Mortality from Alzheimer's, motor neuron and Parkinson's disease in relation to magnetic field exposure: findings from the study of UK electricity generation and transmission workers, 1973–2004

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Background: There are a number of reports linking magnetic field exposure to increased risks of Alzheimer's disease and motor neuron disease.

Methods: The mortality experienced by a cohort of 83 997 employees of the former Central Electricity Generating Board of England and Wales was investigated for the period 1973–2004. All employees were employed for at least six months with some employment in the period 1973–82. Computerised work histories were available for 79 972 study subjects for the period 1971–93. Information on job and facility (location) were used to estimate exposures to magnetic fields. Two analytical approaches were used to evaluate risks, indirect standardisation ($n=83\ 997$) and Poisson regression ($n=79\ 972$).

Results: Based on serial mortality rates for England and Wales, deaths from Alzheimer's disease and motor neuron disease were unexceptional. There was an excess of deaths from Parkinson's disease of borderline significance. No statistically significant trends were shown for risks of any of these diseases to increase with lifetime cumulative exposure to magnetic fields (RR per 10 μ T-y: Alzheimer's disease 1.10 (95% CI 0.90 to 1.33); motor neuron disease 1.06 (95% CI 0.86 to 1.32); Parkinson's disease 0.88 (95% CI 0.74 to 1.05)).

Conclusions: There is no convincing evidence that UK electricity generation and transmission workers have suffered increased risks from neurodegenerative diseases as a consequence of exposure to magnetic fields.

A large number of studies have investigated risks of cancer and other diseases in "electrical and electronic" workers. In addition, large-scale cohort mortality studies of electric utility workers that incorporate magnetic field exposure assessments are also available.^{1–5} The question has also been raised as to whether employment in "electrical" occupations or exposure to magnetic fields might have an effect on risks of neurodegenerative disease.

The literature relating to Alzheimer's disease and magnetic fields is difficult to assess. It was suggested that increased risks could be substantial.⁶ Although this initial report was based on the combined results of three sub-studies, it should be regarded only as hypothesis forming, as the findings were much influenced by the reclassification of exposure groups. The Alzheimer's/magnetic fields hypothesis was supported by the findings of another case-control study⁷ and was weakly supported by a proportional mortality ratio analysis of causes of death as recorded on US death certificates.⁸ The hypothesis was not supported, however, by the three studies that were able to provide quantified estimates of individual exposures.^{9–11} One case-control study⁹ did not show risk to be associated with the individual's primary occupation, but did show a substantial and statistically significant risk with the last recorded occupation, which would have been the association recorded in the death certificate study.⁸ Neither of the cohort studies,^{10–11} however, provided evidence of a risk with increasing exposure, nor, in the one study that provided such information, was there any excess mortality in power plant workers. However, these studies relied on mortality records that are known to under-report Alzheimer's disease and the distinction between Alzheimer's disease and dementia is not always clearly made on death certificates. Three more recent studies also provided mixed findings: one providing weak evidence of a risk for males in the

highest exposure group,¹² another (overlapping) study focusing on resistance welders showed a positive effect,¹³ and a third study showed an effect in males, but not in females.¹⁴ While initial, hypothesis-generating studies indicated a potential threefold risk, most of the subsequent research has found risks at or below unity, with only a few elevated risks of around 2.0 in selected subgroups. Thus the hypothesis that 50–60 Hz electromagnetic fields (EMFs) increase the risk of Alzheimer's disease is neither proven nor excluded.

More consistent evidence is available for motor neuron disease (some studies are concerned with its principal subtype amyotrophic lateral sclerosis (ALS)).^{8–10–13–15–22} A number of reports investigating the relation between electrical work or the experience of electrical shocks have been published since the original suggestion was made that electric shocks might increase the risk of the disease.²⁰ Two early studies from Japan (reported in a single paper), where the prevalence both of electrical work (as recorded in medical histories) and electrical shock was low, failed to provide any support for the hypothesis.²¹ However, an increased risk of ALS from electric shocks has been reported in several later studies.^{16–22} The US study also found an increased risk associated with the employment in electrical occupations¹⁶ and this was supported by other studies from Sweden¹⁸ and the USA.⁸ Later studies focused on magnetic field exposure^{10–11–15} and found twofold risks to be associated with exposure, albeit these excess risks were not always statistically significant. Recent and overlapping studies from Sweden focusing on magnetic field exposure and electric shock are inconsistent, with one showing

