

Neurodegenerative Diseases in Welders and Other Workers Exposed to High Levels of Magnetic Fields

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Background: Previous work has suggested an increase in risk of amyotrophic lateral sclerosis (ALS) and Alzheimer's disease among workers exposed to extremely low-frequency magnetic fields (ELF-MF). We evaluated the relation between ELF-MF from occupational exposures and mortality from neurodegenerative diseases.

Methods: The study was based on a cohort of Swedish engineering industry workers, comprising 537,692 men and 180,529 women. The cohort was matched against the 3 most recent censuses and The Causes of Death Registry. Levels of ELF-MF exposure were obtained by linking occupation according to the censuses to a job exposure matrix. We used 4 levels of exposure and considered both the primary and contributing causes of death, 1985-96.

Results: The risk of Alzheimer's disease as primary or contributing cause of death increased with increasing exposure to ELF-MF among both men and women, with a relative risk (RR) of 4.0 and a 95% confidence interval (95% CI) of 1.4-11.7 in the highest exposure group for both sexes combined. There was a RR of 2.2 (95% CI: 1.0-4.7) for ALS in the highest exposure group with the suggestion of an exposure-response relationship. No evidence of increased risk was seen for Parkinson's disease or multiple sclerosis.

Conclusions: The findings support previous observations of an increased risk of Alzheimer's disease and ALS among employees occupationally exposed to ELF-MF. Further studies based on morbidity data are warranted.

Key Words: Alzheimer's disease, Amyotrophic Lateral Sclerosis, Electromagnetic Fields, Neurodegenerative Disease, Occupation

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In 1995, Sobel et al¹ reported a higher incidence of Alzheimer's disease among individuals with occupational exposure to extremely low frequency magnetic fields (ELF-MF). The study consisted of 3 independent case-control series (two from Finland and 1 from the U.S.), showing an overall OR of 3.0 (95% CI 1.6, 5.4) for occupations with medium to high ELF-MF exposure.¹ A subsequent study by the same research group showed a consistent result for Alzheimer's disease among both men and women.² Other studies have followed,³⁻⁵ and the National Radiologic Protection Board (NRPB) in the United Kingdom, summarizing these results, concluded that there is only very weak evidence to suggest that ELF-MF could cause Alzheimer's disease.⁶

Davanipour et al⁷ suggested an association between ELF-MF and risk of amyotrophic lateral sclerosis (ALS). Subsequently, a case-control study based on U.S. mortality data revealed a modest increase in risk for ALS among subjects in electrical occupations.⁴ Other studies of ALS and ELF-MF have also indicated an association.^{5,8,9} Electrical shocks have been offered as a potential explanation.^{8,10} Taken as a whole, the evidence is stronger for an effect of employment in electrical occupations on risk of ALS than on risk of Alzheimer's disease.^{6,11} Only a few studies have investigated ELF-MF in relation to Parkinson's disease^{4,5} and multiple sclerosis (MS).¹²

The aim of this nationwide study was to evaluate the relation between ELF-MF and mortality from diseases of the nervous system, specifically Alzheimer's disease, ALS, Parkinson's disease and multiple sclerosis (MS), with an emphasis on exposure-response relationships.

METHODS

The study is based on a cohort with a large proportion of resistance welders, who are exposed to high levels of ELF-MF. This type of welding includes spot, flash, butt,

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projection and seam welding and involves electrical currents as high as 1,000-100,000 Ampere, yielding peak ELF-MF exposures in the milliTesla range. This technique is used in various types of production, including the car industry, manufacturing of radio- and television transmitters, and manufacturing of metal products such as kitchen sinks, metal signs, thermos flasks.

The first step in the formation of the cohort was to identify industrial branches where resistance welding could take place. The list of standard codes of branches used in Sweden (SNI 92) was scrutinized and about 40 types of branches were selected. The second step was to identify all companies and work places within these branches during the study period, by searching the "BASUN" registry at Statistics Sweden, for the years 1985-94. Two different coding systems (SNI69, SNI92) had to be taken into account to find the work places. Thirdly, we searched income tax returns for each year, 1985 through 1994, to identify all subjects employed at any of the selected work places, no matter what their work tasks had been. The cohort comprised 537,692 men and 180,529 women. This cohort has been used previously in a study evaluating cancer in relation to ELF-MF.¹³

We obtained information on occupation from the censuses of 1980, 1985, and 1990. The censuses provide occupational codes corresponding to the Nordic version of the International Standard for Classification of Occupations (ISCO), as it was used in the census of 1980. We also used the work descriptions given in text by the subjects in the censuses, and this enabled us to identify additional resistance welders, ie, those who had specified resistance welding but who showed an occupational code other than "welder". These subjects (n = 1697) were allocated to the highest exposure group in the analyzes.

