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A Population-Based Job Exposure Matrix for Power-Frequency Magnetic Fields

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A population-based job exposure matrix (JEM) was developed to assess personal exposures to power-frequency magnetic fields (MF) for epidemiologic studies. The JEM compiled 2317 MF measurements taken on or near workers by 10 studies in the United States, Sweden, New Zealand, Finland, and Italy. A database was assembled from the original data for six studies plus summary statistics grouped by occupation from four other published studies. The job descriptions were coded into the 1980 Standard Occupational Classification system (SOC) and then translated to the 1980 job categories of the U.S. Bureau of the Census (BOC). For each job category, the JEM database calculated the arithmetic mean, standard deviation, geometric mean, and geometric standard deviation of the workday-average MF magnitude from the combined data. Analysis of variance demonstrated that the combining of MF data from the different sources was justified, and that the homogeneity of MF exposures in the SOC occupations was comparable to JEMs for solvents and particulates. BOC occupation accounted for 30% of the MF variance ($p \ll 10^{-6}$), and the contrast (ratio of the between-job variance to the total of within- and between-job variances) was 88%. Jobs lacking data had their exposures inferred from measurements on similar occupations. The JEM provided MF exposures for 97% of the person-months in a population-based case-control study and 95% of the jobs on death certificates in a registry study covering 22 states. Therefore, we expect this JEM to be useful in other population-based epidemiologic studies.

[Supplementary materials are available for this article. Go to the publisher's online edition of the Journal of Occupational and Environmental Hygiene for the following free Supplemental resources: Appendices A–D and Formula Proofs.]

Keywords ELF, EMF, exposure assessment, extremely low frequency, JEM

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INTRODUCTION

The job-exposure matrix (JEM) has been the preferred method for assessing exposures to power-frequency magnetic fields (MF) in retrospective epidemiologic studies of cancer and other chronic diseases.[1] In occupational MF studies with personal monitoring,[2–5] a subset of workers is surveyed and the data are used to construct the JEM, from which exposures are assigned to the rest of the study subjects. The underlying assumption behind all these JEM methodologies is that jobs relate to magnetic field exposure. The JEM can assess MF exposures whenever an investigator knows the jobs held by the cases and controls, whether obtained from company records, interviews, or death certificates.

Many studies of utility workers have developed magnetic field JEMs,[2–7] but less has been done to characterize MF exposures for workers in the general population. A population-based case-control study in Sweden[8] led to the first JEM applicable to men in the general work force.[9] This JEM has been used in Swedish studies of male breast cancer, testicular cancer, leukemia, central nervous system tumors, neurodegenerative diseases, cardiovascular disease, and the interaction between MF and chemicals in brain tumor risks.[10–15] The primary focus of our JEM is to augment the Swedish data with measurements from the United States and elsewhere to assess occupational MF exposures for men and women from all sectors of the modern economy.

The JEM described in this article was originally developed to assess occupational MF exposure for subjects of an adult glioma study in the San Francisco Bay area (SFBA)[16] This original JEM grouped the subject's jobs with the 1980 Standard Occupational Classification system (SOC) from the U.S. Department of Commerce.[17] The JEM was later adapted to the occupational categories of the 1980 U.S. Census[18] for a study of neurodegenerative diseases conducted by the National Institute for Occupational Safety and Health (NIOSH).[19] The population-based JEMs developed for these two studies contain MF measurement data on many jobs that were not in previous JEMs and can be applied to other populations.

METHODS

Magnetic Field Data Sources

We combined workplace MF measurements from seven primary data sources (six of which were original data from the study authors) plus supplemental data from three other publications to create a large diverse database of exposures for common jobs in the general population. The overwhelming majority (97%) of the MF data selected for this JEM comes from full-shift personal sampling, while spot measurements collected early in the SFBA adult glioma study make up only 3% of the total JEM data.

All MF measurements were taken with a model of the EMDEX monitor, either the EMDEX 100, EMDEX II, or EMDEX Lite made by Enertech Consultants (Campbell, Calif.) or the EMDEX C (Electric Field Measurements, Inc., Stockbridge, Mass.). The EMDEX measures the magnetic field as the magnetic flux density or B-field, which is the exposure metric traditionally used by health studies at power frequencies.[20] Specifically, the EMDEX determines the MF's resultant $B = \sqrt{B_x^2 + B_y^2 + B_z^2}$ in a bandwidth = 40–1000 Hz. B_x, B_y, and B_z are the root-mean-squared components of the time-varying vector $\mathbf{B}(t)$ measured sequentially throughout the meter's sampling period, which ranges from 1–4 sec for the different EMDEX models. According to the manufacturer, the EMDEX II and EMDEX C measure the resultant with a typical accuracy of $\pm 1\%$ over a dynamic range of 0.01–300 μT; the EMDEX Lite has an accuracy of $\pm 2\%$ over 0.01–70 μT. With personal monitoring, the summary metric[20] in the JEM is the time-weighted average (TWA) of the resultant over a work shift. In the case of the spot measurements, the summary metric is the average of 15 readings taken at a subject's workstation(s).[21]

Table I summarizes basic information about the MF exposure data obtained from the primary sources and additional details about each data source follow.

Swedish JEM

The Swedish JEM[9] was constructed from monitoring data collected for a case-control of leukemia and brain cancer.[8] This JEM used the MF measurement data for the 100 most common occupations, which were coded by the Nordic version of the International Standard Classification of Occupations (ISCO). "Some job categories assumed to be similar with regard to tasks and exposures"[9,p.227] (e.g., teachers of different subjects) were replaced with their higher-level grouped category in the hierarchical ISCO system. A JEM with 90 ISCO codes was then published that contained the following summary statistics for each occupation: the number of full-shift measurements (N), the arithmetic mean (AM) of the TWA data, and their geometric mean (GM). Because the standard deviations (SD) and geometric standard deviations (GSD) were not in the publication, we inferred these summary statistics from the AM and GM:

$$SD = AM\sqrt{\frac{AM^2}{GM^2} - 1} \tag{1}$$

$$GSD = \mathrm{Exp}\left[\sqrt{\mathrm{Ln}\frac{AM^2}{GM^2}}\right] \tag{2}$$

These formulas assume the TWA data are distributed log-normally.[22]

Office Worker Study

The objective of this study[23] was to characterize magnetic fields in the office environment at a large employer in Seattle, Washington. For the JEM, EMDEX data taken during three work shifts were extracted and combined using time-activity diaries kept by subjects to estimate the TWA for a single shift. This study was sponsored and reviewed by the EMF Research and Public Information Dissemination (RAPID) Program of the U.S. government,[24] which then disseminated the results on its website.[23] One of the authors of this paper (MY) participated in collecting these data.

