Summary

Background Previous studies have suggested an association between exposure to power-frequency electromagnetic fields (EMF) and the development of childhood malignant disease, especially leukaemia and tumours of the central nervous system. We investigated the relation between all childhood cancer and exposure to power-frequency magnetic fields.

Methods The UK Childhood Cancer Study was a population case-control study covering the whole of England, Wales, and Scotland. All children with a confirmed malignant disorder were potentially eligible. For each case, we matched two controls on date of birth and sex, randomly chosen from the list of the Family Health Services Authority in England and Wales or Health Board in Scotland. In the main study, 3838 cases and 7629 controls were interviewed. The EMF part of the study included only one control per case, and household EMF measurements and school measurements where relevant were taken on 2226 matched pairs. These measurements, adjusted for historical line load and appliance fields, were used to estimate average exposure in the year before the date of diagnosis, or an equivalent date for controls. Analyses were by conditional logistic regression, incorporating a census-derived deprivation index used as a measure of socioeconomic status.

Findings For children with mean exposures of more than 0·2 μT compared with children with mean exposures of less than 0·1 μT, the adjusted odds ratios were 0·92 (95% CI 0·47–1·79) for acute lymphoblastic leukaemia, 0·90 (0·49–1·63) for all leukaemia, 0·46 (0·11–1·86) for central-nervous-system tumours, 0·97 (0·46–2·05) for other malignant disease, and 0·87 (0·56–1·35) for all malignant disease combined. Higher exposures (>0·4 μT) were recorded for only 17 (<0·4%) individuals (eight cases, nine controls).

Interpretation This study provides no evidence that exposure to magnetic fields associated with the electricity supply in the UK in99ses risks for childhood leukaemia, cancers of

We measured the 50 Hz magnetic fields (and harmonics <800 Hz) generated by the distribution and use of electricity in homes and, when relevant, schools to obtain estimates of individual exposure. Each measurement consisted of a series of readings, summarised as the arithmetic mean. We tested the hypothesis that a mean exposure of more than 0·2 μT in the year before diagnosis would increase risk of childhood leukaemia, specifically acute lymphoblastic leukaemia, and cancers of the central nervous system, compared with a mean exposure of less than 0·1 μT in the year before diagnosis. A further hypothesis was that risk of the same diagnoses would increase smoothly with increasing mean exposure in the year preceding diagnosis. Residential electric fields were measured in a subset of the study, which will be reported elsewhere.

Methods

The UKCCS was a population-based collaborative case-control study covering the whole of England, Wales, and Scotland, based on eight regional centres in England and a centre each in Scotland[11,12] and Wales.[11]

UKCCS participants

In England and Wales, the UKCCS study population was defined as children aged 0–14 years, registered with one of the Family Health Service Authorities (FHSAs). In Scotland, which has an independent system, the study population was defined as children registered with one of the 13 Health Boards.

The study began in Scotland on Jan 1, 1991, and in England and Wales on April 1, 1992. All children registered with an FHSA or Health Board after these dates who had pathologically confirmed malignant disease (except for some cancers of the central nervous system diagnosed by scan or radiography alone), as defined in the classification scheme devised by Birch and Marsden,[13] were potentially eligible for the study. In Scotland, case accrual ended in December, 1994, and in England and Wales it was restricted to children who had leukaemia and non-Hodgkin lymphoma throughout 1995, and leukaemia alone throughout 1996.

For each case two controls, matched for sex and date of birth, were randomly selected, from the list of the same FHSA or Health Board as the case. In England and Wales, computerised lists of children registered with each FHSA on Jan 1 and July 1 each year were obtained and ten potential controls randomly selected from the list on which cases appeared immediately before diagnosis. When the case child was less than I year old at diagnosis, we chose controls from the first FHSA list on which the case appeared. The general practitioners (family physicians) of the first two potential controls were approached and, with their permission, the parents of those children were contacted and asked to participate in the study. If the general practitioner or parents refused permission, we approached the next control in the same way until two control families participated.

