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Magnetic fields and leukaemia risks in UK electricity supply workers

T. Sorahan

Institute of Occupational and Environmental Medicine, University of Birmingham, Edgbaston, Birmingham, West Midlands B15 2TT, UK.

Correspondence to: T. Sorahan, Institute of Occupational and Environmental Medicine, University of Birmingham, Edgbaston, Birmingham, West Midlands B15 2TT, UK. Tel: +44 (0)121 414 3644; fax: +44 (0)121 414 6217; e-mail: t.m.sorahan@bham.ac.uk

Aims To investigate whether leukaemia risks are related to occupational exposure to low-frequency magnetic fields.

Methods Leukaemia risks experienced by 73 051 employees of the former Central Electricity Generating Board of England and Wales were investigated for the period 1973–2010. All employees were hired in the period 1952–82 and were employed for at least 6 months with some employment in the period 1973–82. Detailed calculations had been performed by others to enable an assessment to be made of exposures to magnetic fields. Poisson regression was used to calculate relative risks (rate ratios) of developing leukaemia or leukaemia subtypes for categories of lifetime, distant (lagged) and recent (lugged) exposure.

Results Findings for all leukaemias combined were unexceptional; risks were close to unity for all exposure categories and there was no suggestion of risks increasing with cumulative (or recent or distant) magnetic field exposures. There were no statistically significant dose–response effects shown for acute myeloid leukaemia, chronic myeloid leukaemia or chronic lymphocytic leukaemia. There was a significant positive trend for acute lymphocytic leukaemia (ALL), but this was based, in the main, on unusually low risks in the lowest exposure category.

Conclusions This study found no convincing evidence to support the hypothesis that exposure to magnetic fields is a risk factor for leukaemia, and the findings are consistent with the hypotheses that both distant and recent magnetic field exposures are not causally related to the generality of leukaemia. The limited positive findings for ALL may well be chance findings.

Key words Acute lymphocytic leukaemia; cohort study; electricity supply industry; leukaemia subtypes.

Introduction

There have been many epidemiological studies into leukaemia risks and occupational exposures to low-frequency electric and magnetic fields (EMFs), and Kheifets *et al.* published a meta-analysis of 56 cohort and case–control studies in 2008 [1]. These reviewers found a small (16%) but significant elevation in risk (different summary measures from the various studies) but concluded that 'the apparent lack of a clear pattern of exposure and risk substantially detracts from the hypothesis that measured magnetic fields in the work environment are responsible for the observed excess of leukaemia'. Other narrative reviews have come to similar conclusions [2,3]. The more important of these 56 studies are the five cohort studies of electric utility workers that present findings for leukaemia risks in relation to quantitative estimates of magnetic field exposure [4–8]. The Southern California Edison Study [4] presented unexceptional findings for all leukaemias combined and the United States Five Utility Study [5] presented unexceptional findings for all leukaemias and for acute myeloid leukaemia (AML) and chronic lymphatic leukaemia (CLL). The Canada–France study [6] presented significant positive findings for AML and non-significant positive findings for all leukaemias, CLL and acute lymphocytic leukaemia (ALL), although all these associations were based on only two exposure groups (below and above median exposure) and leukaemia cases were only compared with a small number of controls from the cohort (nested case–control study) rather than the whole cohort. The Danish utility workers study [7] presented unexceptional findings for all leukaemias combined. Earlier analyses of the UK cohort [8] found no discernible excess leukaemia risks as a consequence of exposure to magnetic fields; these earlier findings were based on mortality data only and did not consider all leukaemia subtypes.

The purpose of this article is to present updated findings for the UK study of cancer risks in employees of the former Central Electricity Generating Board (CEGB). An additional 13 years of mortality data are now available together with cancer registration (incidence) data for the whole period under study (1973–2010); the analysis commenced without strong prior evidence of any association between risk of leukaemia subtypes and magnetic field exposure.

Methods

The materials and methods have been summarized in a companion paper on brain tumours [9]. This analysis is based on the same cohort of 73 051 study subjects (62 825 men and 10 226 women) first employed in the period 1952–82 for whom a work history was available. The survey was established with the approval of the Central Ethical Committee of the British Medical Association, and the author is currently accredited by the Office for National Statistics as the 'Approved Researcher' of this cohort study.

