



## Occupational Magnetic Field Exposure and Cardiovascular Mortality in a Cohort of Electric Utility Workers

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In electric utility workers, occupational exposure to magnetic fields has previously been associated with mortality from acute myocardial infarction (AMI) and arrhythmia but not from chronic coronary heart disease (CCHD) or atherosclerosis. To investigate these health endpoints further, the authors examined mortality from AMI ( $n = 407$ ) and CCHD ( $n = 369$ ) in a cohort of 35,391 male workers at the Southern California Edison Company between 1960 and 1992. Exposure was estimated according to duration of employment in occupations associated with high levels of magnetic field exposure and was calculated as cumulative exposure to magnetic fields expressed in micro-Tesla-years. Adjustment was made for age, calendar time, socioeconomic status, race, and worker status (active or inactive). The authors found that men working longer in high-exposure occupations or working as electricians, linemen, or power plant operators had no increased risk of dying from either AMI or CCHD compared with men who never worked in high-exposure occupations. For cumulative exposure, no association was observed with mortality from AMI (rate ratio per 1  $\mu$ T-year = 1.01, 95% confidence interval: 0.99, 1.02) or CCHD (rate ratio per 1  $\mu$ T-year = 1.00, 95% confidence interval: 0.99, 1.02). These results, indicating no exposure-related risk increase for AMI mortality, do not confirm previous results.

cardiovascular diseases; electromagnetic fields; mortality; occupational exposure

Abbreviations: AMI, acute myocardial infarction; CCHD, chronic coronary heart disease; CI, confidence interval; COPD, chronic obstructive pulmonary disease; ICD-9, *International Classification of Diseases*, Ninth Revision; RR, rate ratio.

Savitz et al. recently reported on cardiovascular mortality in a cohort of nearly 140,000 men employed from the early 1950s through 1988 at five electric utility companies in the United States (1). Mortality was analyzed with respect to parameters reflective of occupational exposure to power-frequency (60-Hz) magnetic fields, including 1) duration of employment in occupations associated with "high" magnetic field exposures (electricians, power station operators, linemen) and 2) a cumulative exposure index, expressed in micro-Tesla-years, based on a job exposure matrix combining employee job histories with representative contemporaneous job-specific measurements at the five companies. Savitz et al. reported positive associations of duration in exposed jobs or cumulative magnetic field expo-

sure with both acute myocardial infarction (AMI) and arrhythmia-related cardiovascular deaths but not with mortality from chronic coronary heart disease (CCHD) or atherosclerosis (1).

The impetus for looking at a connection between magnetic field exposure and cardiovascular mortality was provided by experimental results on heart rate variability in human volunteers exposed to magnetic fields and the implications of altered heart rate variability on subsequent cardiovascular health outcomes (2). Heart rate variability reflects the autonomic nervous system's control of cardiac activity. Reduced heart rate variability was first found to be associated with mortality following an initial AMI (3–6). This relation was later observed for mortality in the elderly, including those

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who were healthy (7, 8), and for mortality and acute cardiac events in the middle-aged, also including those who were healthy (7, 9, 10). A relation between autonomic nervous system impairment and acute cardiac episodes (including AMI and arrhythmia) has been also noted by others (11).

In the initial laboratory studies linking heart rate variability to magnetic field exposure (2), volunteers exposed to intermittent (15 seconds on and then 15 seconds off; magnetic field activated every other hour) magnetic fields (28.3  $\mu$ T resultant, circularly polarized) displayed altered heart rate variability compared with subjects exposed to continuous fields or to sham fields. Specifically, low-frequency (0.04–0.15-Hz) heart rate variability decreased and high-frequency (0.15–0.40-Hz) power increased during the exposure sessions (the subjects quickly reverted to normal heart rate variability after exposure ended). On the basis of these observations, Savitz et al. postulated that magnetic fields should be related to AMI mortality but not to CCHD mortality (1). Subsequent studies with volunteer subjects did not always produce consistent results regarding heart rate variability and exposures to magnetic fields (12). After conducting a multistudy analysis, it was concluded that differences in study design factors related to physiologic arousal might explain the apparent inconsistency (12).

