall grouping efficiency of the *a posteriori* scheme in the original and refined approaches was similar.

After refinement, occupational categories with a magnetic field exposure of 0.20 μT and higher were similar to the original 5-level JEM (data not shown). Based on the annual exposure, occupational categories represented in the sub-cohort with a magnetic field exposure of 0.20 μT and higher were machinists [Power Plant & Shop], electricians [Not Otherwise Specified (NOS), Power Plant, Substation], relay technicians, cable splicers,

Table 3. Arithmetic mean of annual exposure[a] (μT) and career exposure[a] (μT-years) and 95% confidence levels, obtained for the original and refined 5-level job-exposure matrices

	Company					
	A	B	C	D	E	All
Annual						
Original	0.090	0.108	0.097	0.078	0.075	0.086
5-level JEM	(0.084–0.096)	(0.105–0.112)	(0.094–0.100)	(0.076–0.080)	(0.074–0.077)	(0.084–0.087)
Refined	0.087	0.098	0.091	0.077	0.092	0.088
5-level JEM	(0.081–0.092)	(0.095–0.101)	(0.088–0.094)	(0.075–0.078)	(0.090–0.094)	(0.087–0.089)
Career						
Original	1.12	2.95	1.51	1.08	1.25	1.40
5-level JEM	(0.74–1.50)	(2.47–3.43)	(1.21–1.81)	(0.96–1.20)	(1.11–1.40)	(1.30–1.50)
Refined	1.08	2.66	1.41	1.06	1.53	1.44
5-level JEM	(0.71–1.44)	(2.21–3.12)	(1.13–1.69)	(0.94–1.19)	(1.34–1.72)	(1.33–1.54)

[a]Not the exact indices that have been used in the original cohort mortality study.

power plant operators [NOS] and substation operators.

The arithmetic mean of the annual and career exposures, classified by refinement status, is presented in Table 3. The levels for the original and refined arithmetic mean annual exposures were similar; for all utilities combined 0.086 and 0.088 μT, respectively. For the career exposure, original and refined JEMs also yielded similar values. The mean for all utilities combined was 1.40 μT-years for the original and 1.44 μT-years for the refined JEM. On company level, the differences in average annual and career exposure were larger; up to 22% of the average exposure of the original 5-level JEM.

The difference in exposure was calculated for each person-year by subtracting the original annual exposure from the refined score and analogously for each person by subtracting the original career exposure from the refined one. Difference scores were divided into seven categories, yielding a proportion of the total number of person-years and subjects for each category, for respectively the annual and career exposures (data not shown). For all companies combined, most differences (about 65%) were within 20% ($-0.015 \leq X < 0.015$ μT) of the absolute mean of 0.09 μT presented in Table 3. However, a small proportion of the differences (over 7%) was at least as large as the absolute mean. For the career exposure, differences were smaller. Most differences were observed around zero (almost 54%). For all companies combined, about 14% of the differences were half the absolute mean of 1.4 μT-years or greater. Annual exposure tended to increase, which was consistent with the slightly higher average annual exposure after refinement.

Table 4. Correlation[a] between the original 5-level job-exposure matrix exposures and the refined 5-level job-exposure matrix exposures

	Company					
	A	B	C	D	E	All
Annual	0.97	0.90	0.79	0.79	0.74	0.81
Career	0.98	0.96	0.96	0.93	0.89	0.93

[a]Spearman.

The relationship between the exposure scores of both systems was examined for the annual exposure and the career exposure by obtaining Spearman correlation coefficients (Table 4). A high correlation between the original and refined JEM was observed; coefficients on company level ranging from 0.74 to 0.97 for annual exposure (across companies: 0.81), and varying from 0.89 to 0.98 for career exposure (across companies: 0.93). Overall, exposure refinement had a greater effect on annual exposure than on career exposure, which incorporates the duration of work and thus dampens the differences.

Comparisons of the worker-exposure rankings from the original cohort and the refined ranking scheme were made (Table 5). Of the 1109 workers in the sub-cohort, 256 (23%) changed exposure ranking relative to initial assignments; 217 moving up or down one rank, 34 moving two ranks and 5 moving three ranks. Of the workers-exposure rankings with changes, 90 (35%) moved to a lower rank and 143 (56%) moved up at least one rank. On company level, most changes in exposure ranking were found for company E (35%).