Results

Relative risks (rate ratios) for any notification of a leukaemia (cancer registration or mention on death certificate: 352 cases in total) are shown in Table 1 for four categories of estimated cumulative occupational exposure to magnetic fields relative to the corresponding rates in the lowest (baseline) category of exposure (Model 1). Corresponding relative risks are also shown for a simultaneous analysis of distant (lagged) and recent (lugged) exposures (Model 2). Rate ratios in the left-hand side of the table were adjusted for age and sex. Rate ratios in the

Table 1. Relative risks of leukaemia[a] by levels of estimated cumulative magnetic field exposure (four separate analyses), UK electricity generation and transmission workers, 1973–2010

Exposure to magnetic fields (μT year)[b]	*n*	RR[c] (95% CI)	RR[d] (95% CI)
Model 1. Occupational cumulative lifetime exposure to magnetic field			
0−	183	1.0	1.0
2.5−	37	1.03 (0.72–1.48)	0.98 (0.69–1.41)
5.0−	64	1.14 (0.85–1.52)	1.07 (0.80–1.44)
10.0−	49	1.00 (0.72–1.38)	0.95 (0.68–1.31)
≥20.0	19	0.84 (0.52–1.35)	0.78 (0.48–1.26)
RR per 10 μT year[e]		0.96 (0.86–1.08)	0.94 (0.84–1.06)
Model 2. Occupational exposure to magnetic fields received >10 years ago (lagged exposure)			
0−	194	1.0	1.0
2.5−	41	1.19 (0.84–1.68)	1.11 (0.78–1.58)
5.0−	59	1.17 (0.86–1.59)	1.08 (0.79–1.49)
10.0−	44	1.08 (0.76–1.53)	1.01 (0.71–1.44)
≥20.0	14	0.78 (0.45–1.36)	0.73 (0.41–1.29)
RR per 10 μT year[f]		0.95 (0.84–1.08)	0.92 (0.81–1.05)
Occupational exposure to magnetic fields received <10 years ago (lugged exposure)			
0−	242	1.0	1.0
0.01−	55	0.99 (0.73–1.34)	0.95 (0.69–1.31)
0.5−	19	0.74 (0.46–1.19)	0.71 (0.42–1.19)
2.0−	19	0.87 (0.53–1.42)	0.89 (0.52–1.51)
≥5.0	17	0.97 (0.57–1.63)	0.99 (0.57–1.75)
RR per 10 μT year[g]		1.00 (0.65–1.54)	1.07 (0.68–1.68)

RR, relative risk or rate ratio.
[a]Cancer registration or any part of death certificate coded to ICD-9 204-208.
[b]One year refers to a working year, ~250 eight-hour shifts.
[c]Analysed simultaneously with sex and attained age (5 year age groups).
[d]Analysed simultaneously with sex, attained age, calendar period (5 year periods) and negotiating body (National Joint Managerial (NJM) and National Joint Board (NJB); National Joint Council (NJC); National Joint Industrial Council (NJIC) and National Joint Building and Civil Engineering Committee (NJ(B&C)E)).
[e]Five exposure categories scored by the mean value in each category, namely 0.47, 3.71, 7.26, 13.97 and 38.60 μT year.
[f]Five exposure categories scored by the mean value in each category, namely 0.45, 3.69, 7.24, 13.82 and 38.27 μT year.
[g]Five exposure categories scored by the mean value in each category, namely 0, 0.19, 1.11, 3.31 and 12.01 μT year.

right-hand side of the table were additionally adjusted for calendar period and socio-economic status (three categories: managers, scientists and engineers; administrative and clerical workers; industrial and construction workers). To be concrete, the table summarizes four separate analyses. None of the individual point estimates of risk are significantly different from unity and there is no suggestion that risks increase with increasing exposure. Findings were little different with or without adjustment for calendar period and socio-economic status.

Findings for chronic myeloid leukaemia (CML) risks are shown in Table 2. The point estimates of risk for the second category of lagged exposures achieved statistical significance (relative risk = 2.55, 95% CI 1.04–6.22), but there was no suggestion that risks increase with increasing exposure. Findings were little different with or without adjustment for calendar period and socio-economic status.

Findings for AML risks are shown in Table 3. None of the individual point estimates of risk are significantly different from unity and there is no suggestion that risks increase with increasing exposure. Findings were little different with or without adjustment for calendar period and socio-economic status.