Spontaneous Abortion Study

The California Department of Health Services conducted this study[25] to determine whether electric bed heater use increased the risk of spontaneous abortions. Data pertaining to time spent at work were extracted based on the time-activity diary information, so the workday TWA could be calculated. One of the authors of this paper (MY) participated in collecting these data.

Electrical Worker Study

In this study[26,27] conducted at the University of Southern California, the goal was to measure TWA magnetic field exposures in electrical occupations and to compare them with a sample of nonelectrical jobs. Companies were recruited in Los Angeles (LA), Washington State (WA), and New Zealand (NZ) where there were workers in electrical or comparison job categories (coded by the 1970 Bureau of Census system).[28] For this JEM, the original EMDEX data was reanalyzed to obtain workday TWAs for 10 electrical and 26 nonelectrical occupations combined across the three regions (Tables II and III).

Where the regional data for an occupation had inhomogeneous variances according to Bartlett's test,[29] exposures for the disparate region are reported separately. Because different work practices in New Zealand (e.g., de-energizing electric lines for maintenance) sometimes resulted in exposures different from the United States, NZ data was not included in the JEM if there were similar LA or WA data. One of the authors of this paper (JB) participated in collecting these data.

Trolley Worker Study

Baseline personal exposure data were collected for 104 trolley (tram) workers at a municipal transit system in Washington State.[30] We used TWA data for each subject for the JEM; however, five subjects were omitted from the JEM due to insufficient job information for coding. One of the authors of this paper (MY) participated in collecting these data.

San Francisco Bay Area (SFBA) Adult Glioma Study

Measurement efforts in the adult glioma study focused on six industries common to the SFBA (business, education, health, transportation, computers, electronics), which were thought to cover the range of MF exposures in this study

TABLE I. Data Sources and Person-Days Monitored for Magnetic Field Exposures

Study and Reference No.	Population	Person-Days Monitored: Original	Person-Days Monitored: JEM	Comments
Swedish JEM[9]	Active male work force (Sweden)	1084	884	The JEM coded jobs from the Swedish case-control study[8] for only the 90 most populous occupations.
Office Workers[23]	Office workers (Washington State)	70	69	Omitted library specialist so exposure for whole occupation would not be based on a single, high data point (1.65 μT).
Spontaneous Abortions[25]	Pregnant women (San Francisco Bay Area)	144	144	
Electrical Workers[26,27]	Male electric and nonelectric workers (Los Angeles County, Washington State, New Zealand)	655	594	Omitted NZ occupations whose exposures were significantly different from the U.S. measurements and unusually high clerical worker data from WA hydro electricity plant. (See Tables II and III.)
Trolley Workers[30]	Municipal transit workers (Washington State)	104	99	Omitted data with insufficient job information for coding.
Adult Gliomas[16,21]	General population (San Francisco Bay Area)	76	62	Data set contains averages of spot measurements rather than personal monitoring. Included spot data only for occupations where there was little (N $\leq$ 10) personal data and the distributions were similar.
Italian Workers[31]	Garment industry, tile production and other industries (Italy)	450	117	Used only data for occupations that we did not already have from other sources.
Semiconductor Workers[32]	Fabrication room workers (USA)	192	192	
Telephone Workers[33]	Telephone linemen and technicians (USA)	204	149	Omitted data with insufficient job information for coding.
Garment Workers[34]	Pilot measurements of garment trades (Finland)	7	7	

Notes: JEM = job exposure matrix, NZ = New Zealand, WA = Washington State.

population.[16,21] A series of 15 spot measurements was collected using an EMDEX II at each workstation where the worker reported spending a majority of the day (average of two work areas per subject). The protocol consisted of three repeat measurements at each of five locations around the workstation. The average of all the spot measurements collected for a worker at one or more workstations was treated as an estimate of the TWA. Spot measurement data was used in the JEM for occupations where we had personal monitoring on 10 or fewer subjects, and the average of the spots lay within two standard deviations of the GM from personal monitoring (if any existed). Two of the authors of this paper (JT, MY) participated in collecting these data.

Italian Worker Study

The Department of Hygienic Science at the University of Pavia surveyed personal exposure to ELF magnetic field exposures in several industries for the Italian Ministry of Labor.[31] Because the Italian data were obtained late in the

TABLE II. TWA Magnetic Field Exposures of Electrical Job Categories

Job Category and Region	SOC	N	Statistics (μT) AM	SD	GM	GSD (Unitless)
Elec. engineer (LA, NZ, WA)	1633	30	0.275	0.329	0.178	2.49
Elec. technician (LA, NZ, WA)	3711	27	0.366	0.277	0.277	2.17
Elec. line worker (LA, NZ, WA)	6433	150	3.607	10.924	0.944	4.24
Electrician[A] (LA, NZ)	6432	26	0.366	0.322	0.314	1.61
Fitter[B] (LA)	6153	25	0.298	0.234	0.227	2.12
Fitter (NZ,WA)	6153	30	1.555	1.629	0.913	3.03
Phone line (LA)	6157	32	0.199	0.134	0.167	1.80
Phone line (NZ)	[C]	14	0.349	0.299	0.277	1.93
Power station operators (LA,WA)	6932	51	1.433	2.236	0.783	2.83
Power station operators (NZ)	[C]	18	0.615	0.556	0.449	2.18
Projectionist (LA)	7479	14	0.795	0.679	0.625	1.98
TV repairer (LA)	6155	25	0.394	0.246	0.297	2.39
TV repairer (NZ)	[C]	16	0.270	0.152	0.240	1.60
Welder (LA,WA)	7714	28	1.753	2.472	0.896	3.20
Welder (NZ)	[C]	5	8.080	7.057	4.797	4.00

Notes: Exposures calculated from the Electrical Worker Study.[26,27] Data for a job are combined across regions only when homogeneous.
TWA = time-weighted average; SOC = Standard Occupational Classification; AM = arithmetic mean; SD = standard deviation; GM = geometric mean; GSD = geometric standard deviation; LA = Los Angeles; NZ = New Zealand; WA = Washington State.
[A]Electricians working in residences, commerce, and construction.
[B]Fitters are electricians working in electric utilities and other industries.
[C]Data not included in JEM, only U.S. data used for this category.

study, we used only TWA magnetic fields measured in the garment industry (N = 96) and tile production (N = 21), since these were missing from our other primary datasets. Measurement data on individual subjects were obtained by personal communication with the study authors.