Children (cases and controls) were ineligible if they had been born outside the UK study area or had had previous malignant disease. For the purposes of the study, all controls were assigned a pseudo-diagnosis date—the date on which they were exactly the same age as the corresponding case at diagnosis. Children who themselves, or whose parents, were resident outside the study area in the 3 months leading up to diagnosis or pseudo-diagnosis date were ineligible for inclusion. Children in residential local-authority care at diagnosis date (<1% of total childhood population) were also excluded.[11]

For the EMF component of the study,[11] we chose only one control per case from the two included in the main study because of limited resources. All cases who had participated in the full study were eligible for inclusion in the EMF study. Eligibility was based on home address, since exposure was based on measurements in the home. Home addresses were eligible if the child had lived there for at least 12 months before diagnosis or pseudo-diagnosis, or since birth for children younger than 1 year at diagnosis or pseudo-diagnosis, and the family still lived there. Fixed-site caravans were included, but not mobile homes. If a case's family refused to participate in the EMF study or if the case was ineligible we did not approach either of the matched controls. Otherwise, we approached the control with the lower identification number of the pair. If the first control family refused to participate or the control was ineligible, we approached the second control's family.

If a child had changed address since the diagnosis or pseudo-diagnosis date, we did not take measurements in the previous home. Because of delays in starting the EMF study, the length of time between the diagnosis or pseudo-diagnosis date and the first measurements varied. This delay affected the number of case-control pairs for which measurements were available. The mean time between diagnosis or pseudo-diagnosis and the initial measurement was 20·8 months (SD 10·8) for cases and 21·3 months (10·8) for controls. The last measurement made was in December, 1998.

Data collection

To address the wide-ranging hypotheses under investigation in the UKCCS, data were collected in stages from several different sources. The first component of the study, without which the others could not proceed, was personal interviews with the parents of cases and controls.

Full residential and occupational histories, including specific information about occupational exposures and individual housing characteristics, were recorded for each parent. To improve the quality of these data, a form asking parents to list the places in which they had lived and the jobs they had had was sent out before the interviews. At interviews, mothers and fathers were also asked about their own health, social habits, and any illnesses in their families. Additional sections on pregnancies and the index child's health, schooling, and social history were incorporated into the mothers' questionnaires.

At the end of the interview, interviewees were asked whether they were willing to be contacted again. Consent was sought for their participation in the ionising radiation (radon and γ) and the non-ionising radiation (EMF) components of the study. Signed agreement was requested for blood samples to be taken at a later date and for medical and other records to be accessed.

The measurement protocols for the EMF study were based on data acquired in a pilot study[14] done by the National Radiological Protection Board. The pilot study showed that a restricted set of measurements would classify, with acceptable sensitivity and specificity, an individual into the lowest 90% of exposure. For exposures in the top 10%, more extensive measurements would be required to give more precise exposure estimates. Since we did not have resources available for making extensive measurements in the households of all cases and controls, we used a two-phase approach.[11]

In the first phase, we gathered information on EMF exposures from five different sources: specified measurements in the child's home (designated the phase I measurement); the proximity and type of overhead powerlines nearby, from an external-sources questionnaire; a questionnaire on electrical appliances in the home (night storage heaters, underfloor heating, and electric blankets); and measurements in schools or other institutions, such as purpose-built nursery schools, attended by the child; and electricity companies' databases of historical load data and other operating characteristics.

A school was eligible if the child had attended for 15 h or more per week during the winter (October to March) immediately before the diagnosis or pseudo-diagnosis date. If the child had attended more than one school in this period, we chose the school at which the most time was spent.

In the second phase, we took further EMF measurements (phase II residential measurements) for all children indicated by phase I to be in the top 10% of exposures (taken as ⩾0·1 μT) and for the relevant matched case or control. We also took further

measurements for individuals who were exposed to specified appliances described in the phase I questionnaire, and those living within specified distances from high-voltage overhead power lines and underground cables.