Abbreviations: ALS, amyotrophic lateral sclerosis; CEGB, Central Electricity Generating Board; EMF, electromagnetic field; SMR, standardised mortality ratio

no effect and the other indicting a twofold risk in the two highest exposure categories.^{12–13} The epidemiological evidence suggests that employment in electrical occupations may increase the risk of ALS. However, separating any increased risk as a result of receiving an electric shock from any increased exposure to magnetic fields is important, albeit difficult.

A number of epidemiological studies have been carried out on environmental associations with Parkinson's disease.^{8–10–13–19–23} No study has provided clear evidence of an association with above average exposures to extremely low frequency EMFs (most risks close to unity) and, in the absence of laboratory evidence to the contrary, it seems unlikely that such exposures are involved in the disease process. Nevertheless, Parkinson's disease was included as a health outcome of interest in this study for the sake of completeness.

This paper seeks to obtain important new information on the topic of occupational magnetic field exposure and risks of mortality from neurodegenerative diseases by examining data from the ongoing epidemiological study of UK electric utility workers; this topic has been identified as a priority in recent reviews.^{23–25}

MATERIALS AND METHODS

Study population

Analyses were based on the ongoing epidemiological study of electricity generation and transmission workers from the former Central Electricity Generating Board (CEGB) of England and Wales. The mortality study (based on the National Epidemiology File) was initiated by the CEGB in 1975; responsibility for maintaining and analysing the study passed to the successor companies of the CEGB, which came into being following the privatisation of the industry in 1990. The cohort available for analysis comprised 83 997 employees (72 954 men and 11 043 women) of the former CEGB for whom computerised information was available. All employees were known to have been employed for at least six months with some period of employment in the period 1973–82. Work history records were available for 79 972 study subjects. Study variables and the treatment of missing data items have been described previously.²⁶

The study received follow-up particulars from the National Health Service Central Register of the Office for National Statistics. Underlying cause and multiple-cause coding were supplied by the Office for National Statistics for all deaths (ICD-8, 1973–8; ICD-9, 1979–2000; ICD-10, 2001–4). A total of 834 (1.0%) subjects had emigrated and 1720 (2.1%) were untraced. Alzheimer's disease was taken to refer to ICD-9 331.0 and ICD-10 G30, motor neuron disease to ICD-8 348, ICD-9 335.2 and ICD-10 G12.2, and Parkinson's disease to ICD-8 342, ICD-9 332 and ICD-10 G20.

Estimation of magnetic field exposures

Occupational exposures to the elevated magnetic fields encountered in parts of the UK electricity generation and transmission industry were assessed by the EMF Research Section of the National Grid Company. Full details are available elsewhere.²⁷ In summary we used a detailed exposure assessment which incorporates both job title and facility.

A list has been developed showing all power stations, transmission districts, substations and non-operational sites open sometime between 1972 and 1993. For subjects with pre-1971 employment, the first known employment details were assumed to apply to the earlier employment. Workers at non-operational sites (central and regional headquarters, design and research centres, control centres) were considered to be unexposed to elevated levels of occupational magnetic fields. The most extensive exposure assessment was possible for power

stations considered to be the work locations of highest exposure. Busbars close to generators in power stations can carry currents up to 20 times higher than those typically carried by the 400 kV transmission system.²⁸ For power station workers, 11 work categories have been identified based on different patterns of working in the various areas of conventional, nuclear and pumped storage power stations. This combination of job and location was used to calculate fields adjusted for historical loads. For transmission workers recent survey measurements and estimates of the time spent in different working locations were used to estimate exposures.

Cumulative occupational lifetime exposures for the period April 1952 to March 1994 were developed for each worker based on coded job histories linked to the exposure assessment.