To further explore the endpoints and exposures reported by Savitz et al. (1), the present study took advantage of the availability of a second cohort of personnel from an electric utility company for whom magnetic field exposure indices had already been applied to evaluate the risks of leukemia and brain cancer (13). The job and task characteristics, as well as the physical environments, of this new cohort and the five-utility cohort were similar. Previous comparative analysis provided additional assurance that the two cohorts were consistent with each other (14). To increase comparability between the present analysis and the Savitz et al. research, we chose to perform the analysis by using the same methods and analytical models as those used by Savitz et al. (1).

On the basis of the Savitz et al. observation (1), we expected to find increased mortality from AMI and arrhythmia but not from CCHD among personnel with increased levels of magnetic field exposures. As a test for potentially uncontrolled confounding by smoking, we carried out similar analyses for mortality due to lung cancer and chronic obstructive pulmonary disease (COPD), diseases not thought to be related to magnetic field exposures.

## MATERIALS AND METHODS

We performed our analysis by using an existing data set of electric utility workers. A detailed description of the study population is available elsewhere (13, 15, 16). Briefly, the cohort was defined as all noncontract male personnel who worked at the Southern California Edison Company (Edison) for at least 1 year between 1960 and 1991. Information regarding workers' age, sex, race, and occupational history was abstracted from company records. Vital status was established by record linkage of former personnel (i.e., retired, terminated, or known deceased) to a variety of California and US mortality registries through 1992. When matches occurred, copies of the death certificates were

requested from each US state. Men were considered alive if they were currently employed or if no record of death was found. The cause of death was coded from the death certificate by using the *International Classification of Diseases, Ninth Revision (ICD-9)*. We included the following categories of cardiovascular and pulmonary deaths as outcomes in our analyses: 1) AMI (ICD-9 code 410), 2) arrhythmia related (ICD-9 codes 426 and 427), 3) CCHD (ICD-9 codes 411–414), 4) atherosclerosis related (ICD-9 code 440), 5) lung cancer (ICD-9 codes 160–165), and 6) COPD related (ICD-9 codes 490–496).

To assess cumulative exposure to occupational magnetic fields, a classification system was used to organize and categorize the complex set of occupational titles. The occupational classification system was based on an evaluation of measured magnetic fields, job titles, work tasks, and environments to create categories of workers whose exposures to magnetic fields were similar. Magnetic field measurements were obtained for personnel in actual work environments over two separate intervals in 1991 and 1992. We used EMDEX-2 meters (Enertech, Campbell, California) that recorded at frequencies of 40–800 Hz, with a sampling rate of 1.5 seconds. Individual Edison employees volunteered to perform their normal duties while wearing the EMDEX-2 meter. On the basis of the combination of field measurements, the occupational classification system, and individual occupational history, each worker in the cohort was assigned a cumulative magnetic field exposure level (15, 17).

Statistical analyses were designed to follow the methods used by Savitz et al. (1). Poisson regression models were used to estimate rate ratios and confidence intervals with SAS statistical software (SAS Institute, Inc., Cary, North Carolina). The models included an exposure term, age as a continuous variable, a marker for socioeconomic status, race, calendar decade of observation, and worker status (active or inactive status with a 2-year lag). Socioeconomic status was assigned one of five categories based on a worker's first job held at the company. White-collar and professional jobs were considered the two "high" socioeconomic status categories, while general "labor" jobs were assigned the "low" socioeconomic status. Administrative and craft jobs were designated as the two intermediate categories. Race was categorized as White or non-White.