Exposure assessment was based on measurements for all participants, except for a few for whom specific adjustments were made. These adjustments were: an addition to the measured exposure made for individuals with exposures from certain household appliances, and addition to or subtraction from the measured exposure because exposure from external sources had changed between the year before diagnosis or pseudo-diagnosis and the time of measurement, as determined by line-load data and circuit configuration over the respective periods.

We measured resultant magnetic fields with Emdex II magnetic field meters (Enertech Consultants Ltd, Campbell, CA, USA) in the broadband frequency range 40-800 Hz.[11] For the shorter measurements, we used sampling intervals of 1·5 s and 3·0 s in the phase I and phase II assessments, respectively. The sampling interval was adjusted to 10 s for 48 h measurements taken in phase II.

To prevent identification of high-exposure and low-exposure households by study technicians, meter readings were not displayed during the assessment. Information on EMF exposure in individual homes and schools was provided to study participants on request, but otherwise remained confidential.

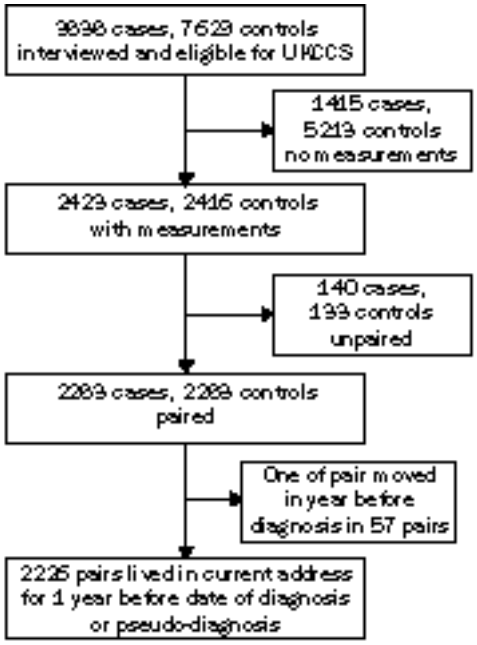
The protocol was designed specifically to estimate the average EMF exposure in the year before diagnosis or pseudo-diagnosis.

The phase I residential measurements comprised (in order): three 3 min spot measurements taken in the centre of the child's bedroom, at the centre of the child's bed, and on the centre of the child's pillow; one 90 min measurement taken in the centre of the main family room; a repeat of the three spot measurements after the 90 min measurement. If the period between measurements in the homes of the case and of the corresponding control was 4 months or more, we tried to repeat the earlier measurements. An interval of less than 4 months was achieved for 98% of case-control pairs. During the phase I household visits, we asked about the time that the child spent in bed and at school and used the information in the calculation of time-weighted average exposures.

We made phase II measurements for the matched case-control pairs as close as possible to each other and within 4 weeks. If the phase I questionnaire had identified possible exposure from a night storage heater or underfloor heating in the bedroom, we took measurements during a period in which the appliance was in use, typically during the winter months. We did all phase II measurements at times agreed with the appropriate electricity company as being typical for operation of the local distribution system. The measurements comprised: four 3 min spot measurements taken at the centre of the family room, at the bedside position to be used for the 48 h measurement, at the centre of the child's bed, and at the centre of the pillow; a 48 h measurement taken by the side of the middle of the child's bed; a repeat of the four spot measurements after the 48 h measurement.

For phase I and phase II all measurements, apart from those made on the bed, were done with the meter held 1 m above the floor in a polypropylene stand, and at least 1 m from any operating appliances. Meters were placed in tamper-proof holders for the 48 h measurements.

We took school measurements when the heating systems were operating normally. In England and Wales, measurements were made from October to March, inclusive. There were two measurement schemes. The first was used when the child spent most of his or her time at school in a single classroom during the relevant winter period, typically in primary schools. For this scheme we made five 2 min spot measurements near the centre and four corners of the room. The second scheme for children who used many classrooms, typically those in secondary schools, consisted of spot measurements in up to five of the rooms most frequently used during the relevant winter period. In each room, one measurement was made near the centre; the measurement time totalled 10 min and the measurements in the different



Selection of patients from UKCCS

rooms were of equal duration. All measurements were made at a height of 1 m from the floor and at least 1 m from any appliance operating on mains electricity.