External standard: standardised mortality ratio

The mortality experience of the cohort was compared with that which might have been expected to occur if rates of mortality for the general population of England and Wales had been operating on the study cohort, having due regard to the composition of the study cohort by sex, age (five-year age groups), and calendar year (five-year calendar periods). Expectations based on person-years-at-risk were calculated using the PERSONYEARS computer program.²⁹ Individuals entered the person-years-at-risk at the end of the first six months of employment or the date of computerisation for the relevant region, whichever was the later. The computerisation date has been selected to be 1 January 1977 for all regions (and functions) except Midlands (1/1/1973), Generation Design and Construction (1/1/1975), North West (1/1/1975) and Transmission and Technical Services (1/1/1979). Individuals left the person-years-at-risk on the date of death, date of emigration, date last known alive or the closing date of the study (31 December 2004), whichever was the earlier. Individuals were "censored" on reaching their 85th birthday—that is, they make no further contributions to expected or observed numbers past this age. This censoring was applied for three reasons. First, published mortality rates are only available for the "open-ended" age group ≥ 85 years and the distribution of the cohort person-years-at-risk by single years of age might be very different from that of the general population; secondly, the reliability of cause of death particulars is probably poorer at later ages; thirdly, any study subjects incorrectly classified as traced alive at the end of the study would have a disproportionate effect on the expected numbers for the open-ended age-group. (All tabulated results in this paper incorporate the above age-censoring.)

Standardised mortality ratios (SMRs) for the three diseases under investigation were calculated as the ratio of observed to expected numbers of deaths expressed as a percentage. In calculating *p* values and confidence intervals, it was assumed that deaths occur as a Poisson process. Any significance tests were two-tailed. National rates are only available for underlying causes and the external analyses were consequently limited to these causes. Analyses involving internal standards are not limited in this way allowing for larger numbers of cases to be considered.

Internal standard: Poisson regression

Five variables were considered to have the potential for influencing mortality (any mention of disease on death certificate) within the subcohort for which work history data were available (*n* = 79 972): attained age, sex, calendar year, estimated magnetic field exposure (either lifetime occupational cumulative exposure or exposure received in most recent five years), and negotiating body (surrogate for socioeconomic status). These variables were not treated as continuous

Table 1 Mortality from neurodegenerative diseases in UK electricity generation and transmission workers (n = 83 923), 1973–2004

	Observed	Expected	SMR (95% CI)
Alzheimer disease†‡			
Males	47	46.4	101 (74 to 135)
Females	4	6.4	62 (17 to 160)
Total	51	52.8	97 (72 to 127)
Motor neuron disease§			
Males	63	72.6	87 (67 to 111)
Females	5	5.8	87 (28 to 203)
Total	68	78.3	87 (67 to 110)
Parkinson disease¶			
Males	96	77.4	124* (101 to 152)
Females	3	3.2	95 (20 to 278)
Total	99	80.5	123 (100 to 150)
All causes			
Males	20580	23746.4	87(*** (85 to 88)
Females	1308	1548.1	84(*** (80 to 89)
Total	21888	25294.5	87(*** (85 to 88)

*p<0.05, ***p<0.001, () indicates deficit.

†Observed and expected numbers limited to the period 1979–2004 (that is, time periods covered by the 9th and 10th revisions of the ICD).

‡ICD-9 331.0, ICD-10 G30.

§ICD-8 348, ICD-9 335.2, ICD-10 G12.2.

¶ICD-8 342, ICD-9 332, ICD-10 G20.

variables, but rather each variable was categorised into a number of levels. In constructing the models, it was necessary to ensure that there was at least one death observed at each level of each variable. The cut points for the exposure categories are those used in previous analyses^{3–26} and are based on the cumulative exposure distributions for deaths from all causes.