Occupation-specific levels of exposure were obtained from a previously developed job exposure matrix (JEM), comprising more than 1000 measurements among the 100 most common occupations (among men) in Sweden.¹⁴ The

levels of exposure according to the JEM were based on measurements in at least 4 employees within each occupation during a minimum of 6 hours of a normal work day. To increase the number of subjects and occupations in the analysis, we used additional exposure information for some rare occupations.¹⁵ The exposure metric used in the analysis was the geometric mean of average workday mean microTesla (μ T) values. We used the geometric mean because it decreases the influence of outliers. We determined cut points from the exposure distribution for men and women in 1985. Cut points at the 25th, 75th and 90th percentile gave 4 exposure groups: low (<0.1636 μ T), medium (0.1637-0.2500 μ T), high (0.2501-0.5300 μ T) and very high exposure (>0.5300 μ T). Seventy percent of the very high exposure group were welders.

We classified and added 3 other occupations to the analyzes that were not included in the JEM. These occupations comprise a large number of women, and they were included to increase the number of women in the analyzes. The occupations were "domestic service" (low exposure) and "computer operator, computress" and "other needlework" (both high exposure). The levels of exposure were based on comparisons with similar occupations in the JEM and were also supported by unpublished exposure measurements.

There were 53,049 (10%) men and 18,478 (10%) women for whom we lacked information on either occupation (ie, those entering working life after the 1990 census) or exposure. These subjects were excluded from the analysis. The number of subjects, person-years and deaths (after these exclusions) are shown in Table 1. This is a comparatively young cohort; the median age at inclusion was 35 years (quartile 1 = 24, quartile 3 = 45).

The cohort was matched against the Causes of Death Registry for the years 1985-96. The causes of death were classified according to the International Classification of Diseases (ICD), using the eighth revision (ICD-8) for the years 1985-86 and the ninth revision (ICD-9) for 1987-96,

TABLE 1. Number of Subjects, Person Years and Deaths, by Exposure Category

		Exposure				
	Sex	All	Low <0.164 μ T	Medium 0.164–0.250 μ T	High 0.250–0.530 μ T	Very High >0.530 μ T
No. of subjects*	Men	484,643	94,706	257,171	72,437	60,329
	Women	162,051	56,801	71,765	28,184	5,301
Person years	Men	4,848,046	965,747	2,619,805	671,922	590,572
	Women	1,599,477	575,736	711,472	261,324	50,945
No. of deaths	Men	16,661	3,819	8,443	2,354	2,045
	Women	2,948	944	1,322	568	114

*The exposure classification may change during the study period; the numbers given refer to the highest exposure values.

TABLE 2. Relative Risk (RR) of Death From Neurological Diseases in Relation to Extremely Low-Frequency Magnetic Field Exposure, Adjusted for Age and Socioeconomic Status: A Cohort of Workers With an Increased Prevalence of ELF-MF Exposure, Sweden 1985–1996