Literature Search

Lastly, we searched the literature through 1998 for full-shift exposure measurements with job categories not covered by the other data sources. By this means, we obtained summary TWA statistics on electronic equipment assemblers,[32] telephone installers,[33] and a few garment workers.[34] With the telephone worker data, we again followed the procedure of including only data where the job description was adequate for coding and, therefore, omitted the "nonlineworker" data (N = 55) from our JEM.

Job Coding

All job titles and occupational categories from each source were coded according to the 1980 Standard Occupational Classification system.[17] A single SOC code was assigned to all measurements in the primary data sets except those from the Swedish and Electrical Worker studies, where we did not have job titles for individual subjects. Occupational code-search software was often used to help convert job descriptions to the SOC codes. Bcause industry information was not available for all sources, industry codes were not used.

The Electrical Worker and Swedish MF data already had been classified into their own job categories; therefore, the 1970 BOC categories in the Electrical Worker Study and the Nordic ISCO categories in the Swedish study were translated to their SOC equivalents. We used lists of equivalent codes modified by our judgments of MF exposures for the occupational descriptors. The authors involved in each original study had the most influence in resolving the uncertainties that frequently arose in mapping one coding system to another.

Because the 1980 SOC codes are more detailed than the Nordic ISCO system, the data from a single ISCO occupation could sometimes be assigned to more than one SOC category. For example, the Swedish data for ISCO code 872 (Crane and hoist operators, GM = 0.24 μT) was assigned to both SOC codes 8314 (Hoist and winch operators) and 8315 (Crane and tower operators). With 35 of the 90 ISCO codes (38.9%), two or more SOC codes corresponded to a single ISCO job category. The greatest multiplicity occurred with toolmakers and machine tool setters (ISCO 750), which we linked to 18 SOC codes such as machinists (SOC 6813) and lathe operators (SOC 7512). Where such "one-to-many" links occurred, the measurement data from the input data source were assigned to all the matching SOC categories. Due to such multiple linkages, the total number of person-days measured in all of the JEMs occupations (Appendix A) is greater than the total in the input data (Table I).

Conversely, two ISCO codes were linked to a single SOC category for 16 of the 251 SOC categories with measurements

TABLE III. TWA Magnetic Field Exposures for Nonelectrical Job Categories

Job Category and Region	SOC	N	Statistics (μT) AM	SD	GM	GSD (Unitless)
Accountant (LA, NZ, WA)	1412	10	0.139	0.076	0.124	1.632
Aeronautical engineer (LA)	1622	8	0.111	0.090	0.087	2.037
Architect (NZ)	1610	3	0.088	0.007	0.087	1.078
Bookkeeper (NZ)	4712	4	0.246	0.135	0.216	1.827
Carpenter (LA, WA)	6422	5	0.364	0.182	0.318	1.867
Clerical (LA)[A]	4630	3	0.156	0.033	0.154	1.223
Clerical (WA)	[B]	8	0.390	0.193	0.352	1.620
Clinical lab technician (LA)[A]	3620	7	0.120	0.060	0.111	1.500
Construction laborer (LA)	8710	3	0.075	0.030	0.070	1.597
Driver (nonelectric)(NZ)	8215	7	0.137	0.035	0.133	1.279
Estimator (LA)[A]	4783	3	0.178	0.088	0.165	1.593
Farm laborer (NZ)	5617	5	0.063	0.031	0.057	1.693
Foreman (nonelectric) (LA)[A]	7100	10	0.166	0.054	0.158	1.416
Janitor (LA, WA)	5244	13	0.171	0.086	0.151	1.716
Machine operator (LA)[A]	75–76	5	0.112	0.111	0.085	2.132
Machinist (LA, WA)	6813	8	0.165	0.063	0.153	1.566
Manager (LA, NZ, WA)[A]	12-13	10	0.111	0.054	0.097	1.818
Medical science teacher (LA)[A]	2231	8	0.151	0.100	0.130	1.720
Mechanics and repairers (LA)[A]	61	3	0.207	0.092	0.190	1.728
Miner (NZ)	6540	3	0.057	0.015	0.055	1.294
Plumber (NZ)	6450	2	0.129	0.130	0.129	1.11
Radiologic technician (LA)	3650	8	0.158	0.035	0.154	1.261
Realtor (LA)	4123	3	0.089	0.029	0.085	1.430
Sales representative (NZ)	424	2	0.105	0.036	0.102	1.420
Sheet metal worker (NZ)	6824	2	0.107	0.065	0.096	1.930
Stock clerk (LA)	4754	8	0.219	0.140	0.178	2.060
Stock clerk (WA)	4754	5	0.407	0.467	0.215	3.660
Teacher, high school (LA)[A]	2330	8	0.122	0.137	0.087	2.225

Notes: Magnetic field exposure data calculated from Electrical Worker Study data.[26,27]
TWA = time-weighted average, LA = Los Angeles, NZ = New Zealand, WA = Washington State
AM = arithmetic mean, SD = standard deviation, GM = geometric mean, GSD = geometric standard deviation.
[A]Originally coded to a miscellaneous BOC category.
[B]Data not included in JEM as the exposures of clericals working at a hydro generating plant were unusually high.

(6.4%). For example, "fine mechanics" (ISCO 741) as well as "toolmakers and machine-tool setters" (ISCO 750) can both be coded as "machinists" in the SOC system. With these "many-to-one" links, the data from the two ISCO codes were combined with any other measurements assigned to that SOC, as described below.

A final coding issue is the ambiguous role of miscellaneous and NEC (not elsewhere classified) categories in many comparison occupations of the Electrical Worker Study (Table III). In that study, the NEC occupations had been selected randomly from the Los Angeles County tumor registry, which obtained its subjects' job titles from hospital records and, therefore, often lacked detail to assign a more specific job category. For example, a plastics molder whose hospital record said only "machine operator" would have been assigned to BOC 777 (Miscellaneous machine operators NEC), rather than the more accurate BOC 755 (Extruding and forming machine operators).

To represent these miscellaneous BOC codes, the Electrical Worker Study decided that it would be inaccurate to measure MFs on the potpourri of jobs listed for the NEC categories (e.g., candle maker and doughnut-machine operator for BOC 777). Instead, they chose some broadly equivalent jobs in a participating workplace, e.g., the operators of metal- and plastic-forming machines in an aircraft factory. To code the measurements of these NEC categories for the JEM, we chose the SOC that best described the monitored workers, rather than an SOC miscellaneous category. For example, the Electrical Worker Study represented Technicians NEC with laboratory technicians from the Physiology Department at the University of Southern California, so their MF exposure data were coded

TABLE IV. Number of Occupations and Classifications

	Total No.	No. in JEM (%) Data (%)	Inferred Values	Both (%)
BOC occupations	503	213 (42.3)	216 (42.9)	429 (85.3)
Primary SOC	665	251 (37.7)	287 (43.2)	538 (80.9)
4-digit codes	538			447
3-digit codes	118			87
2-digit codes	9			4
Minor SOC groups (3-digit codes)	96	79 (82.3)	16 (16.7)	95 (99.0)
Major SOC groups (2-digit codes)	50	44 (88.0)	3 (6.0)	47 (94.0)

Notes: BOC = Bureau of Census, SOC = standard occupational classifications.

for the JEM as SOC 3620 (Clinical laboratory technologists and technicians).