Table 2 Mortality from neurodegenerative diseases by type of work,†‡ UK electricity generation and transmission workers, 1973–2004

	Observed	Expected	SMR (95% CI)
Alzheimer's disease§			
Managers	0	1.0	0
Engineers and scientists	12	9.7	124 (64 to 216)
Admin and clerical	7	7.0	100 (40 to 206)
Industrial workers	29	31.1	93 (62 to 134)
Building and construction	0	0.6	0
Total	48	49.3	97 (72 to 129)
Motor neuron disease			
Managers	0	1.1	0
Engineers and scientists	17	16.9	101 (59 to 161)
Admin and clerical	5	8.1	62 (20 to 144)
Industrial workers	40	47.3	85 (60 to 115)
Building and construction	0	0.9	0
Total	62	74.3	83 (64 to 107)
Parkinson's disease			
Managers	1	1.5	67 (2 to 371)
Engineers and scientists	14	12.1	116 (63 to 194)
Admin and clerical	14	7.5	187* (102 to 313)
Industrial workers	61	49.6	123 (94 to 158)
Building and construction	2	1.1	182 (22 to 657)
Total	92	71.8	128* (103 to 157)

*p<0.05.

†Based on "negotiating body" for first computerised period of work history: National Joint Managerial (NJM) representing managers, National Joint Board (NJB) representing engineers and scientists, National Joint Council (NJC) representing administrative and clerical workers, National Joint Industrial Council (NJIC) representing industrial workers, and the National Joint Building and Civil Engineering Committee (NJ(B&C)E) representing construction and building workers.

‡Information on type of work available for 79 820 employees.

§Observed and expected numbers limited to the period 1979–2004 (that is, time periods covered by the 9th and 10th revisions of the ICD).

The analyses allowed subjects to contribute person-years-at-risk to contemporaneous categories.

The EPICURE computer program was used to provide both person-years-at-risk (as defined previously) and numbers of deaths for each of the three selected diseases for all combinations of all levels of the variables mentioned above.³⁰ The EPICURE program was also used to carry out statistical modelling by means of Poisson regression.³¹ The purpose of the modelling was to provide point estimates of rate ratios (relative risks) for each category of magnetic field exposure compared with the baseline (lowest) category, with and without adjustment for other variables. The statistical significance of any trend in risk across the exposure categories was assessed by repeating the analysis while treating exposure as a single variable (scored by the person-year weighted mean dose for each of the five exposure categories), and examining the p value associated with the resulting regression coefficient.

RESULTS

Overall observed and expected numbers of deaths for three categories of neurodegenerative disease and for all causes are shown for males, females and the total study cohort in table 1. Given the size of the study cohort the shortfall of deaths for all causes was highly statistically significant. A similar non-significant deficit is shown for motor neuron disease, and mortality from Alzheimer's disease was close to expectation. A significant excess mortality is shown for Parkinson's disease in male workers. Median values for year of hire and duration of employment were 1969 and 16 years respectively. (SMRs were also calculated without age censoring (not shown in table 1). SMRs for Alzheimer's disease, motor neuron disease and Parkinson's disease were 92, 85 and 129 in males, and 65, 86 and 126 in females, respectively.)

Overall observed and expected numbers of deaths in the total study cohort for three categories of neurodegenerative disease are shown by type of work in table 2 and by industry sector in table 3. Information on type of work was available for 95.1% of the cohort and on industry sector for 93.9% of the cohort. Consequently, numbers of events will not tally with those shown in table 1. There is no significant heterogeneity in any of the sets of SMRs, although a significant excess is shown for Parkinson's disease in administrative and clerical workers (observed, 14; expected, 7.5; SMR, 187).

Table 3 Mortality from neurodegenerative diseases by industry sector,† UK electricity generation and transmission workers, 1973–2004

	Observed	Expected	SMR (95% CI)
Alzheimer's disease‡			
Power stations	34	34.1	100 (69 to 139)
Substations and transmission	4	2.3	174 (47 to 445)
Non-operational sites	9	12.4	73 (33 to 138)
Total	47	48.8	96 (71 to 128)
Motor neuron disease			
Power stations	49	52.7	93 (69 to 123)
Substations and transmission	2	3.5	57 (7 to 206)
Non-operational sites	11	17.5	63 (31 to 112)
Total	62	73.7	84 (65 to 108)
Parkinson's disease			
Power stations	67	52.7	127 (99 to 161)
Substations and transmission	2	3.3	61 (7 to 219)
Non-operational sites	21	15.1	139 (86 to 213)
Total	90	71.1	127* (102 to 156)

*p<0.05.

†Information on industry sector available for 78 815 employees.

‡Observed and expected numbers limited to the period 1979–2004 (that is, time periods covered by the 9th and 10th revisions of the ICD).