Exposure was scored in three ways. First, men who worked as linemen, electricians, or power plant equipment operators were compared with men in occupations associated with low exposures. Second, we combined men who had ever worked in "high-exposure" jobs (the same set of jobs defined in the Savitz et al. study (1)) and compared their outcomes with those of men who had never held these jobs. The duration of employment in years was the exposure score. We established intervals of never working in "exposed" jobs (reference category) and of working in any exposed jobs for less than 10 years, 10–20 years, or more than 20 years. Third, we examined calculated cumulative magnetic field exposures for each worker, accounting for changes in jobs over the duration of employment; these exposures were expressed in micro-Tesla-years. By using the distribution of exposures among all of the cohort's decedents, we divided micro-Tesla-years into five strata based on

**TABLE 1. Cardiovascular mortality by duration of employment in selected occupations, California, 1960–1992**

Exposed occupations	Duration of employment	AMI*			CCHD*		
		Cases (no.)	RR <sup>†</sup> , †	95% CI*	Cases (no.)	RR	95% CI
All‡	None	172	1.00		138	1.00	
	>0–<10 years	63	0.60	0.44, 0.81	59	0.78	0.58, 1.08
	10–<20 years	63	0.82	0.60, 1.11	64	1.02	0.74, 1.41
	≥20 years	109	0.76	0.58, 0.99	108	1.00	0.75, 1.32
Electricians	None	172	1.00		138	1.00	
	>0 years	35	0.52	0.35, 0.77	44	0.89	0.62, 1.28
Linemen	None	172	1.00		138	1.00	
	>0 years	123	0.77	0.60, 0.99	100	0.82	0.62, 1.09
Power plant operators	None	172	1.00		138	1.00	
	>0 years	85	0.71	0.53, 0.95	96	1.09	0.82, 1.45

\* AMI, acute myocardial infarction; CCHD, chronic coronary heart disease; RR, rate ratio; CI, confidence interval.

† Adjusted for age, calendar time, socioeconomic status, race, and worker status (active or inactive).

‡ All exposed occupations, including craft supervisors; operators (apprentice, control, plant, power house, substation); electricians; groundmen; linemen/splicers; helpers, maintenance; machinists, maintenance; mechanics, boiler and condenser; mechanics, maintenance; repairmen, electrical; technicians, instrument; technicians, communication; and welders.

percentile cutpoints: <30 (reference category), 30–<50, 50–<70, 70–<90, and ≥90. These exposure categories were then applied to the entire cohort. We also examined the possibility that cumulative exposure is relevant only at various time periods; in addition to total cumulative exposure, we also modeled the effect of cumulative exposure with lag periods of 2, 5, 10, and 20 years (i.e., omitting exposure accumulated during the most recent 2, 5, 10, and 20 years) and cumulative exposure within an exposure window of 5 years (i.e., exposure accumulated during the most recent 5 years). Because of the high number of deaths associated with 0  $\mu$ T-years, representing the reference category in the 5-year exposure window (33 percent), the percentile cutpoints were slightly different for this exposure score; 33, 50, 70, and 90 percentile values were used.

To help evaluate potential confounding from age and year, we explored statistical models including calendar year as a continuous variable rather than a categorical variable representing decade of observation, models including start year of work in place of calendar year, and models also including quadratic terms for start year.

## RESULTS

Our cohort consisted of 35,391 men who accumulated 570,171 years of follow-up. We observed 407 deaths due to AMI and 369 deaths due to CCHD. We had insufficient numbers of arrhythmia-related ( $n = 10$ ) and atherosclerosis-related ( $n = 22$ ) deaths to conduct an informative analysis. We also observed 304 deaths due to lung cancer and 93 deaths due to COPD.

Length of time working in occupations with high exposures to magnetic fields was not associated with an increased risk of death from AMI; rather, a decrease in mortality for all employment durations was observed (table 1). Mortality from AMI also decreased for men who ever worked as electricians, linemen, or power plant operators when compared with men who had never worked in exposed occupations. Our data were too sparse to complete an analysis by duration of employment for the individual employment categories. No association was observed between mortality from CCHD and duration of employment in exposed occupations or employment as an electrician, lineman, or power plant operator (table 1).