We also used the hierarchical structure of the SOC system to code NEC data from the Electrical Worker Study. In the SOC hierarchy, the primary job codes are aggregated into major and minor groups, which are identified by the number of digits in the SOC codes (Table IV). In the above example from the aircraft plant, the collection of machine operators was assigned to the major group SOC 75-76 (Machine operators and tenders). Similarly, all data collected by the Electrical Worker Study for NEC job categories were reclassified to the appropriate unit or aggregate SOC codes (Table III).

Combining Data

A database was created that contained the raw data from all sources. Data entry quality control was accomplished by employing a sequential sampling plan that randomly sampled data to check for entry and coding errors in the database. Error correction and validation sampling continued until the quality control process indicated an error rate <0.1% at greater than 98% confidence.

Along with the job code, each record in the database contains either the TWA for a single worker, the mean of spot measurements from the workstation(s) of a single worker, or the following summary statistics for a job category obtained from a single source:

- N, the number of measurements of a person's daily mean magnetic field exposure (TWAs or means of spot measurements on a single worker)
- arithmetic mean (AM) of the daily mean magnetic field exposure
- standard deviation (SD) of the daily means
- geometric mean (GM)
- geometric standard deviation (GSD)

The database was then programmed to calculate the means and standard deviations for each SOC category i from all data sources j with values for that occupation, using the following formulas:

$$AM_i = \frac{\sum_j N_{ij} AM_{ij}}{N_i} \quad (3)$$

$$SD_i^2 = \frac{\sum_j \left[(N_{ij}-1)SD_{ij}^2 + N_{ij}AM_{ij}^2\right] - N_i AM_i^2}{N_i - 1} \quad (4)$$

$$\ln GM_i = \frac{\sum_j N_{ij} \ln GM_{ij}}{N_i} \quad (5)$$

$$\ln^2 GSD_i = \frac{\sum_j[(N_{ij}-1)\ln^2 GSD_{ij} + N_{ij}\ln^2 GM_{ij}] - N_i \ln^2 GM_i}{N_i - 1} \quad (6)$$

where $N_i = \sum_j N_{ij}$. As shown in the online Mathematical Supplement to this paper, these formulas are exact. Equations 3–5 are also used to combine published summary statistics with exposure measurements for a single person-day, for which $N_{ij} = 1$, $AM_{ij} = GM_{ij}$ = TWA or mean of spot measurements, $SD_{ij} = 0$ and $GSD_{ij} = 1$.

Exposure was inferred for SOC codes that had not been monitored by using data from neighboring codes (close codes) that were present in the JEM. Where we judged the potential for MF exposure was similar, data from close codes were used for inferred values. For example, code 6412 (brick masons) was used to infer the exposure for code 6312 (supervisors; brick masons, stonemasons, and hard tile setters) because it is assumed that supervisors work alongside their workers in this type of profession. As shown in the Mathematical Supplement, summary statistics for the dataless SOC codes were inferred by taking weighted averages of summary statistics for all close codes i:

$$AM_w = \frac{\sum_i w_i AM_i}{\sum_i w_i} \quad (7)$$

$$SD_w^2 = \frac{\sum_i w_i\left[\frac{N_i-1}{N_i}SD_i^2 + AM_i^2\right]}{\sum_i w_i} - AM_w^2 \quad \textbf{(8)}$$

$$\ln GM_w = \frac{\sum_i w_i \ln GM_i}{\sum_i w_i} \quad \textbf{(9)}$$

$$\ln^2 GSD_w = \frac{\sum_i w_i\left[\frac{N_i-1}{N_i}\ln^2 GSD_i + \ln^2 GM_i\right]}{\sum_i w_i} - \ln^2 GM_w \quad \textbf{(10)}$$

In this case, equal weights $w_i = 1$ were used because we had no quantitative information on the relative validity of the different close codes. Occupations with no clear relationship to a code with existing MF data were omitted from the JEM.

Because the SOC hierarchy allows multiple levels of data aggregation, our final SOC JEM can be represented by either the primary or grouped job codes (Table IV). A minor SOC group combines the MF statistics Eqs. 3–6 for all 4-digit codes that have the same first 3 digits. Only when a minor group code has no measurements in any of its component 4-digit codes were inferred values combined with Eqs. 3–6. Likewise, the major SOC groups consist of the combined data for all occupations that share the same first two digits. To provide complete coverage of the work force, JEMs at the 2-digit and 3-digit levels combine grouped occupations with all the primary codes with the same number of non-zero digits. For example, the JEM for 2-digit SOCs includes 50 major groups like Machine Operators and Tenders (SOC 75-76) and 9 primary categories like Military Occupations (SOC 9100).

To test whether the data sources for each SOC are sufficiently homogeneous for such pooling, the total variances SD_i^2 (Eq. 4) for all occupations with raw data were partitioned into within-group and between-group variances, and homogeneity of the data was tested by the F-test.[35] The homogeneity tests were performed on the primary SOCs as well as the major and minor groups.

JEM with BOC Occupational Codes

We converted the JEM developed with the SOC job categories to BOC codes for occupations in the NIOSH study of neurodegenerative diseases.[19] All 4-digit SOC codes whose summary statistics were based on MF measurements (251 occupations) were converted to BOC codes by querying a BOC-to-SOC conversion list. Twenty-six BOC categories correspond to more than one SOC code with measurement data, and in those cases, weighted averages of the statistics for the SOC codes were calculated with the number of workers employed in each SOC as weights (Eqs. 7–10). This weighting comes from the assumption that the mean exposure in the larger BOC category is the average of TWAs for all workers in the component SOC jobs. For example, BOC exposures for the electrical and electronic engineer category (BOC 55) were calculated from statistics for the SOC category of the same name (SOC 1633) plus computer engineers (SOC 1636).