Table 4 Relative risks of mortality from neurodegenerative diseases by levels of estimated cumulative exposure to magnetic fields, UK electricity generation and transmission workers, 1973–2004

Cumulative exposure to magnetic fields ($\mu\text{T-y}$)*	n	RR† (95% CI)	RR‡ (95% CI)
Alzheimer's disease§			
0–2.4	42	1.0	1.0
2.5–4.9	12	1.53 (0.80 to 2.92)	1.55 (0.80 to 3.00)
5.0–9.9	16	1.14 (0.63 to 2.07)	1.15 (0.63 to 2.13)
10.0–19.9	24	1.93* (1.14 to 3.26)	1.91* (1.11 to 3.30)
≥20.0	5	1.10 (0.43 to 2.81)	1.02 (0.40 to 2.64)
Total	99		
RR per 10 $\mu\text{T-y}$ ¶		1.10 (0.90 to 1.33)	1.07 (0.88 to 1.31)
Motor neuron disease††			
0–2.4	31	1.0	1.0
2.5–4.9	15	2.47** (1.32 to 4.60)	2.43** (1.29 to 4.58)
5.0–9.9	16	1.55 (0.84 to 2.87)	1.51 (0.80 to 2.85)
10.0–19.9	10	1.08 (0.52 to 2.23)	1.05 (0.50 to 2.19)
≥20.0	6	1.53 (0.63 to 3.70)	1.45 (0.60 to 3.55)
Total	78		
RR per 10 $\mu\text{T-y}$ ¶		1.06 (0.86 to 1.32)	1.04 (0.84 to 1.30)
Parkinson's disease‡‡			
0–2.4	97	1.0	1.0
2.5–4.9	10	0.49 (0.25 to 0.93)	0.47 (0.24 to 0.91)
5.0–9.9	45	1.16 (0.81 to 1.66)	1.14 (0.78 to 1.68)
10.0–19.9	29	0.83 (0.55 to 1.27)	0.83 (0.54 to 1.28)
≥20.0	7	0.54 (0.25 to 1.17)	0.57 (0.26 to 1.23)
Total	188		
RR per 10 $\mu\text{T-y}$ ¶		0.88 (0.74 to 1.05)	0.88 (0.74 to 1.06)
All causes			
0–2.4	9404	1.0	1.0
2.5–4.9	2282	1.19*** (1.14 to 1.25)	1.07** (1.02 to 1.12)
5.0–9.9	3762	1.12*** (1.08 to 1.16)	0.99 (0.95 to 1.03)
10.0–19.9	3422	1.13*** (1.09 to 1.18)	1.01 (0.97 to 1.05)
≥20.0	1161	0.94* (0.88 to 1.00)	0.91* (0.85 to 0.97)
Total	20031		
RR per 10 $\mu\text{T-y}$ ¶		1.0 (0.98 to 1.01)	0.98** (0.96 to 0.99)

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

†One year refers to a working year, approximately 250 eight-hour shifts.

‡Analysed simultaneously with sex and attained age.

§Analysed simultaneously with sex, attained age, calendar period, and negotiating body (socioeconomic status).

¶Any part of death certificate coded to ICD-9 331.0 or ICD-10 G30.

**Five exposure categories scored by the mean value in each category, namely 0.36, 3.67, 7.24, 13.93, 38.53 $\mu\text{T-y}$. See text for details.

††Any part of death certificate coded to ICD-8 348, ICD-9 335.2 or ICD-10 G12.2.

‡‡Any part of death certificate coded to ICD-8 342, ICD-9 332 or ICD-10 G20.

Mortality rates for three categories of neurodegenerative disease (any mention of disease on death certificate) and for all causes are shown in table 4 for four levels of estimated cumulative occupational exposure to magnetic fields relative to the corresponding rates in the lowest (baseline) category of exposure ($<2.5 \mu\text{T-y}$). Rate ratios (relative risks) in the left hand side of the table were adjusted for age and sex. Rate ratios in the right hand side of the table were further adjusted for calendar period and negotiating body (surrogate for socioeconomic status). This inclusion of socioeconomic status in particular had a marked effect on findings for all causes, bringing rate ratios closer to unity, but had little effect on the individual rate ratios for neurodegenerative diseases. Significant trends of disease risk with cumulative magnetic field exposure were not shown for any of the three neurodegenerative diseases, although for Alzheimer's disease and motor neuron disease all rate ratios were above unity and there were isolated significantly elevated rate ratios for both diseases.