Diagnosis (ICD9)	Sex	Cause of Death*	All Cases			Low Exposure [†] <0.164 μ T			Medium Exposure 0.164–0.250 μ T			High Exposure 0.250–0.530 μ T			Very High Exposure >0.530 μ T		
			n	RR	95%CI	n	RR	95%CI	n	RR	95%CI	n	RR	95%CI	n	RR	95%CI
All deaths (140–209)	All†		19610	1.00		4764	1.00		9765	0.91	0.87–0.94	2922	0.96	0.91–1.00	2159	0.98	0.93–1.03
	Men		16661	1.00		3819	1.00		8443	0.89	0.85–0.92	2354	0.94	0.90–0.99	2045	0.96	0.91–1.01
	Women		2948	1.00		944	1.00		1322	1.02	0.94–1.12	568	1.03	0.93–1.15	114	1.16	0.95–1.41
Hereditary and degenerative diseases of the NS (330–337)	All†	P + C	276	1.00		54	1.00		150	1.33	0.97–1.83	33	1.29	0.85–1.96	33	1.67	1.07–2.62
		P	154	1.00		29	1.00		85	1.34	0.87–2.04	22	1.31	0.75–2.29	18	1.58	0.86–2.90
	Men	P + C	229	1.00		42	1.00		127	1.29	0.91–1.83	28	1.17	0.72–1.89	32	1.64	1.02–2.62
		P	133	1.00		25	1.00		72	1.17	0.74–1.85	18	1.22	0.66–2.25	18	1.54	0.83–2.86
	Women	P + C	47	1.00		12	1.00		23	1.66	0.81–3.40	11	1.94	0.83–4.56	1	1.12	0.14–8.80
		P	21	1.00		4	1.00		13	2.41	0.76–7.64	4	1.65	0.39–6.93	0		
Alzheimer's disease (331.0)	All†	P + C	40	1.00		7	1.00		17	1.34	0.55–3.25	8	2.25	0.80–6.30	8	4.04	1.40–11.66
		P	16	1.00		4	1.00		7	0.89	0.26–3.09	4	1.95	0.47–7.99	1	0.90	0.10–8.57
	Men	P + C	30	1.00		6	1.00		12	0.96	0.36–2.56	5	1.59	0.48–5.26	7	2.70	0.88–8.25
		P	12	1.00		4	1.00		4	0.43	0.11–1.73	3	1.51	0.33–6.86	1	0.74	0.08–6.95
	Women	P + C	10	1.00		1	1.00		5	5.44	0.62–47.38	3	9.04	0.90–91.30	1	22.70	1.32–390.82
		P	4	1.00		0			3			1			0		
Parkinson's disease (332.0)	All†	P + C	45	1.00		9	1.00		32	1.89	0.90–4.00	1	0.26	0.03–2.08	3	1.11	0.29–4.18
		P	15	1.00		3	1.00		11	1.84	0.50–6.74	0			1	1.33	0.13–13.61
	Men	P + C	41	1.00		8	1.00		29	1.80	0.82–3.95	1	0.29	0.04–2.30	3	1.06	0.28–4.07
		P	13	1.00		2	1.00		10	2.27	0.49–10.50	0			1	1.55	0.14–17.69
	Women	P + C	4	1.00		1	1.00		3	4.03	0.42–38.78	0			0		
		P	2	1.00		1	1.00		1	1.35	0.09–21.61	0			0		
Amyotrophic lateral sclerosis (ALS) (335.2)	All†	P + C	97	1.00		15	1.00		52	1.58	0.88–2.81	17	1.95	0.97–3.92	13	2.16	1.01–4.66
		P	91	1.00		14	1.00		49	1.61	0.89–2.93	16	1.98	0.96–4.09	12	2.19	0.99–4.87
	Men	P + C	86	1.00		14	1.00		45	1.32	0.72–2.41	14	1.69	0.80–3.57	13	2.04	0.94–4.42
		P	80	1.00		13	1.00		42	1.34	0.72–2.49	13	1.71	0.79–3.70	12	2.06	0.92–4.61
	Women	P + C	11	1.00		1	1.00		7	4.49	0.54–37.72	3	4.03	0.40–40.78	0		
		P	11	1.00		1	1.00		7	4.49	0.54–37.72	3	4.03	0.40–40.78	0		
Multiple sclerosis (MS) (340)	All†	P + C	30	1.00		9	1.00		13	0.63	0.27–1.50	5	0.87	0.29–2.63	3	0.80	0.20–3.14
		P	15	1.00		6	1.00		5	0.43	0.13–1.47	2	0.59	0.12–3.03	2	1.21	0.21–6.97
	Men	P + C	22	1.00		4	1.00		12	1.03	0.33–3.22	4	1.42	0.35–5.76	2	0.84	0.15–4.76
		P	8	1.00		2	1.00		4	0.63	0.12–3.46	1	0.71	0.06–7.91	1	0.97	0.08–11.49
	Women	P + C	8	1.00		5	1.00		1	0.13	0.01–1.12	1	0.28	0.03–2.60	1	1.50	0.16–14.35
		P	7	1.00		4	1.00		1	0.17	0.02–1.59	1	0.40	0.04–3.90	1	2.13	0.20–22.40
Epilepsy (345)	All†	P + C	156	1.00		40	1.00		86	0.87	0.60–1.27	19	0.64	0.37–1.11	11	0.45	0.23–0.88
		P	79	1.00		23	1.00		43	0.75	0.45–1.25	7	0.40	0.17–0.93	6	0.40	0.16–1.00
	Men	P + C	130	1.00		34	1.00		72	0.77	0.51–1.16	15	0.57	0.31–1.05	9	0.35	0.17–0.73
		P	65	1.00		21	1.00		34	0.58	0.34–1.00	6	0.36	0.14–0.89	4	0.24	0.08–0.70
	Women	P + C	26	1.00		6	1.00		14	1.58	0.59–4.21	4	1.14	0.31–4.17	2	2.79	0.54–14.43
		P	14	1.00		2	1.00		9	2.47	0.53–11.62	1	0.70	0.06–7.78	2	5.97	0.82–43.52