For BOC job categories where there was still no data, exposures were inferred from neighboring codes, using the same procedures described above. Where more than one SOC category approximated a BOC job without measurements, our inferred value for the BOC job was the combined SOC statistics with equal weighting (Eqs. 7–10). We did not weight by the number of workers in the SOC jobs (as above) because these are various *approximations* to the BOC occupation, rather than subcategories. For example, BOC exposures for the chemical technicians (BOC 224) were inferred from statistics for the chemists (SOC 1845) and science technicians NEC (SOC 3890). For NEC and miscellaneous BOCs, we assumed they were used by tumor registries and death certificate databases to code people with incomplete job information, as in the Electric Worker Study (above). Therefore, these miscellaneous BOC codes were assigned the exposure statistics from the equivalent major or minor SOC groups.

Analysis of Variance with the Complete JEM

To gauge the JEM's suitability for assessing exposures, an ANOVA of the MF arithmetic means vs. the BOC occupations was performed with the completed JEM both with and without the inferred values. In addition to variance explained by occupation, the ANOVA results were used to calculate the contrast of the JEM. The contrast is defined by the ratio of the between-group variance of the JEM categories divided by the sum of the between- and within-group variance. (The contrast is also referred to as elasticity by some authors.[36])

Because our JEM does not include multiple days of measurement for individuals, we cannot estimate within-worker variance components in a job category. Because the contrast, by definition, reaches unity if each worker is assigned to a unique exposure group, we likely overestimated the contrast of the JEM. In addition, the homogeneity of MF exposures in the BOC occupations was examined by computing the ratio of the 95th to the 5th percentiles for individual measurements in each BOC category ($R_{.95}$).[37] The $R_{.95}$ value represents the between-worker spread of values in a BOC category and was computed from the GSD of a category. When computing the contrast and $R_{.95}$ for subset analysis, only categories with >2 workers were included.

RESULTS

This job-exposure matrix consists of measurements taken on 2317 worker days. The primary (4-digit) SOC version of the JEM (online Appendix A) contains 251 job categories with measurements and 287 occupations with inferred values, leaving 127 nonaggregated codes with no exposure assessment (19.1%). The 3-digit SOC version contains exposure data for 186 of the 223 occupations (83.4%), including 2- and 3-digit primary categories as well as the minor groups (online Appendix B). The 2-digit SOC version contains exposure data for 51 of the 59 occupations (86.4%) (online Appendix C). The BOC version of the JEM (online Appendix D) has measurement data for 213 job categories, inferred values for 216 jobs, and no exposure assessment for 74 jobs (14.7%).

TABLE V. Occupations Without Complete Measurement Data or a Reliable Inferred Value

BOC	BOC Occupation	SOC
86	Veterinarians	2700
96	Pharmacists	3010
164	Librarians[23,55]	2510
189	Photographers	3260
226	Airplane pilots and navigators[59]	8250
227	Air traffic controllers	3920
228	Broadcast equipment operators	3930
345	Duplicating machine operators	4722
385	Data entry keyers	4793
403	Launders and ironers	5030
457	Barbers	5252
598	Drillers, earth	6474
647	Precious stones and metals workers (jewelers)	6822
677	Optical goods workers	6864
678	Dental laboratory and medical appliance technicians	6865
694	Water and sewage treatment plant operators	6910
714	Numerical control machine operators	7326
723	Metal plating machine operators (unpublished spot measurements)	7343
774	Photographic process machine operators	7671
784	Solderers and brazers[60]	7533
824	Locomotive operating operators[56]	8232
828	Ship captains and mates, exc. fishing boats	8241
829	Sailors and deckhands	8243
834	Bridge, lock, and lighthouse tenders	8245

Notes: Incomplete measurements cited suggest that some of these occupations will be highly exposed.

Common BOC job categories with neither measurements nor reliable inferred values are in Table V.

The JEM comprises 97% personal exposure measurements and 3% spot measurements. Spot measurement data was used only when there was little personal monitoring data ($N \leq 10$) and their distributions were similar. The number of measurements of a person's daily mean exposure for each primary SOC job category ranged from 1 to 192 with a median of 7 person-days (Figure 1).

The distributions of the arithmetic and geometric means of the TWA magnetic fields from the primary SOC occupational categories are shown in Figure 2. As is expected with log-normally distributed data, the distribution statistics are less for the GM (median = 0.16 μT over all occupations) than for the AM (median = 0.21 μT). As shown in Table VI, the most highly exposed jobs are dominated by those labeled "electrical occupations" in previous epidemiologic studies.[1] Other occupations with high exposures were the logging occupations (BOC 496) with a GM of 0.76 μT (N = 9) and sewing machine operators (BOC 744) with GM = 0.68 μT (N = 85).

In the F-tests for combining multiple data sources into a single SOC, only a few categories (16.2% of the 68 primary SOC codes) had p-values less than 0.05 with combined data, demonstrating that the combining of MF data from the different sources was generally justified. The percentage of occupations with significant inhomogeneity between data sources was progressively higher with the upper levels of the SOC hierarchy (20.3% for 3-digit occupations and 27.0% for 2-digit occupations). It makes sense that upper-level SOC codes with fewer occupations would allow more opportunities for heterogeneity in exposures within a single code.

In an ANOVA, the BOC occupation accounted for 30% of the MF variance ($p \ll 10^{-6}$), and the contrast (ratio of the between-job variance to the total of within- and between-job variances) was 88%. The homogeneity of MF exposures in the BOC occupations as measured by the $R_{.95}$ ratio ranged from 1.5 to 351 with a median value of 11 in this JEM. A separate analysis on the BOC occupations that excluded inferred values had a small 1% increase in contrast, an explained variance of 34% and produced a median $R_{.95}$ ratio 10.

A similar analysis of 4-digit SOC codes without inferred values also showed a small increase in contrast and explained variance (33%) and tightening of the $R_{.95}$ values. This analysis suggests that the inclusion of the inferred values in the JEM has a small effect in terms of decreasing the contrast and precision of the within-category exposure estimates. The range of $R_{.95}$ ratios was unchanged by excluding inferred values, and although some job categories have large within-group variability, this range of $R_{.95}$ is comparable to JEMs for solvents and particulates.[36]

We further examined the importance of spot measurements in the JEM by excluding all spot measurements and recompiling the ANOVA tables. For the 4-digit SOC classification, the results were essentially unchanged except for a slight increase in the median $R_{.95}$ ratio. For the BOC classification, the explained variance decreased to 21%, and the median $R_{.95}$ ratio increased to 14. This analysis suggests that excluding spot measurements has little impact for the SOC coding scheme, but may somewhat adversely impact the BOC JEM.