In order to focus on a subgroup for which the most reliable exposure assessment was available, the analysis summarised in table 4 was repeated for power station workers only with a further restriction that employees had to be first hired in the period 1952 or later (the period for which historical loading data are available); findings are shown in table 5. Significant

trends of disease risk with cumulative magnetic field exposure are not shown for any of the three neurodegenerative diseases, although for motor neuron disease the rate ratio in the second exposure category was significantly elevated.

The analyses summarised in table 5 were repeated following the application of a 10-year lag to the exposure histories—that is, an exposure is not considered to have the potential for influencing mortality until 10 years have elapsed; the findings are shown in table 6. Findings are little changed and significant trends of disease risk with cumulative magnetic field exposure are not shown for any of the three neurodegenerative diseases. The possible influence in power station workers of exposures received in the most recent five years was also examined (not shown in table). These analyses were based on smaller numbers of deaths with follow-up limited to the end of 1994 (work histories were not available after this date). Findings were unexceptional.

DISCUSSION

This large cohort of UK electricity generation and transmission workers did not suffer increased mortality rates from Alzheimer's disease or motor neuron disease, on the basis of comparisons with national mortality rates. In addition there were no indications of risks for these diseases increasing with increasing occupational exposure to magnetic fields. There was

Table 5 Relative risks of mortality from neurodegenerative diseases by levels of estimated cumulative exposure to magnetic fields in workers first employed in 1952 or later at UK electricity power stations, 1973–2004

Cumulative exposure to magnetic fields ($\mu\text{T-y}$)†	n	RR‡ (95% CI)	RR§ (95% CI)
Alzheimer's disease¶			
0–2.4	20	1.0	1.0
2.5–4.9	11	1.41 (0.67 to 2.97)	1.47 (0.70 to 3.08)
5.0–9.9	12	0.95 (0.46 to 1.98)	0.98 (0.47 to 2.05)
10.0–19.9	16	1.59 (0.80 to 3.14)	1.61 (0.81 to 3.20)
≥20.0	4	1.24 (0.42 to 3.70)	1.17 (0.39 to 3.48)
Total	63		
RR per 10 $\mu\text{T-y}$ ††		1.09 (0.85 to 1.40)	1.07 (0.83 to 1.37)
Motor neuron disease‡‡			
0–2.4	15	1.0	1.0
2.5–4.9	14	2.37* (1.14 to 4.93)	2.43* (1.17 to 5.05)
5.0–9.9	11	1.14 (0.52 to 2.49)	1.15 (0.53 to 2.53)
10.0–19.9	8	1.02 (0.43 to 2.42)	1.02 (0.43 to 2.43)
≥20.0	5	1.62 (0.59 to 4.49)	1.52 (0.55 to 4.23)
Total	53		
RR per 10 $\mu\text{T-y}$ ††		1.05 (0.81 to 1.36)	1.03 (0.80 to 1.33)
Parkinson's disease§§			
0–2.4	41	1.0	1.0
2.5–4.9	10	0.57 (0.29 to 1.15)	0.57 (0.28 to 1.14)
5.0–9.9	35	1.17 (0.74 to 1.85)	1.17 (0.74 to 1.86)
10.0–19.9	20	0.83 (0.48 to 1.43)	0.84 (0.49 to 1.45)
≥20.0	6	0.78 (0.33 to 1.83)	0.81 (0.34 to 1.92)
Total	112		
RR per 10 $\mu\text{T-y}$ ††		0.95 (0.77 to 1.17)	0.96 (0.78 to 1.18)
All causes			
0–2.4	4701	1.0	1.0
2.5–4.9	1918	1.04 (0.98 to 1.09)	1.03 (0.96 to 1.07)
5.0–9.9	2973	0.97 (0.93 to 1.02)	0.95* (0.90 to 0.99)
10.0–19.9	2444	0.98 (0.94 to 1.03)	0.97 (0.92 to 1.02)
≥20.0	711	0.78*** (0.72 to 0.84)	0.82*** (0.76 to 0.89)
Total	12747		
RR per 10 $\mu\text{T-y}$ ††		0.94*** (0.92 to 0.96)	0.95*** (0.94 to 0.97)

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

†One year refers to a working year, approximately 250 eight-hour shifts.