An external-sources questionnaire was completed for each EMF study participant to identify important sources of electricity supply, such as power lines, near to homes and schools. The questionnaire was designed in cooperation with the National Grid Company, the regional electricity companies for England and Wales, and ScottishPower and Scottish Hydro-Electric in Scotland. The specific purposes of the questionnaire were: to identify high-voltage lines or underground cables that were capable of producing annual average fields of more than 0·1 μT in the home or school; to obtain load and other circuit information to enable reconstruction of historical exposure; to check that the electricity distribution system was operating typically at the time of measurement; to identify substations and particular types of low-voltage circuits that were near to the location of interest. The questionnaires, masked for case or control status, were assessed by the National Radiological Protection Board.

Entry into phase II, based on the external-sources questionnaire, was determined by the following criteria for England and Wales: a National Grid Company overhead line within 400 m or underground cable located within 100 m of the home; a regional electricity company line of 66 kV or more at various threshold distances of up to 200 m from a home; a regional electricity company line of 11–33 kV at up to 80 m from a home; an operating substation or a phase-separated underground cable of 33 kV or more within 20 m of a home or school; a three-phase 415 V distribution circuit within 2 m of the home; atypical conditions of distribution circuits at the time of the phase I measurement. In Scotland, we used equivalent criteria based on line voltages.

Deprivation index	First-choice controls (%) (n=7632)	Interviewed (%)		EMF measurements (%)	
		Cases (n=3838)	Controls (n=7629)	Cases (n=2226)	Controls (n=2226)
1	14·0	13·8	15·1	15·6	17·1
2	14·3	15·7	15·9	17·2	16·4
3	13·7	15·4	15·2	16·9	16·7
4	14·5	14·5	15·1	15·4	15·8
5	13·9	13·1	13·6	13·0	12·4
6	14·3	13·3	13·0	12·3	12·1
7	15·2	14·2	12·1	9·7	9·5

Table 1: **Distribution of deprivation index**

	ALL	Other leukaemia	Cancer of CNS	Other malignant disease
Age				
All pairs	906 (40·7%)	167 (7·5%)	387 (17·4%)	766 (34·4%)
Age 0–4 years	465 (47·8%)	72 (7·4%)	133 (13·7%)	302 (31·1%)
Age 5–9 years	274 (41·6%)	39 (5·9%)	147 (22·3%)	198 (30·1%)
Age 10–14 years	167 (28·0%)	56 (9·4%)	107 (18·0%)	266 (44·6%)
Sex				
M	515 (40·2%)	90 (7·0%)	198 (15·4%)	479 (37·4%)
F	391 (41·4%)	77 (8·2%)	189 (20·0%)	287 (30·4%)
Deprivation index				
1				
Control	148 (38·9%)	25 (6·6%)	75 (19·7%)	132 (34·7%)
Case	148 (42·5%)	23 (6·6%)	60 (17·2%)	117 (33·6%)
2				
Control	147 (40·2%)	21 (5·7%)	73 (19·9%)	125 (34·2%)
Case	159 (41·6%)	35 (9·2%)	69 (18·1%)	119 (31·2%)
3				
Control	149 (40·1%)	26 (7·0%)	62 (16·7%)	135 (36·3%)
Case	154 (41·0%)	24 (6·4%)	72 (19·1%)	126 (33·5%)
4				
Control	162 (46·2%)	30 (8·5%)	53 (15·1%)	106 (30·2%)
Case	137 (39·9%)	17 (5·0%)	63(18·4%)	126 (36·7%)
5				
Control	101 (36·7%)	25 (9·1%)	47 (17·1%)	102 (37·1%)
Case	118 (40·8%)	20 (6·9%)	47 (16·3%)	104 (36·0%)
6				
Control	114 (42·2%)	19 (7·0%)	40 (14·8%)	97 (35·9%)
Case	109 (39·9%)	20 (7·3%)	43 (15·8%)	101 (37·0%)
7				
Control	85 (40·1%)	21 (9·9%)	37 (17·5%)	69 (32·5%)
Case	81 (37·7%)	28 (13·0%)	33 (15·3%)	73 (34·0%)

ALL=acute lymphoblastic leukaemia; CNS=central nervous system.