The JEM's ability to assess MF exposure in population-based epidemiologic studies can be evaluated from the results of the SFBA adult glioma study[16] and the NIOSH neurodegenerative disease study.[19] The geometric mean MF from the completed JEMs was assigned to each job held by subjects in the glioma study and to the "usual occupation" reported on the death certificates in the neurodegeneracy study. The GM was the chosen summary statistic because it is the best measure of the central tendency in a lognormal distribution—the most common case for our magnetic field exposure data.

The SFBA adult glioma study reported 491,167 person-months of work for 7094 jobs of more than 3 months duration for 1396 subjects. The 4-digit version of the SOC JEM (Appendix A) has data matching the job codes of SFBA subjects at the most detailed coding level that account for 67% of jobs and 69% of the total person-months of work. However, if inferred values are excluded the 4-digit SOC JEM

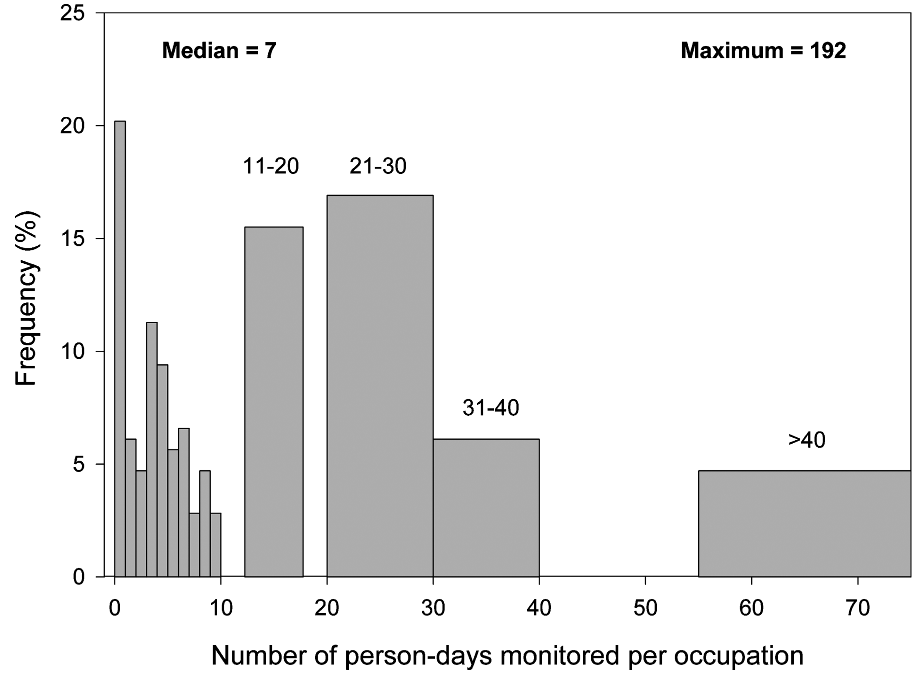

FIGURE 1. Distribution of the number of person-days monitored in primary SOC occupations with measurement data (n = 251)

only matches about 40% of the jobs and about 58% of the total person-months of work. By adding inferred values and matching with major or minor SOC groups (2 and 3 digit level), the frequencies with MF exposures increased to 95% of the reported jobs and 97% of the total person-months of work. These matching frequencies remained reasonably stable within a few percent over the entire study period from 1991–2004.

The NIOSH neurodegenerative study had death certificates with occupations for 2,614,346 adults, and the JEM provided exposure estimates for 94.4% of these subjects. Table VII gives the distribution of MF exposures assessed by the JEM for the NIOSH subjects, and compares them with personal monitoring from the 1000-Person Study, a random sample of U.S. adults.[38] Exposures assessed by the JEM are slightly higher at the median (0.14 μT vs., 0.10 μT from the

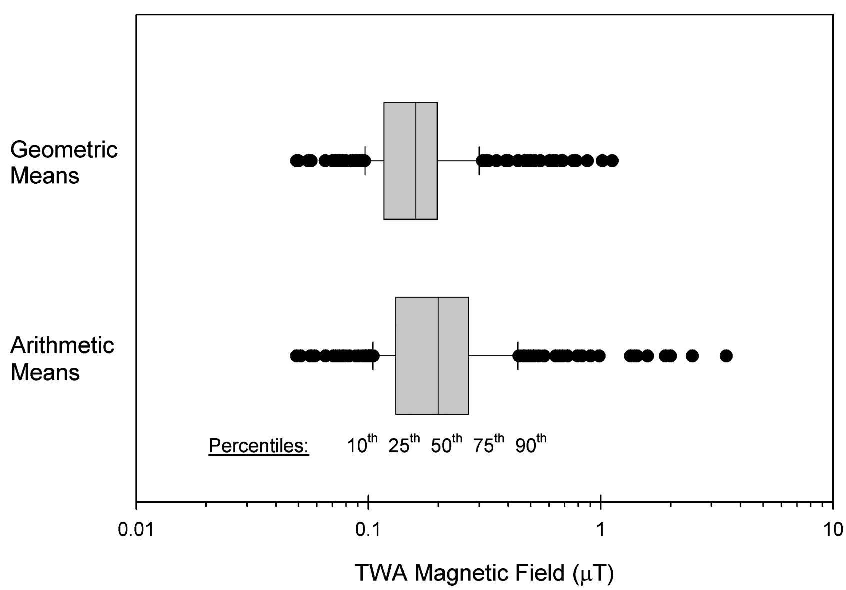

FIGURE 2. Distribution of arithmetic and geometric means for the TWA magnetic field in primary SOC occupations with measurement data (n = 251)

TABLE VI. Exposures for Occupations Identified as Electrical Work in Epidemiologic Studies

BOC	Occupation	N	GM (μT)
577	Electrical power installers and repairers	156	0.88
695	Power plant operators	51	0.78
773	Motion picture projectionists	14	0.63
533	Miscellaneous electrical and electronic equipment repairers	6	0.60
526	Household appliance and power tool repairers	38	0.40
575, 576	Electricians, electrician apprentices	81	0.37
213	Electrical and electronic technicians	36	0.22
527	Telephone line installers and repairers	133	0.22
523	Electronic repairers, communications, and industrial equipment	65	0.21
55	Electrical and electronic engineers	66	0.18
525	Data processing equipment repairers	1	0.15
529	Telephone installers and repairers	25	0.15
228	Broadcast equipment operators	no data	
555	Supervisors, electricians, and power installers and repairers	no data	

1000-Person Study) but lower at the 95th percentile (0.35 μT vs. 0.50 μT). However, these differences between the two distributions are not significant in a chi-squared test of the percentiles in Table VII ($\chi^2 = 0.486$ for 8 degrees of freedom, $p = 0.999$).