‡Analysed simultaneously with sex and attained age.

§Analysed simultaneously with sex, attained age, calendar period, and negotiating body (socioeconomic status).

¶Any part of death certificate coded to ICD-9 331.0 or ICD-10 G30.

††Five exposure categories scored by the mean value in each category, namely 0.36, 3.67, 7.24, 13.93, 38.53 $\mu\text{T-y}$. See text for details.

‡‡Any part of death certificate coded to ICD-8 348, ICD-9 335.2 or ICD-10 G12.2.

§§Any part of death certificate coded to ICD-8 342, ICD-9 332 or ICD-10 G20.

a small excess of deaths from Parkinson's disease of borderline significance, which was found not to be caused by magnetic field exposure. It is of course possible that this excess is a chance finding or it may reflect a low prevalence of smoking in this cohort. A meta-analysis has suggested that non-smokers have higher risks of Parkinson's disease than smokers³² and this cohort is known to have reduced lung cancer rates compared to the general population.³³

Strong magnetic fields are encountered mainly in close proximity to high currents. In the electric power industry, high currents are found in overhead lines and underground cables, and in busbars in power stations and substations. Exposure to the strong fields produced by these currents can occur either as a direct result of the job—for example, a lineman or cable splicer—or as a result of work location—for example, when office workers are located in a power station or substation site.³⁴ One of the strengths of this study is the exposure assessment, which combines information on job and location in assigning exposures. Some early validation work on the power station model has been completed (Renew, personal communication). Mean magnetic field exposures have been calculated for 29 job/facility combinations; these means were based on some 4200 personal full-shift magnetic field measurements taken in the period January to July 1999, for employees at three power stations. There was a significant correlation ($p < 0.05$) between

the predicted and measured mean fields. It is recognised that the exposure assessments for transmission workers (5.7% of the cohort) do not involve a similar degree of sophistication, although they are comparable to methods used in other studies.

Some limitations have to be attached, however, to our exposure assessment. As in other assessments, it has been necessary to assume that a particular job category is associated with the same pattern of departmental working in different power stations, in different time periods and among different workers. In addition, exposures associated with employment before 1 April 1952, are not assessed, and first known employment details are assumed to apply to all pre-1971 employment with the CEGB. Additionally, some of the assignments to non-operational jobs were solely for administrative purposes. A recent analysis of mesothelioma risks in this cohort indicated that some workers based at non-operational sites spend an important percentage of time in power stations.³³ The extent of exposure misclassification is unknown.

The study has other strengths and limitations. Mortality follow-up and death certificate ascertainment are almost complete. The cohort is dominated, however, by a survivor subcohort—those in employment in the 1970s but hired in earlier years. This cohort definition is likely to introduce selection effects that are difficult to predict or adjust for. Our reliance on death certificates is problematic, especially for

Table 6 Relative risks of mortality from neurodegenerative diseases by levels of estimated cumulative exposure to magnetic fields in workers first employed in 1952 or later at UK electricity power stations, exposure histories lagged by 10 years, 1973–2004