For total calculated cumulative exposure to magnetic fields as a continuous variable, we did not observe an association between micro-Tesla-years and mortality risk for AMI (rate ratio (RR) per 1  $\mu$ T-year = 1.01, 95 percent confidence interval (CI): 0.99, 1.02) or for CCHD (RR per 1  $\mu$ T-year = 1.00, 95 percent CI: 0.99, 1.02) (table 2). For continuous cumulative exposure, varying the length of the lag periods did not result in a dramatic change in rate ratio estimates. For cumulative exposure during the most recent 5-year period, however, we observed an increase in risk by increasing exposure for both AMI (RR per 1  $\mu$ T-year = 1.14, 95 percent CI: 1.06, 1.24) and CCHD (RR per 1  $\mu$ T-year = 1.09, 95 percent CI: 0.99, 1.19).

When total cumulative exposure was aggregated into five strata and was analyzed as a categorical variable, elevated risks were observed for AMI and CCHD in some of the intermediate exposure categories, but no excess risks were observed for the highest exposure categories (table 2). However, we observed statistically significant risk increases

**TABLE 2. Cardiovascular mortality by cumulative occupational exposure to magnetic fields, California, 1960–1992**

	$\mu$ T-years	AMI*			CCHD*		
		Cases (no.)	RR*,†	95% CI*	Cases (no.)	RR	95% CI
No lag	0–8.90	99	1.00		82	1.00	
	8.90–13.17	76	1.09	0.79, 1.51	69	1.03	0.73, 1.45
	13.17–18.75	87	1.35	0.97, 1.87	89	1.31	0.93, 1.83
	18.75–27.55	101	1.51	1.08, 2.12	79	1.16	0.81, 1.65
	$\geq 27.55$	44	0.99	0.65, 1.51	50	1.19	0.79, 1.77
RR/1 $\mu$ T-year		407	1.01	0.99, 1.02	369	1.00	0.99, 1.02
2-year lag	0–8.41	94	1.00		74	1.00	
	8.41–12.71	82	1.18	0.85, 1.63	74	1.20	0.84, 1.70
	12.71–18.24	87	1.43	1.02, 1.99	86	1.43	1.00, 2.03
	18.24–27.30	100	1.50	1.06, 2.11	84	1.34	0.93, 1.93
	$\geq 27.30$	44	1.01	0.66, 1.55	51	1.34	0.89, 2.03
RR/1 $\mu$ T-year		407	1.00	0.99, 1.02	369	1.00	0.99, 1.02
5-year lag	0–7.43	92	1.00		69	1.00	
	7.43–11.85	81	1.21	0.87, 1.69	71	1.19	0.83, 1.71
	11.85–17.35	89	1.39	0.99, 1.96	89	1.47	1.02, 2.11
	17.35–26.43	97	1.38	0.97, 1.97	90	1.40	0.96, 2.03
	$\geq 26.43$	48	1.05	0.68, 1.60	50	1.27	0.83, 1.95
RR/1 $\mu$ T-year		407	1.00	0.99, 1.02	369	1.00	0.99, 1.02
10-year lag	0–5.72	87	1.00		66	1.00	
	5.72–10.08	78	1.25	0.88, 1.78	72	1.24	0.85, 1.81
	10.08–15.15	94	1.45	1.00, 2.10	85	1.25	0.84, 1.86
	15.15–24.75	97	1.34	0.92, 1.97	97	1.32	0.89, 1.96
	$\geq 24.75$	51	1.13	0.72, 1.78	49	1.11	0.70, 1.77
RR/1 $\mu$ T-year		407	1.00	0.99, 1.01	369	1.00	0.99, 1.01
20-year lag	0–1.67	78	1.00		69	1.00	
	1.67–5.61	85	1.84	1.25, 2.71	60	0.98	0.66, 1.48
	5.61–10.20	112	2.05	1.37, 3.08	87	1.09	0.72, 1.64
	10.20–18.69	76	1.19	0.76, 1.87	106	1.13	0.74, 1.72
	$\geq 18.69$	56	1.53	0.92, 2.53	47	0.86	0.52, 1.42
RR/1 $\mu$ T-year		407	0.99	0.98, 1.01	369	0.99	0.98, 1.01
5-year window	0	152	1.00		168	1.00	
	0–0.97	66	1.16	0.83, 1.62	67	1.27	0.91, 1.77
	0.97–2.13	91	2.39	1.70, 3.36	60	1.70	1.15, 2.51
	2.13–3.46	76	3.26	2.18, 4.88	56	2.36	1.51, 3.69
	$\geq 3.46$	22	2.36	1.33, 4.19	18	1.75	0.93, 3.30
RR/1 $\mu$ T-year		407	1.14	1.06, 1.24	369	1.09	0.99, 1.19