DISCUSSION

This job exposure matrix gathers available magnetic field exposure data and groups them into the 1980 Standard Occupational Classification and Bureau of the Census occupational categories for use in epidemiologic studies. This JEM allows investigators to assign magnetic field exposures based on workplace measurements to study subjects when they only have job titles from death certificates, cancer registries, company records, etc., or work histories from interviews. With little effort the JEM data can be linked to study populations by the appropriate job codes, giving reasonable estimates of a subject's MF exposure.

Population-based studies such as the SFBA adult glioma study and the NIOSH study of neurodegenerative diseases require a systematic and broad scheme for classifying the occupational MF exposures of a diverse study population. For registry studies such as the NIOSH study, exposures must be deduced from occupations already coded into a standardized system that can be used for many different purposes. Registries of tumors or death certificates in the United States usually code jobs with either the SOC or BOC classification system, so these occupational classification systems work best for linking exposures to disease outcomes.

TABLE VII. Distribution of U.S. Occupational Magnetic Field Exposures

	Workday TWA Magnetic Field Exposure (μT)			
	Neurodegenerative Disease Study			EMF RAP ID 1000-PersonSurvey (Work)
Summary Statistic	All Controls	Men	Women	
N	2,466,775	1,567,497	899,278	525
Arithmetic mean	0.16	0.17	0.16	0.173
Standard deviation	0.13	0.14	0.13	0.309
99th percentile	0.78	0.95	0.78	1.350
95th	0.35	0.39	0.30	0.500
90th	0.24	0.24	0.24	0.332
75th	0.19	0.20	0.18	0.178
50th (median)	0.14	0.15	0.14	0.099
25th	0.09	0.10	0.09	0.060
10th	0.07	0.07	0.08	0.030
5th	0.04	0.04	0.05	0.024
1st	0.04	0.04	0.04	0.014

Notes: Exposures from the JEM applied to the controls of the neurodegenerative disease study,[19] compared with the 1000-Person Survey conducted by the EMF RAPID (Research and Public Information Dissemination) Program.[38]

The JEM contains data for a variety of jobs present in the modern economy and will probably provide exposure estimates for a large percentage of the population. Many of the jobs were measured repeatedly and in more than one study, so the resulting estimate for each job category reflects variability within the job. For example, the JEM's exposures agree well with occupational magnetic fields from the EMF-RAPID program's random survey of the U.S. population,[24,38] as shown by the comparison with controls in the NIOSH neurodegenerative disease study (Table VII). These matched controls were selected randomly from NIOSH's registry of over 2 million death certificates from 22 states, whose demographics conform well with the general U.S. working population.[39,40] This indicates that the MF exposures from the JEM are representative of the working men and women in the United States.

As a method for assessing occupational MF exposures, our JEM has both strengths and weaknesses. Although the occupational coding systems enable the JEM to tap into many data resources, these classification schemes are organized by skill level, training, education, and licensing and credential requirements. Occupations that have different codes may not necessarily be different in terms of their potential exposure to MF. For example, SOC code 1412 (accountants and auditors, GM = 0.12 μT) and code 4712 (bookkeepers and accounting and auditing clerks, GM = 0.16 μT) have the same types of exposures, mainly due to office equipment such as computer terminals, and consequently have similar MF estimates. One solution would be to group the 4-digit SOC or BOC categories into more precise exposure groups by statistical criteria, as has been done with electric utility exposure data.[4]

On the other hand, significant variations in MF exposures are sometimes found within a standard job category. For example, the Electric Worker Study data on electricians (Table II) show that residential and construction electricians have lower MF exposures than industrial and utility electricians (or fitters). Also, fitter exposures are lower in the Los Angeles region, due in part to combining measurements on electricians from an aircraft manufacturer with those from utilities. Nonetheless, all kinds of electricians are classified into BOC category 575.

These standardized classification systems developed for census and economic statistics have long recognized deficiencies in assessing exposures to workplace agents.[41–43] Although industrial hygiene groups have proposed a coding system designed for occupational health research,[42,44,45] they require a long-term commitment of substantial resources. "In reality, such a system is not on the horizon, and perhaps not even feasible"[46,p.1310] Therefore, the standardized occupational codes will remain the best option for JEMs in population based studies when the subject's job title is the only datum related to exposure.[47] Fortunately, our MF JEM has a homogeneity of exposures within occupations and a contrast between occupations comparable with JEMs with job classifications developed for a single industry.[36]

These misclassifications in the standardized occupational codes were magnified when we had to convert MF data between the SOC, BOC, and ISCO systems. Our approach to translating job codes was to manually assign each occupation in one system to all jobs in the other system whose definitions overlapped in any way. These one-to-many links bring the mean exposures of the occupations involved closer together than they truly are, reducing the JEM's specificity.

On the other hand, these intercode translations enabled us to combine data from more sources, which should make the JEM more representative. In addition, using data sources with different occupational codes improved the number of jobs covered by the JEM. Fortunately, a study of the accuracy of such JEM translations reported that the resulting errors in the exposure estimates are little more than those due to original coding.[47]

Similar translations will also be needed to update our JEM from the 1980 SOC to the ISCO and 2000 SOC codes now in use. "Crosswalks" are available from the National Crosswalk Service Center that mechanically convert the 1980 SOC or BOC codes to other systems. However, these publicly available crosswalks need to be validated for assessing MF exposures.

Magnetic field exposures could be assessed more accurately if the JEM was supplemented with data on exposure variations due to industry, tasks, and sources within an occupational category.[48] When an epidemiologic study has information on these other exposure determinants for individuals from interviews, company records, etc., assessments of an individual's MF exposure may be improved by adjusting the occupational mean from the JEM with an algorithm using these supplementary data. When a death certificate or disease registry codes subjects by industry and occupation, exposure assessments can be improved by adding industry-specific data to our JEM and where there is significant between-industry variability, averaging over both industry and occupation. For example, electricians' MF exposures vary greatly between the construction, utility, manufacturing and service sectors.

The hierarchical SOC classification scheme allows the assignment of exposures at the aggregated 2-digit level and the more specific codes at the 4-digit level. At the 2-digit level, 30 codes would account for about 90% of the more than 7000 job titles reported for the SFBA adult glioma study population, and 47 codes would match about 98% of the reported jobs if our JEM had data for all these categories. This aggregation by SOC categories gives us a more complete assessment of exposures, but the 2-digit job categories are not necessarily uniform MF exposure groups.[37] The 4-digit level retains much more detail and presumably provides more uniform exposure groupings, but it takes many more codes to describe the population.