Cumulative exposure to magnetic fields ($\mu\text{T-y}$)†	n	RR‡ (95% CI)	RR§ (95% CI)
Alzheimer's disease¶			
0–2.4	20	1.0	
2.5–4.9	11	1.41 (0.67 to 2.97)	1.47 (0.70 to 3.08)
5.0–9.9	12	0.97 (0.46 to 2.02)	0.99 (0.47 to 2.07)
10.0–19.9	16	1.64 (0.82 to 3.24)	1.63 (0.82 to 3.25)
≥20.0	4	1.34 (0.45 to 3.99)	1.23 (0.41 to 3.68)
Total	63		
RR per 10 $\mu\text{T-y}$ ††		1.11 (0.87 to 1.42)	1.08 (0.85 to 1.39)
Motor neuron disease‡‡			
0–2.4	20	1.0	
2.5–4.9	13	1.90 (0.94 to 3.84)	1.87 (0.92 to 3.78)
5.0–9.9	7	0.70 (0.29 to 1.67)	0.68 (0.29 to 1.64)
10.0–19.9	8	1.11 (0.48 to 2.57)	1.06 (0.46 to 2.47)
≥20.0	5	2.03 (0.75 to 5.47)	1.75 (0.64 to 4.80)
Total	53		
RR per 10 $\mu\text{T-y}$ ††		1.15 (0.88 to 1.50)	1.11 (0.85 to 1.45)
Parkinson's disease§§			
0–2.4	42	1.0	
2.5–4.9	12	0.68 (0.36 to 1.30)	0.68 (0.36 to 1.30)
5.0–9.9	34	1.17 (0.74 to 1.86)	1.19 (0.75 to 1.89)
10.0–19.9	19	0.84 (0.48 to 1.45)	0.86 (0.50 to 1.50)
≥20.0	5	0.73 (0.29 to 1.85)	0.77 (0.30 to 1.97)
Total	112		
RR per 10 $\mu\text{T-y}$ ††		0.93 (0.75 to 1.16)	0.95 (0.76 to 1.18)
All causes			
0–2.4	5430	1.0	
2.5–4.9	1943	1.01 (0.95 to 1.06)	1.01 (0.96 to 1.06)
5.0–9.9	2757	0.94* (0.89 to 0.98)	0.95* (0.91 to 1.00)
10.0–19.9	2091	0.96 (0.91 to 1.01)	1.00 (0.95 to 1.05)
≥20.0	526	0.73*** (0.67 to 0.80)	0.83** (0.75 to 0.91)
Total	12747		
RR per 10 $\mu\text{T-y}$ ††		0.93*** (0.91 to 0.95)	0.96*** (0.94 to 0.98)

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

†One year refers to a working year, approximately 250 eight-hour shifts.

‡Analysed simultaneously with sex and attained age.

§Analysed simultaneously with sex, attained age, calendar period, and negotiating body (socioeconomic status).

¶Any part of death certificate coded to ICD-9 331.0 or ICD-10 G30.

††Five exposure categories scored by the mean value in each category, namely 0.36, 3.67, 7.24, 13.93, 38.53 $\mu\text{T-y}$. See text for details.

‡‡Any part of death certificate coded to ICD-8 348, ICD-9 335.2 or ICD-10 G12.2.

§§Any part of death certificate coded to ICD-8 342, ICD-9 332 or ICD-10 G20.

Alzheimer's and Parkinson's disease, as these conditions are known to be under-reported on death certificates; diagnostic accuracy is also a concern. In ICD-9 the four digit code 335.2 (motor neuron disease) includes ALS. Likewise for the four digit code G12.2 in ICD-10. It is not possible, therefore, to separate ALS from other motor neuron disease on the basis of standard ICD codes. We have reviewed all death certificates with a multiple cause coding described above. The overwhelming majority (86%) had the textual entry "motor neuron disease". It is also not possible, therefore, to separate ALS from other motor neuron disease on the basis of what is written on UK death certificates. It is likely that some studies that refer to ALS really refer to motor neuron disease. Our information on potential confounders was also limited. It has been recently suggested that polychlorinated biphenyls exposure may be associated with Parkinson's disease and ALS³⁵ and employees of the electric industries may historically have been exposed to

these agents in insulating fluids.³⁶ We are currently not in a position to incorporate the possible role of co-exposures in any formal way into these analyses.

In conclusion, our results provide no convincing evidence for an association between occupational exposure to magnetic fields and neurodegenerative diseases.

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Policy implication

Given that amyotrophic lateral sclerosis is an extremely rare condition, a pooled analysis of existing occupational cohorts combined with refined job-exposure matrices may contribute to the aetiological roles, if any, of polychlorinated biphenyls, electric shocks and magnetic fields.

Main message

Our results provide no convincing evidence for an association between occupational exposure to magnetic fields and risks of neurodegenerative diseases.

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