Table 6 shows the average annual exposure for each of the occupational subcategories. Refinement of exposure assessment resulted in a good differentiation within subdivided occupational categories. In general, the use of more specific groups within each occupational category yielded distinct exposures between subcategories. Average annual exposures for general occupational categories without subdivisions were quite similar for both the original and refined 5-level JEM (data not shown).

Table 5. Number of subjects (row %) in percentile group when original ranking was compared to refined ranking

Original	Refined					
	< 30	≥ 30– < 50	≥ 50– < 70	≥ 70– < 90	≥ 90	Total
< 30	392 (89.5)	39 (8.9)	5 (1.1)	2 (0.5)	0 (0.0)	438
≥ 30– < 50	18 (7.9)	157 (69.2)	45 (19.8)	7 (3.1)	0 (0.0)	227
≥ 50– < 70	12 (5.7)	32 (15.2)	137 (64.9)	28 (13.3)	2 (1.0)	211
≥ 70– < 90	2 (1.2)	7 (4.2)	25 (14.9)	119 (70.8)	15 (8.9)	168
≥ 90	0 (0.0)	1 (1.5)	1 (1.5)	15 (23.1)	48 (73.9)	65
Total	424	236	213	171	65	1109

DISCUSSION

The organization and classification of work history data in the electric power industry has been extensively discussed by Loomis *et al.* (1994a). In this report, we have refined the original occupational classification scheme in order to obtain more specific occupational categories and examined and quantified the effects of this refinement relative to the original approach. The results of this study indicate that the use of more specific occupational categories allowed quantitative differentiation of exposures. However, refinements have modest influence on the average annual and career exposures.

The refinements made to the original cohort mortality study exposure assignment consisted of two parts. First, sampled job titles allowed further differentiation of distinct job groups because of known differences in work environments or tasks performed. For instance, electricians could work in a power plant, a substation, or a shop. Furthermore, linemen could be divided into distribution and transmission linemen. Other refinements in the original cohort mortality study exposure assignment included reassignment of misclassified jobs. For instance, "switchman" at one company was a railway switch operator, not a power plant operator as originally coded. The changes affected 34% of the 2842 exposure measures, and generated 20 new subcategories within 11 out of the original 28 occupational categories. The second part of the refinement consisted of linking the work history of each sub-cohort member to the occupational categories, thereby obtaining a more refined estimation of annual and career exposure. Additionally, re-evaluation of individual employment histories allowed more detailed classification of ambiguous job titles. While the original cohort consisted of close to 25000 raw job titles, the sub-cohort population of 1109 workers represented fewer than 2000 raw job titles. Many of these distinct job titles were variations in spellings and grades or classes of the

Table 6. Average annual exposures (μT) and 95% confidence levels in occupational categories, obtained for refined 5-level job-exposure matrix

Occupational category	Arithmetic mean (95% CI)	Occupational category	Arithmetic mean (95% CI)
Technical Workers		*Machinists*	
NOS[a]	0.055 (0.053–0.057)	NOS	0.047 (0.042–0.052)
Shop	0.071 (0.068–0.073)	Power Plant & Shop	0.211 (0.200–0.222)
Plant	0.087 (0.083–0.090)	*Boilermakers/steamfitters*	
Gas	0.078 (0.036–0.120)	NOS	0.079 (0.076–0.083)
I&C, Telecom, Relay	0.109 (0.101–0.117)	Power Plant	0.078 (0.075–0.081)
Supervisors[b]		*Electricians*	
NOS	0.034 (0.033–0.035)	NOS	0.259 (0.253–0.264)
Transmission & Distribution	0.161 (0.139–0.184)	Power Plant	0.229 (0.205–0.252)
Gas	0.024 (0.022–0.026)	Substation	0.266 (0.262–0.271)
Power Plant	0.061 (0.058–0.064)	Shop	0.048 (0.040–0.056)
Administrative Support[c]		*Linemen*	
NOS	0.066 (0.064–0.069)	NOS	0.082 (0.078–0.086)
Meter Reader	0.029 (0.028–0.030)	Transmission & Distribution	0.153 (0.149–0.156)
Services		*Power Plant Operators*	
NOS	0.075 (0.072–0.077)	NOS	0.200 (0.195–0.205)
Power Plant/Substation	0.032 (0.018–0.046)	Gas	0.024 (0.021–0.027)
Mechanics		Coal Yard	0.048 (0.038–0.058)
NOS	0.042 (0.041–0.044)	*Welders*	
Plant/Substation—Power Plant	0.095 (0.087–0.102)	NOS	0.098 (0.094–0.103)
Plant/Substation—Gas	0.041 (0.040–0.043)	Gas	0.025 (0.021–0.029)

[a]Not Otherwise Specified.
[b]Field/Craft/Trade.
[c]Administrative Support/Clerical Workers.

same job. Assignment of jobs into the redefined occupational categories was based on work environments and job responsibilities.