Table 2: **Distribution of cases and controls by age, sex, deprivation index, and diagnosis of case**

	<0·1 μT	0·1–<0·2 μT	0·2–<0·4 μT	⩾0·4 μT
Age (years)				
0–4				
Control	891 (91·5%)	63 (6·5%)	16 (1·6%)	4 (0·4%)
Case	893 (91·9%)	59 (6·1%)	17 (1·7%)	3 (0·3%)
5–9				
Control	611 (93·3%)	30 (4·6%)	12 (1·8%)	2 (0·3%)
Case	617 (93·8%)	31 (4·7%)	7 (1·1%)	3 (0·5%)
10–14				
Control	552 (92·5%)	35 (5·9%)	7 (1·2%)	3 (0·5%)
Case	557 (93·5%)	30 (5·0%)	7 (1·2%)	2 (0·3%)
Deprivation index				
1				
Control	360 (94·7%)	14 (3·7%)	4 (1·1%)	2 (0·5%)
Case	335 (96·3%)	12 (3·4%)	0	1 (0·3%)
2				
Control	350 (95·6%)	10 (2·7%)	5 (1·4%)	1 (0·3%)
Case	361 (94·5%)	14 (3·7%)	7 (1·8%)	0
3				
Control	350 (94·1%)	17 (4·6%)	5 (1·3%)	0
Case	358 (95·2%)	14 (3·7%)	3 (0·8%)	1 (0·3%)
4				
Control	321 (91·5%)	22 (6·3%)	5 (1·4%)	3 (0·9%)
Case	312 (91·0%)	26 (7·6%)	4 (1·2%)	1 (0·3%)
5				
Control	252 (91·6%)	20 (7·3%)	2 (0·7%)	1 (0·4%)
Case	264 (91·3%)	17 (5·9%)	7 (2·4%)	1 (0·3%)
6				
Control	234 (86·7%)	27 (10·0%)	8 (3·0%)	1 (0·4%)
Case	243 (89·0%)	26 (9·5%)	2 (0·7%)	2 (0·7%)
7				
Control	187 (88·2%)	18 (8·5%)	6 (2·8%)	1 (0·5%)
Case	194 (90·2%)	11 (5·1%)	8 (3·7%)	2 (0·9%)

Table 3: **Distribution of exposure by age and deprivation status among cases and controls**

The threshold distances used to determine the relevant phase II high-voltage circuits were based on design-rating considerations, and were judged conservative. Typical loads on a regional electricity company line were found to be less than 20% of the circuit rating. Analysis of load data from a sample of National Grid Company circuits during a winter period had shown previously that 50% and 95% of the circuits had average loads of less than 30% and 50%, respectively, of their rating (D C Renew, National Grid Company, personal communication).

External-source questionnaires were also issued for interviewed cases and controls who were either ineligible for EMF measurements (because they had moved house during or since the year of interest) or who were eligible but had declined to participate in this part of the study.

To investigate the possible effects of refusal bias, we issued questionnaires for a random sample of 1000 of the 1582 first-choice controls who had refused to participate in the full study.

To account for potentially large variability in exposure from high-voltage lines and cables, we used load data to reconstruct historical exposure for the year of interest. Line-load data were requested for all overhead lines with voltages of 66 kV or more within threshold distances from the location of interest. Thresholds were used to define magnetic flux density reference levels from annual average load data or circuit rating, together with relative circuit phasing. Similarly, we requested load data for phase-separated underground cables of 66 kV or more located within 20 m of the property. Line-load data for the time of measurement and the year of interest (ie, the year before date of diagnosis or pseudo-diagnosis) were requested. The extent to which data were available varied among electricity companies: 70% of annual load data returned covered all or part of the year of interest; 84% fell within 4 years of diagnosis.