\* AMI, acute myocardial infarction; CCHD, chronic coronary heart disease; RR, rate ratio; CI, confidence interval.

† Adjusted for age, calendar time, socioeconomic status, race, and worker status (active or inactive).

by increasing exposures accumulated during the most recent 5-year period (table 2). Models including calendar year as a continuous variable rather than a categorical variable representing decade of observation, models including start year of work in place of calendar year, and models also including quadratic terms for start year did not result in substantially different effect estimates (data not shown).

Lung cancer mortality was not associated with any of the exposure scores (RR per 1  $\mu$ T-year = 1.00, 95 percent CI: 0.99, 1.01) except exposure accumulated during the most recent 5-year period (RR per 1  $\mu$ T-year = 1.14, 95 percent CI: 1.04, 1.24). COPD risk estimates were significantly elevated for almost all exposure metrics (RR per 1  $\mu$ T-year = 1.03, 95 percent CI: 1.018, 1.06), however. When total

cumulative exposure was aggregated into five strata, COPD rate ratio estimates were significantly elevated for the fourth (70th–90th percentile) and fifth (>90th percentile) strata, with rate ratios of 3.17 (95 percent CI: 1.52, 6.58) and 2.78 (95 percent CI: 1.21, 6.38), respectively.

## DISCUSSION

Neither AMI nor CCHD was consistently and positively associated with any of the magnetic field exposure scores in our analyses. Thus, our results for AMI are not consistent with those reported by Savitz et al. (1).

Heart disease is complex, with many factors contributing to mortality. Age is a strong predictor of mortality from AMI and CCHD, with the risk increasing 50-fold and 100-fold, respectively, between ages 40–44 and 80–84 years (18). The historical changes for AMI and CCHD have also been dramatic. Mortality rates for both causes of death in the 1970s were much higher than in the 1990s. The age-adjusted mortality rate for AMI was 176/100,000 in 1970 and 90/100,000 in 1992, while the age-adjusted mortality rate for CCHD was 150/100,000 in 1970 and 97/100,000 in 1992 (18).

Temporal characteristics are important as potential confounders, since we found strong relations between a worker's age, calendar year of work, number of years worked, and cumulative exposure expressed in micro-Tesla-years. Younger workers predominantly populated lower exposure groups. Start year was also related to risk of disease, to age, and to exposure score. The combination of a strong relation between age and mortality risk and age and exposure scores sets the stage for confounding of exposure by other time-related factors. Thus, separately and jointly, these terms could strongly confound the associations of heart disease endpoints with exposure.

The craft of an electric utility lineman and an electrician, and to a lesser extent a power plant operator, involves substantial physical activity. The decreased risk estimates that we observed for AMI by duration of employment in specific occupations could be explained by the increased level of physical activity associated with those occupations. The reference group in our analysis included occupations that involve less physical activity.