*P + C, primary or contributing cause of death; P, primary cause of death; NS, nervous system.

†Adjusted for sex.

‡Reference category.

with the ICD-8 codes transformed into ICD-9 codes for the diagnoses of interest (Table 2). We considered primary cause of death, as well as primary and contributing causes of death combined.

We estimated relative risks (RRs) by Cox-regression.^{16,17} If a subject, according to the 3 censuses, moved from a higher to a lower exposure level during the study period, the higher level was retained for the subject. This was done to allow for a certain (unknown) latency period after disease onset and to account for the subsequent survival time. If information was lacking for a certain census year, the information from a previous census was used (ie, if there was no useful information from either 1985 or 1990, we used data from 1980, if available). Of 646,694 subjects in the analyzes, 2.3% had information on occupation from 1980 only. In the regression the basic time dimension was calendar years, and the subjects were considered to be at risk from 1985 (or if later than 1985, the first year of entry into the cohort), up to year of death or end of follow-up in 1996, whichever came first. RRs were calculated using the lowest exposure group as the reference. Age was entered into the regression by ten-year groups based on age at year of entry. We also used a socio-economic variable in the analyzes, roughly divided in 2 categories - blue-collar workers and others. A test for trend across the 4 exposure groups was performed with the mean μ T value of each group taken as the level of exposure, using Cox-regression.

RESULTS

The association between ELF-MF exposure and overall mortality was close to unity for all exposure groups (Table 2). In analyzing primary and contributing causes of death combined, we found an increased relative risk among exposed subjects for both Alzheimer's disease and ALS. The association was attributable to both men and women and the risk for Alzheimer's disease seemed to increase with increasing exposure level (Fig. 1). The exposure-response analysis yielded an RR of 3.2 for an increase of 1 μ T (95% confidence interval (CI): 1.4- 7.3). The outcome for ALS also suggested an exposure-response relationship (Fig. 1), with an RR of 1.5 for an increase of 1 μ T (95% CI: 0.80-2.7).

For all hereditary and degenerative diseases of the central nervous system we observed an increased relative risk among subjects in the very high exposure group. This effect was exclusively attributable to Alzheimer's disease and ALS. We found no increased relative risk for Parkinson's disease or for MS, but the number of cases of MS was small ($n = 30$). For epilepsy we found a decreased relative risk among men. The analyzes restricted to primary causes of death were based on small numbers. For ALS, however, coherent risk estimates were observed.

DISCUSSION

An increased risk of Alzheimer's disease and ALS was observed among workers exposed to ELF-MF. An exposure-