Findings for CLL risks are shown in Table 4. None of the individual point estimates of risk are significantly different from unity and there is no suggestion that risks increase with increasing exposure. Findings were little different with or without adjustment for calendar period and socio-economic status.

Findings for ALL risks are shown in Table 5. A number of individual point estimates of risk are significantly different from unity (albeit based on small observed numbers) and a significant positive trend was shown for cumulative lifetime exposure (Model 1). Findings from Model 2 indicated that this association relied more on recent exposures than on distant exposures. Findings for lifetime exposures were little different with or without adjustment for calendar period and socio-economic status.

Standardized registration ratios (SRRs) for ALL based on cancer incidence rates for England and Wales

Table 2. Relative risks of chronic myeloid leukaemia (CML)[a] by levels of estimated cumulative magnetic field exposure (four separate analyses), UK electricity generation and transmission workers, 1973–2010

Exposure to magnetic fields (μT year)[b]	*n*	RR[c] (95% CI)	RR[d] (95% CI)
Model 1. Occupational cumulative lifetime exposure to magnetic field			
0−	17	1.0	1.0
2.5−	6	1.67 (0.66–4.25)	1.68 (0.65–4.37)
5.0−	11	1.96 (0.91–4.23)	1.95 (0.87–4.37)
10.0−	5	1.03 (0.38–2.83)	1.04 (0.37–2.92)
≥20.0	2	0.88 (0.20–3.83)	0.95 (0.21–4.22)
RR per 10 μT year[e]		0.97 (0.70–1.34)	0.97 (0.70–1.36)
Model 2. Occupational exposure to magnetic fields received >10 years ago (lagged exposure)			
0−	18	1.0	1.0
2.5−	8	2.33 (0.99–5.51)	2.55 (1.04–6.22)
5.0−	9	1.81 (0.78–4.24)	2.06 (0.84–5.03)
10.0−	5	1.28 (0.45–3.64)	1.56 (0.52–4.62)
≥20.0	1	0.59 (0.08–4.54)	0.79 (0.10–6.37)
RR per 10 μT year[f]		0.93 (0.64–1.35)	0.96 (0.65–1.43)
Occupational exposure to magnetic fields received <10 years ago (lugged exposure)			
0−	24	1.0	1.0
0.01−	6	0.90 (0.36–2.27)	0.71 (0.27–1.86)
0.5−	6	1.73 (0.67–4.45)	1.06 (0.36–3.13)
2.0−	2	0.66 (0.15–2.95)	0.43 (0.09–2.11)
≥5.0	3	1.26 (0.34–4.60)	0.84 (0.20–3.45)
RR per 10 μT year[g]		1.32 (0.47–3.74)	1.06 (0.34–3.28)

RR, relative risk or rate ratio.
[a]Cancer registration or any part of death certificate coded to ICD-9 205.1.
[b]One year refers to a working year, ~250 eight-hour shifts.
[c]Analysed simultaneously with sex and attained age (5 year age groups).
[d]Analysed simultaneously with sex, attained age, calendar period (5 year periods) and negotiating body (National Joint Managerial (NJM) and National Joint Board (NJB); National Joint Council (NJC); National Joint Industrial Council (NJIC) and National Joint Building and Civil Engineering Committee (NJ(B&C)E)).
[e]Five exposure categories scored by the mean value in each category, namely 0.47, 3.71, 7.26, 13.97 and 38.60 μT year.
[f]Five exposure categories scored by the mean value in each category, namely 0.45, 3.69, 7.24, 13.82 and 38.27 μT year.
[g]Five exposure categories scored by the mean value in each category, namely 0, 0.19, 1.11, 3.31 and 12.01 μT year.

Table 3. Relative risks of AML[a] by levels of estimated cumulative magnetic field exposure (four separate analyses), UK electricity generation and transmission workers, 1973–2010