The variety of data sources included in the JEM is a mixed blessing. There are some important common features across sources (Table I). All used the EMDEX whose measurement specifications have stayed constant across models.[26] All sources (except for spot measurements on 62 workers) used full-shift personal monitoring and reported TWA data. The authors participated in the data collection from most of the original data sources as noted earlier, and all these studies included routine quality control procedures, such as frequent meter calibration, data entry, and consistency checks, and checks for meter failure and missing data. In the case of the Office Worker Study,[23] the EMF-RAPID program under the U.S. Department of Energy supervised extensive quality assurance measures.[24]

On the negative side, different methods were used to select subjects for the various studies, so the JEM has variations in how well the measurement statistics from the different studies represent exposures of the general population. Because the studies were done in the United States, Sweden, Italy, Finland, and New Zealand, the data also have variations in the countries' work practices and electrical characteristics (e.g., 60 Hz, 110-volt electricity in the United States vs. 50 Hz, 220 volts in the other countries).

In the Electrical Worker Study, MF exposures in New Zealand were significantly higher for telephone line workers and welders than in the United States; they were lower for power station operators and TV repairers (Table II). These discordant New Zealand data were omitted from the JEM because it was originally developed for use in U.S. studies. Otherwise, we found little evidence that these country differences significantly affected occupational exposures to the TWA MF magnitude. Of the 90 Swedish occupations incorporated into our JEM,[9] the only occupation whose MF exposures were significantly inhomogeneous from U.S. measurements were carpenters (SOC 6422, 0.17 ± 0.12 μT vs. 0.36 ± 0.18 μT from the Electrical Worker Study, $p = 0.011$ in the F-test).

A statistical issue arising from the different data sources were the estimates for the SD and GSD (Eqs. 1 and 2) in the Swedish JEM,[9] which assume the TWAs are log-normally distributed. Because log-normality has been validated for many but not all occupational groups,[49] the SDs and GSDs in our JEM should be reasonably accurate. The JEM includes these standard deviations so users can perform Monte Carlo simulations of individual exposures or calculate other MF statistics and accuracy indicators like the 95% confidence interval on the mean, coefficient of variation, empirical Bayes estimators, minimum variance unbiased estimator,[50] etc. The AM is included in the JEM as well as the GM because arguments have been advanced for both statistics as the appropriate metric for summarizing group exposures.[51,52]

We did restrict the JEM to MF measurements taken after 1988 when the Electrical Worker Study commenced. However, the time and date of the measurements are not included in the JEM. This may affect the accuracy of exposure assessments in cases where electric and electronic technologies have changed over a study's time span (e.g., manual typewriters → electric typewriters → word processors). Especially in the SFBA adult glioma and NIOSH neurodegenerative disease studies, the patients are typically older and their prime working years came before the JEM's measurements. Because personal MF exposure monitors did not exist prior to the start of the Electrical Worker Study in 1988, quantitative JEMs can be used only for assessing exposures over the entire work career by assuming that present day measurements are valid for past eras. Two alternatives for assessing past exposures are (1) expert judgment that takes technology changes into account,[53] and (2) measurements where the equipment has not yet been modernized.[33]

Our JEM does represent women's MF exposures better than the original Swedish JEM,[9] which came from a study of males. Monitoring data on women came from the spontaneous abortion, office worker, and adult glioma studies, but they comprise only about 9% of the total measurement data. No difference in MF exposures by gender has been shown within an occupation, but there is an obvious gender bias in the number of measurements in the JEM, e.g., $N = 14$ for nurses vs. $N = 192$ for electrical and electronic equipment assemblers. (Other investigators later augmented the Swedish JEM with measurements of predominantly female occupations,[54] but our JEM does not include these new data.)

In general, the number of measurements is highly variable across different job categories (Figure 1), which affects the representativeness of the population and the confidence limits on the means. As an example, the Finnish data on sewing machine operators[34] had only two measurements with $GM = 2.99$ μT and $GSD = 1.10$, an unrealistically narrow distribution. The Italian Worker Study,[31] which measured 85 seamstresses, provided a more reasonable distribution ($GM = 0.69$ μT and $GSD = 2.29$).

Nonetheless, the primary SOC JEM still has 43 jobs based on only one worker and 13 jobs based on two, which result in large sampling errors around the mean exposure. Methods to adjust for this sampling error from sparse exposure data are beyond the scope of this article. However, the standard deviations and N for each job in the JEM, plus the SOC's hierarchical structure, provide input data for the many statistical tools that have been developed to handle sampling error and impute more accurate exposures for risk analyses.

An issue more difficult than sparse measurements is the many jobs without measurements and no "close category" that could be used to infer MF exposures (Table V). For some of these jobs, reliable measurements that do not meet the inclusion criteria for our JEM show a potential for very high MF exposures. In the librarian category (BOC 164), one measurement on a library specialist in the Office Worker Survey[23] had a TWA of 1.65 μT. Even though such high MFs might be due to the electronic book surveillance systems that had just been installed in libraries,[55] we decided that exposures for the whole occupation should not be based on this single high measurement.

In another example, personal monitoring on Swedish locomotive engineers gave a mean TWA of 4.03 μT[56] but did not meet the JEM's inclusion criterion because they covered only partial shifts. Similar partial-shift measurements were reported for electrosteel furnace operators with TWAs = 10.79–16.87 μT[57] compared with the JEM's value of 0.52 ± 0.36 μT (AM ± SD) for furnace, oven, and kiln operators (BOC 766). Likewise, heat treatment equipment operators (BOC 724) have 0.36 ± 0.43 μT in the JEM, but spot measurements of up to 1390 μT have been reported on the operators of resistance heaters.[58] Because our current JEM cannot reliably determine exposures in the jobs listed in Table V, more personal MF monitoring is clearly needed before all exposures can be accurately assessed for the general working population.

CONCLUSIONS

We have gathered a large proportion of the magnetic field exposure measurements available for jobs held by subjects in the SFBA adult glioma study and the NIOSH study of neurodegenerative diseases. This JEM classifies occupations into two standardized coding schemes from the U.S. government that are applicable to the general working population. Although we have exposure estimates for a large portion of these subjects, assessing MF exposure accurately for studies of brain cancer, neurodegenerative diseases, and other diseases is still difficult because of variations over time and location, as well as limitations in the available measurements.

Applying our JEM to population-based epidemiologic studies can be as simple as linking the GM magnetic fields with the death certificate databases by the subject's job code, as was done in NIOSH's neurodegenerative disease study. However, this article identifies many other techniques that can broaden the JEM's applicability and improve its accuracy.

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