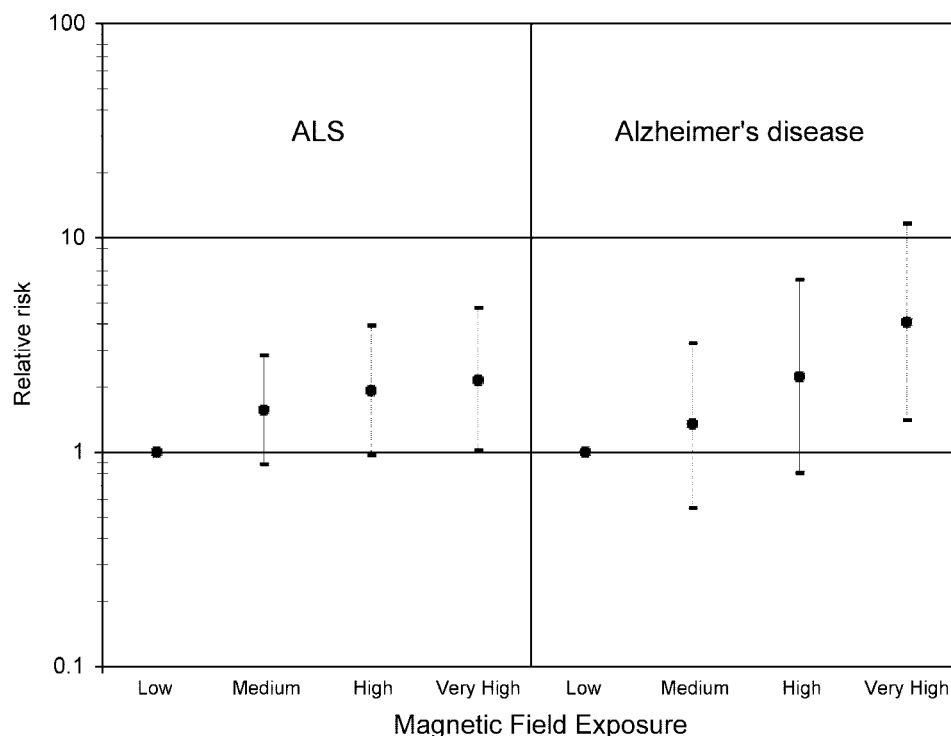


FIGURE 1. Relative risks (with 95% confidence limits) for ALS and Alzheimer's disease in relation to magnetic field exposure level.

response relation was indicated, and a similar relationship was seen among both men and women. The results are probably not due to chance, and are in line with other studies. The risk estimates of this study were comparable to those of previous studies, and occasionally higher.

Nevertheless, it could be questioned whether the increased risk of ALS among the high exposed subjects could be due to electric shocks rather than exposure to ELF-MF. Patients with ALS have been shown to have had more episodes of electric shocks prior to disease onset than control subjects,⁸ and persons experiencing electric shocks resulting in unconsciousness were shown to be at higher risk of developing ALS.¹⁰ On the other hand, the links to electric shocks could be confounded by long term exposure to ELF-MF. The results could also be confounded by electrical fields or a simultaneous occurrence of electromagnetic fields of higher frequency bands.

There are no well-established occupational risk factors for Alzheimer's disease and ALS. The risk of Alzheimer's disease and solvent exposure has been discussed and some^{18,19} but not all studies²⁰⁻²² have shown an association. The employees of industries included in the cohort were not exposed to solvents to any large extent, and it seems unlikely that solvent exposure should follow ELF-MF exposure well enough to explain the observed exposure-response relationship. A potential role of metals and free radicals in neurodegeneration has been pointed out,²³⁻²⁶ but the extent to which this could be linked to occupational or nonoccupational metal exposure is unknown. It could be that exposure to metals may affect the study results by confounding, a question that should be further explored in future studies as well as the possibility of interaction between metal exposure and ELF-MF.

There are no established nonoccupational risk factors for neurodegenerative diseases, and other than the importance of hereditary factors for Alzheimer's disease, the etiology is mostly unknown. Biologic mechanisms that could explain the relation between exposure to ELF-MF and chronic diseases have not been identified. It has been suggested that ELF-MF exposure may contribute to an increased production of amyloid beta in the brain and that this production eventually may lead to Alzheimer's disease.²⁷ Fragmentary data suggest an interaction between ELF-MF and the central nervous system. For example, some experimental studies on rats and mice have shown that exposure to ELF-MF may affect spatial learning and cause a deficit in spatial reference memory.^{28,29}

We have no definite explanation for the decreased risk of epilepsy among highly exposed men. However, people with epilepsy probably do not work with equipment run by high electrical currents. We found that the cases with a diagnosis of epilepsy on the death certificate often had a diagnosis of alcohol abuse as well. In an additional analysis we excluded epilepsy cases that also had a diagnosis of alcoholism, brain tumor or chronic liver disease & cirrhosis.

This analysis yielded even lower RRs for the medium (0.7) and high (0.4) exposure group, while the RR for the very high exposure group was unchanged (0.3). This indicates that the negative association between ELF-MF and epilepsy was not solely produced by a selection of individuals without alcohol problems into high exposed occupations.