Exposure to magnetic fields (μT year)[b]	*n*	RR[c] (95% CI)	RR[d] (95% CI)
Model 1. Occupational cumulative lifetime exposure to magnetic field			
0−	53	1.0	1.0
2.5−	10	1.10 (0.55–2.18)	1.11 (0.55–2.22)
5.0−	16	1.19 (0.67–2.12)	1.19 (0.65–2.16)
10.0−	17	1.49 (0.84–2.63)	1.50 (0.83–2.70)
≥20.0	4	0.76 (0.27–2.13)	0.75 (0.27–2.13)
RR per 10 μT year[e]		1.00 (0.81–1.24)	0.99 (0.80–1.24)
Model 2. Occupational exposure to magnetic fields received >10 years ago (lagged exposure)			
0−	57	1.0	1.0
2.5−	10	1.15 (0.57–2.29)	1.14 (0.56–2.31)
5.0−	15	1.22 (0.66–2.25)	1.22 (0.65–2.29)
10.0−	15	1.53 (0.82–2.86)	1.55 (0.81–2.97)
≥20.0	3	0.69 (0.21–2.29)	0.71 (0.21–2.38)
RR per 10 μT year[f]		1.02 (0.81–1.30)	1.01 (0.79–1.29)
Occupational exposure to magnetic fields received <10 years ago (lugged exposure)			
0−	66	1.0	1.0
0.01−	20	1.35 (0.79–2.29)	1.28 (0.73–2.23)
0.5−	5	0.70 (0.27–1.79)	0.66 (0.24–1.77)
2.0−	4	0.64 (0.23–1.83)	0.63 (0.21–1.91)
≥5.0	5	0.93 (0.35–2.45)	0.90 (0.32–2.54)
RR per 10 μT year[g]		0.88 (0.39–1.99)	0.90 (0.38–2.12)

RR, relative risk or rate ratio.
[a]Cancer registration or any part of death certificate coded to ICD-9 205.0.
[b]One year refers to a working year, ~250 eight-hour shifts.
[c]Analysed simultaneously with sex and attained age (5 year age groups).
[d]Analysed simultaneously with sex, attained age, calendar period (5 year periods) and negotiating body (National Joint Managerial (NJM) and National Joint Board (NJB); National Joint Council (NJC); National Joint Industrial Council (NJIC) and National Joint Building and Civil Engineering Committee (NJ(B&C)E)).
[e]Five exposure categories scored by the mean value in each category, namely 0.47, 3.71, 7.26, 13.97 and 38.60 μT year.
[f]Five exposure categories scored by the mean value in each category, namely 0.45, 3.69, 7.24, 13.82 and 38.27 μT year.
[g]Five exposure categories scored by the mean value in each category, namely 0, 0.19, 1.11, 3.31 and 12.01 μT year.

are shown for the five exposure categories under investigation in Table 6. Overall, there was a non-significant deficit (observed (Obs) 10, SRR 74, 95% CI: 35–136). There was a non-significant trend with SRRs by exposure category and an SRR of only 39 in the baseline (index) exposure group (Obs 3, SRR 39, 95% CI: 8–115).

The analyses summarized in Tables 1–5 were then repeated for the sub-cohort of those 48 768 employees first employed in power stations, and findings are presented in Supplementary Tables S1–S5 at *Occupational Medicine* Online (see website). These analyses were carried out because the exposure assessments for power station workers are more detailed than for other groups of workers. Findings were little different to those shown in Tables 1–5.

Discussion

This study found no convincing evidence to support the hypothesis that exposure to magnetic fields is a risk factor for CML, AML or CLL, and the findings are consistent with the hypotheses that both distant and recent magnetic field exposures are not causally related to any of these three diseases. The same statements could be made for the generality of leukaemia considered as a single entity, and these statements are not dependent on the selection of co-variates in the analysis or on the selection of sub-cohorts for analysis (all employees or power station workers only). It is not possible, however, to be as confident for the findings for ALL, because, while based on a total of only 14 cases in the cohort under study, there was a statistically significant relationship between risks of ALL and estimated cumulative magnetic field exposure.

The study has many strengths including its large size, long period of follow-up, availability of mortality and cancer registration data, large number of leukaemia cases available for analysis (though not for all leukaemia subtypes) and detailed exposure assessments that used the physics of exposure to magnetic fields as a starting

Table 4. Relative risks of CLL[a] by levels of estimated cumulative magnetic field exposure (four separate analyses), UK electricity generation and transmission workers, 1973–2010