Refinements were based on the same monitoring results used for the original cohort mortality study. This is an inherent limitation of this study. On average, about 24 measurements per company-occupational category were obtained during the exposure assessment phase of the original study. The average number of measurements per combination decreased to eighteen after generation of 20 new occupational subcategories. Consequently, refinements yielded similar homogeneity but somewhat less statistical precision in the *a priori* exposure assignment schemes, and perhaps the generation of new subcategories yielded some losses. Nevertheless, refinements resulted in similar homogeneity as well as similar precision for the *a posteriori* scheme. In 13% of the company specific occupational categories no magnetic field measurements were obtained. For those combinations, the average daily exposure was estimated using a statistical model that only explained 7% of the total variability, undoubtedly adding error in the exposure assignment. Collection of additional exposure measurements, in particular for those company specific occupational categories with few samples, could improve the ability to make refinements to the original exposure assignment.

Inevitable problems in classifying jobs and workers should be acknowledged (Loomis *et al.*, 1994a). Furthermore, JEMs have several limitations (Boleij *et al.*, 1995): exposure categories are chosen arbitrarily, job definitions do not necessarily reflect information important to exposures, and the matrix might not show exposure changes over time. Consequently, our study refinements may only have made a very rough exposure assessment slightly less crude.

Estimates of both annual and career exposures to 60 Hz magnetic fields were insensitive to the refinements made to the occupational classification scheme used in the original mortality cohort study. Although a high proportion of workers were assigned to another exposure ranking after refinement (23%), the average annual and career exposure did not change substantially. Furthermore, the grouping efficiency in the both approaches was similar and there was a good correlation between original and refined 5-level JEM exposures. Nevertheless, refinement of exposure assessment resulted in a better differentiation within general occupational categories; substantial differences in average annual exposures between subcategories were observed. Yet, the annual and career exposures were insensitive to refinements, with several possible explanations. First, 20 new occupational categories were generated as distinct subcategories within 11 of the original 28 occupational categories, and reassignments of misclassified jobs were made. Substantial differences in average annual exposures were observed between occupational subcategories, representing about half of the person-years in the sub-cohort. However, average annual exposures for 17 general occupational categories without subdivisions were very similar for both the original and refined 5-level JEM. Second, career exposure was integrated over time and the time factor would dampen the differences between the original and refined method. Third, 85% of the subjects who were assigned to another exposure ranking after refinement moved to an adjacent group, which implied that the differences in ranking were marginal. For instance, 22% of the subjects with changes moved from very low to low ranking or vice versa. In addition, the movement in ranking was symmetrical, with nearly equal proportions moving up and down in exposure.

Although minor effects of refinements on average annual and career exposure were observed, implications on the association of brain cancer with magnetic field exposure could be substantial. The generation of new subcategories affected magnetic field exposures considerably, separating gas workers from electrical jobs, amongst others. In the Ontario Hydro study (Miller *et al.*, 1996), adding details like job site information to a job-based exposure assessment greatly changed risk estimates. Implications of the refinements on the risk estimates of brain cancer and leukemia cases could not be predicted. A 23% change in exposure ranking may have increased nondifferential exposure misclassification or reduced it depending on its relationship to the "true" exposure, which is unknown. In addition, although nondifferential misclassification likely produced bias toward the null, under certain circumstances bias away from the null may occur (Dosemeci *et al.*, 1990; Brenner and Loomis, 1994; Weinberg *et al.*, 1994; Thomas, 1995).

CONCLUSION

In conclusion, the results of this study indicate that refinements did not greatly affect the estimated annual and career exposures. This is encouraging, since this suggests that the methods of organization and classification of work history data in the original cohort mortality study were robust. Our study refinements, however, may only have made a very rough exposure assessment slightly less crude. In addition, a high proportion of workers were assigned to another exposure ranking after refinement, indicating that nondifferential exposure misclassification in the original cohort mortality study may have occurred. Implications of these results on the risk estimates of brain cancer and leukemia cases will be examined since the effect of the refinements is not readily predicted.

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