The lack of precision in the analyzes of MS makes the results inconclusive. A previous study on ELF-MF and MS did not find an association but that study, too, was based on small numbers ($n = 32$).¹² In accordance with previous studies, the outcome for Parkinson's disease did not support the hypothesis of an association.

An advantage of this study is the large size of the cohort, which also contains a comparatively large fraction (10%) of highly exposed subjects ($> 0.5 \mu\text{T}$) compared with 3.5% in the general workforce based on data from the census of 1985. Even though the study is large, the number of cases for some diagnoses was limited (eg, MS), especially among women and among analyzes based on primary cause of death only. Compared with the total population, the cohort had lower mortality. The standardized mortality rate ratio (SMR) of the cohort was 0.75 and 0.77 for men and women respectively, which indicates an overall healthy worker effect. This selection bias was similar for men with low and high exposure. Among women a slightly increased mortality was seen among the very high exposed women, but presumably this bias was not large enough to produce false positive results.

A limitation is that the study was based on mortality rather than morbidity data. This means that we could not take disease onset or age at diagnosis into account. On the other hand, disease onset would be difficult to determine from incidence data especially for Alzheimer's disease. A long latency and survival might bias results based on mortality data, particularly if a diagnosis or a long premorbid phase has an effect on the exposure (eg, leads to a change from high to low exposed occupations). We anticipate that a person who gets a neurodegenerative disease changes to a less exposed occupation more often than the opposite, which is why we decided to retain a higher exposure level prospectively throughout the maximum follow-up of 12 years.

The question of exposure misclassification should be considered. The exposure assessment was based on a JEM. Individual exposures are ideal but unrealistic. The method we have used should mainly lead to nondifferential misclassification and to risk estimates closer to unity, particularly for the very high exposure group.³⁰

The outcome measure used in this study is in some sense the prevalence of the disease at death. Since there was no clear association between exposure to ELF-MF and overall mortality in the cohort, there was a comparable probability of observing the diseases studied, which otherwise would have invalidated the inclusion of contributing causes of death in the analyzes. Death certificates may be written differently

depending on occupation or socio-economic class of the patient. For example, the completeness of contributing causes may vary, which then could be a source of bias when including contributing causes of death in the outcome measure. We evaluated the possibility of such an effect on the present results by an analysis of Alzheimer's disease among manual workers only. The results were: 1.7 (0.49-6.3), 2.3 (0.55-9.7) and 4.5 (1.2-17.0) for the medium, high and very high exposure group respectively. These risk estimates are similar to those of the entire cohort.

The study is dependent on the quality of the death certificate diagnoses. The validity of the primary cause of death for the diseases studied is probably high, but for contributing causes of death there are limitations, especially if no autopsy was performed. Our main findings rely on the analyzes of both primary and contributing causes of death. The results based on primary cause only yielded fewer cases and a lower precision, but the point estimates were partly coherent. For ALS there is a high concordance between the 2 analyzes because of the high lethality of the disease; the life expectancy of ALS patients is about 3 to 5 years from the time of diagnosis.³¹ A person with Alzheimer's disease lives for about 7-15 years after diagnosis, usually dying from a complication of the main disease (often pneumonia).³² Of the 24 cases of Alzheimer's disease recorded as contributing causes, the primary cause of death was "presenile dementia (onset <65 years of age)" (ICD = 290.1) in eleven cases, 9 were "cardiovascular and other circulatory deaths", 2 were cancer, and the remaining 2 were other causes.

The diagnostic criteria for Alzheimer's disease were not well developed at the middle of the 20th century. However, the diagnostic procedures and awareness of the disease have improved during the last 2 decades. The follow-up of this study starts in 1985, and very few subjects were older than 76 years at the end of follow-up. These circumstances should strengthen the validity of the disease classification. If these comparatively young subjects had a clinical diagnosis of Alzheimer's disease, it seems likely that this was recognized on the death certificate, while the premorbid cases or those without a clinical diagnosis were lost. Men tended to have a slightly higher overall percentage of autopsies in the very high exposure group compared with the reference group.

Our results give further support for an association of ELF-MF with Alzheimer's disease and ALS, but not with Parkinson's disease. For MS there were too few cases for a firm conclusion. Further research on neurodegenerative diseases, in particular on ALS and morbidity from Alzheimer's disease, is warranted.

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