Exposure to magnetic fields (μT year)[b]	*n*	RR[c] (95% CI)	RR[d] (95% CI)
Model 1. Occupational cumulative lifetime exposure to magnetic field			
0–	94	1.0	1.0
2.5–	15	0.77 (0.44–1.33)	0.68 (0.39–1.18)
5.0–	28	0.88 (0.57–1.34)	0.77 (0.50–1.18)
10.0–	21	0.74 (0.46–1.20)	0.65 (0.40–1.06)
≥20.0	11	0.84 (0.45–1.58)	0.74 (0.39–1.39)
RR per 10 μT year[e]		0.93 (0.79–1.10)	0.90 (0.76–1.07)
Model 2. Occupational exposure to magnetic fields received >10 years ago (lagged exposure)			
0–	96	1.0	1.0
2.5–	18	0.99 (0.59–1.66)	0.89 (0.53–1.49)
5.0–	27	0.99 (0.64–1.55)	0.89 (0.56–1.39)
10.0–	18	0.82 (0.48–1.39)	0.74 (0.44–1.26)
≥20.0	10	1.04 (0.53–2.04)	0.95 (0.48–1.89)
RR per 10 μT year[f]		0.96 (0.81–1.15)	0.93 (0.77–1.11)
Occupational exposure to magnetic fields received <10 years ago (lugged exposure)			
0–	128	1.0	1.0
0.01–	22	0.78 (0.49–1.26)	0.74 (0.45–1.20)
0.5–	6	0.50 (0.21–1.14)	0.45 (0.19–1.08)
2.0–	10	1.01 (0.51–1.98)	0.91 (0.45–1.85)
≥5.0	6	0.77 (0.32–1.80)	0.69 (0.29–1.66)
RR per 10 μT year[g]		0.85 (0.42–1.70)	0.81 (0.39–1.66)

RR, relative risk or rate ratio.
[a]Cancer registration or any part of death certificate coded to ICD-9 204.1.
[b]One year refers to a working year, ~250 eight-hour shifts.
[c]Analysed simultaneously with sex and attained age (5 year age groups).
[d]Analysed simultaneously with sex, attained age, calendar period (5 year periods) and negotiating body (National Joint Managerial (NJM) and National Joint Board (NJB); National Joint Council (NJC); National Joint Industrial Council (NJIC) and National Joint Building and Civil Engineering Committee (NJ(B&C)E)).
[e]Five exposure categories scored by the mean value in each category, namely 0.47, 3.71, 7.26, 13.97 and 38.60 μT year.
[f]Five exposure categories scored by the mean value in each category, namely 0.45, 3.69, 7.24, 13.82 and 38.27 μT year.
[g]Five exposure categories scored by the mean value in each category, namely 0, 0.19, 1.11, 3.31 and 12.01 μT year.

point [10]. However, there are limitations to be attached to the work. Most notably, it was necessary to assume that for those workers hired before 1973, job and place of work in the 1950s and 1960s were the same as those pursued in the early 1970s, and it was also assumed that working patterns (time spent by different groups of workers in different parts of power stations) are the same in different power stations. These assumptions will have introduced errors into the exposure assessments, but we remain confident that the exposure assessments have value particularly if we accept the relative rankings of the five exposure categories and do not attach overwhelming importance to their absolute values. It must be the case, however, that the current exposure estimates fall short of an ideal survey that would include measured individual exposures over time.

Earlier published comparisons with national mortality rates (total cohort and males and females combined) are consistent with the absence of occupational risk factors for the generality of leukaemia (Obs 141, expected (Exp) 178.0, standardized mortality ratio (SMR) 79, 95% CI: 67–93) [11]. Likewise, earlier comparisons with national incidence rates (total cohort and males and females combined) are also consistent with the absence of occupational risk factors for the generality of leukaemia (Obs 357, Exp 381.5, SRR 94, 95% CI: 84–104) and for ALL (Obs 12; Exp 14.6, SRR 82, 95% CI: 42–144) [12].

A key issue in the interpretation of the positive findings for ALL is whether the trend was based on unusually low risks in the lowest exposure category or unusually high risks in the highest exposure category or both. The comparisons with national cancer registration rates suggest that the former is the case, and taken together with the lower than average rates of ALL in the total cohort, these findings argue against a causative explanation for the trend obtained from the Poisson regression (internal) analyses. These latter findings may well be no more than chance findings based on multiple testing of leukaemia subtypes.