There are several possible explanations for why our results were not consistent with those reported by Savitz et al. (1) for the five-utility cohort. Most notably, workers in the five-utility cohort resided in different geographic regions of the United States, and AMI and CCHD mortality rates vary substantially by region. For example, the 1980 AMI and CCHD mortality rates in the "east south central" United States were 153/100,000 and 81/100,000, respectively (18). By comparison, the 1980 AMI and CCHD mortality rates in the "Pacific" region of the United States were 92/100,000 and 104/100,000, respectively (18). The five-utility cohort also covered a different time period between the early 1950s and 1988 compared with the Edison cohort's follow-up between 1960 and 1992. The Edison cohort was also smaller; thus, our results may have been more likely to be affected by random variation. However, it is noteworthy that, in a comparative analysis of studies of magnetic fields and

cancer in electric utility workers, the Edison cohort contributed more information than would be suggested by its sample size because of its relatively larger number of cases in higher exposure categories (14). There were also differences in exposure assessment, including use of different magnetic field measurement devices and how the samples were selected.

To assess the potential impact of cigarette smoking as an uncontrolled confounder, we looked at the relation between magnetic field exposures and two diseases, lung cancer and COPD, known to be associated with smoking. Similarly to Savitz et al., we did not observe an association between magnetic field exposures and lung cancer mortality (19), but we did find an elevated risk of COPD death associated with increased exposures to magnetic fields. COPD was not analyzed in the five-utility cohort. Unpublished data show that electric utility craft workers smoke cigarettes more than do other electric utility personnel. However, lack of actual information on smoking, and given the inconsistency between COPD and lung cancer results in our study, the COPD results are difficult to interpret.

We observed an unexpected increase in the risk of dying from all four included diseases in association with exposure accumulated during the most recent 5 years. These associations—not specific to any of the outcomes examined—are likely to be the result of some form of residual healthy worker effect. Exposure accumulated during the most recent years is closely related to current occupation. Workers recently reaching higher-level or managerial occupations and therefore being less exposed in recent years (i.e., more likely to be in the reference category) may have substantially different personal characteristics (e.g., they may be more health conscious) than workers remaining in more exposed occupations. However, Savitz et al. (1) did not observe a similar trend.

There are weaknesses equally relevant to both our study and the Savitz et al. report (1). Included are the inability to control for potentially important factors that may influence mortality due to cardiovascular disease, the use of death certificates to identify the cause of death, and the reliability of the distinction between AMI and CCHD as recorded on the death certificate (20).

A previous study analyzing the same data on this cohort reported a standardized mortality ratio of 0.63 for cardiovascular mortality among males (16). This finding is consistent with the results of a standardized mortality ratio analysis of the University of North Carolina (Chapel Hill, North Carolina) data set (1). In an additional analysis, Kelsh and Sahl also looked at cardiovascular mortality (categorized by ICD-9 as codes 3900–4489) by using an internal reference group (16). The rate ratios were 1.42 (95 percent CI: 1.18, 1.71) for linemen and 1.56 (95 percent CI: 1.26, 1.94) for power plant operators (16). However, a number of differences in these analyses likely account for the differences reported here when compared with the previous report. In the analyses by Kelsh and Sahl, men older than age 80 years were excluded, a person's exposure was defined on the basis of the worker's usual occupation as opposed to a detailed occupational history, and different reference groups were used (16). In our analysis, meter readers were considered part of the reference

group (following the Savitz et al. (1) team definition and because these workers' levels of exposure to magnetic fields in their work environment are low). In the Kelsh and Sahl analysis, meter readers had a relative cardiovascular mortality risk of 1.71 (95 percent CI: 1.13, 2.58) (16). Since this risk is higher than the one for linemen or power plant equipment operators, moving them to the reference category would decrease the estimated relative risks reported previously (16).

In conclusion, unlike the previous analysis by Savitz et al. (1), our results provide no support for the hypothesis linking AMI mortality to occupational magnetic field exposure. Similarly, our results showed no evidence for an association between CCHD mortality and occupational magnetic field exposure, a finding consistent with the results of Savitz et al. (1) An ongoing study based on the Swedish twin registry may provide further information on a potential association between AMI mortality and occupational exposure to magnetic fields (21).

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