The suggestion from the Canada–France study [6] that AML may be linked to magnetic field exposure receives no support from the new UK findings. In conclusion, the current UK study indicates that neither

Table 5. Relative risks of acute lymphatic leukaemia (ALL)[a] by levels of estimated cumulative magnetic field exposure (four separate analyses), UK electricity generation and transmission workers, 1973–2010

Exposure to magnetic fields (μT year)[b]	*n*	RR[c] (95% CI)	RR[d] (95% CI)
Model 1. Occupational cumulative lifetime exposure to magnetic field			
0−	4	1.0	1.0
2.5−	3	5.23 (1.09–25.2)	5.58 (1.13–27.5)
5.0−	2	2.83 (0.47–17.0)	3.02 (0.49–18.7)
10.0−	3	5.57 (1.09–28.4)	5.88 (1.12–30.8)
≥20.0	2	7.67 (1.25–47.1)	7.70 (1.22–48.5)
RR per 10 μT year[e]		1.54 (1.05–2.27)	1.52 (1.03–2.25)
Model 2. Occupational exposure to magnetic fields received >10 years ago (lagged exposure)			
0−	8	1.0	1.0
2.5−	2	1.42 (0.28–7.28)	1.15 (0.22–5.96)
5.0−	1	0.59 (0.07–5.24)	0.44 (0.05–3.97)
10.0−	2	1.71 (0.30–9.62)	1.11 (0.18–6.69)
≥20.0	1	1.95 (0.21–18.5)	1.08 (0.10–11.6)
RR per 10 μT year[f]		1.28 (0.75–2.20)	1.21 (0.69–2.12)
Occupational exposure to magnetic fields received <10 years ago (lugged exposure)			
0−	4	1.0	1.0
0.01−	3	3.04 (0.64–14.5)	4.31 (0.81–22.9)
0.5−	2	3.46 (0.57–21.1)	6.19 (0.83–46.1)
2.0−	3	5.63 (1.06–30.0)	11.48 (1.65–79.7)
≥5.0	2	3.77 (0.55–26.0)	8.12 (0.87–75.3)
RR per 10 μT year[g]		1.91 (0.53–6.83)	2.23 (0.58–8.66)

RR, relative risk or rate ratio.
[a]Cancer registration or any part of death certificate coded to ICD-9 204.0.
[b]One year refers to a working year, ~250 eight-hour shifts.
[c]Analysed simultaneously with sex and attained age (5 year age groups).
[d]Analysed simultaneously with sex, attained age, calendar period (5 year periods) and negotiating body (National Joint Managerial (NJM) and National Joint Board (NJB); National Joint Council (NJC); National Joint Industrial Council (NJIC) and National Joint Building and Civil Engineering Committee (NJ(B&C)E)).
[e]Five exposure categories scored by the mean value in each category, namely 0.47, 3.71, 7.26, 13.97 and 38.60 μT year.
[f]Five exposure categories scored by the mean value in each category, namely 0.45, 3.69, 7.24, 13.82 and 38.27 μT year.
[g]Five exposure categories scored by the mean value in each category, namely 0, 0.19, 1.11, 3.31 and 12.01 μT year.

Table 6. SRR for acute lymphocytic leukaemia[a] by levels of estimated cumulative magnetic field exposure

Exposure to magnetic fields (μT year)[b]	Obs	Exp	SRR (95% CI)
0−	3	7.6	39 (8–115)
2.5−	3	1.4	213 (44–626)
5.0−	1	2.0	51 (1–279)
10.0−	2	1.6	124 (15–451)
≥20.0	1	0.8	130 (3–696)
Total	10	13.4	75 (35–136)

[a]Cancer registration coded to ICD-9 204.0.
[b]One year refers to a working year, ~250 eight-hour shifts.

recent nor distant magnetic field exposures are a risk factor for AML, CML or CLL. The limited positive findings for ALL may well be chance findings; comparisons with national cancer registration rates did not support a causal interpretation.

Key points

- This large UK study found no evidence to support the hypothesis that exposure to magnetic fields is a risk factor for chronic myeloid leukaemia, acute myeloid leukaemia, chronic lymphatic leukaemia or for the generality of all leukaemias combined.
- The findings are consistent with the hypotheses that both distant and recent magnetic field exposures are not causally related to chronic myeloid leukaemia, acute myeloid leukaemia or chronic lymphatic leukaemia or to the generality of all leukaemias combined.
- There were some significant positive findings for acute lymphatic leukaemia and magnetic field exposure based on a small number of cases; comparisons with national cancer registration rates did not support a causal interpretation.

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Conflicts of interest

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