The National Grid Company's EM2D program was used to compute magnetic flux densities generated by overhead lines or underground cables. The program, assessed by the National Radiological Protection Board for the purposes of the study, generated a time-averaged value of magnetic flux density, which was used in the exposure algorithm.

We calculated historical exposure for all cases and controls whose residences and schools met inclusion criteria and for whom line-load data were received. To allow for changes in line loading and circuit configuration between the year of interest and the time of measurement, individuals' exposure measurements were adjusted appropriately.[11] Previous studies examined distance from power lines as a potential indicator of magnetic-field exposure. We took distance into account in selection for phase II and in the historical exposure calculations. Specific information on proximity to power lines will be reported separately.

Because we took heating appliances to contribute to exposure only during winter months, average exposure in the year preceding date of diagnosis was estimated according to the following algorithm: average exposure=$W_1\times$(bed: winter exposure)+$W_2\times$(bed: summer exposure) in year of interest+$W\times$(school exposure)+$W_4\times$(home non-bed exposure).

This algorithm provides an estimate of the arithmetic mean of exposure in the year before diagnosis or pseudo-diagnosis.

The weights (W_1–W_4, $\Sigma W_i=1$) were individually calculated for each child to reflect the time spent in bed and in school, as recorded in the study questionnaire. If any of the information needed to calculate the weights was missing, we used average age-related values. There was no evidence of differential recall between cases and controls; the average value of the total bed exposure weight (W_1+W_2) was 0·46 for cases and controls, and the average weight for school exposure (W_3) was 0·093 for cases and 0·095 for controls.

In phase I, bed and non-bed home exposures were estimated from measurements in appropriate locations covered by a 2 h period. Bed exposure was estimated from the bedroom spot measurements, and the average of the 90 min family-room measurement was used as an estimate of exposure for time not spent in bed or at school. In phase II, bed exposure was estimated by the 48 h measurement. Non-bed home exposure was estimated by the phase I family-room measurement. School exposure was common to phases I and II.

If necessary, we adjusted all home and school exposures for appropriate historical measures and bed-winter exposure for appliance exposure.

About 20% of case-control pairs had phase II measurements. Average annual exposures based on the phase II measurements

	<0·1 μT	<0·1–0·2 μT	⩾0·2 μT	0·2–<0·4 μT	⩾0·4 μT
Acute lymphoblastic leukaemia					
Cases	845	44	17	14	3
Controls	825	63	18	16	2
Odds ratio (95% CI)	1·00	0·69 (0·46–1·02)	0·90 (0·47–1·76)	0·84 (0·41–1·73)	1·40 (0·23–8·40)
Adjusted odds ratio (95% CI)	1·00	0·69 (0·47–1·03)	0·92 (0·47–1·79)	0·84 (0·41–1·74)	1·51 (0·25–9·18)
Total leukaemia					
Cases	995	57	21	16	5
Controls	977	73	23	20	3
Odds ratio (95% CI)	1·00	0·77 (0·54–1·10)	0·89 (0·49–1·61)	0·78 (0·41–1·51)	1·62 (0·39–6·77)
Adjusted odds ratio (95% CI)	1·00	0·78 (0·55–1·12)	0·90 (0·49–1·63)	0·78 (0·40–1·52)	1·68 (0·40–7·10)
Cancers of central nervous system					
Cases	359	25	3	3	0
Controls	371	10	6	4	2
Odds ratio (95% CI)	1·00	2·50 (1·20–2·00)	0·50 (0·13–2·00)	0·75 (0·17–3·35)	..
Adjusted odds ratio (95% CI)	1·00	2·44 (1·17–5·11)	0·46 (0·11–1·86)	0·70 (0·16–3·17)	..
Other malignant disease					
Cases	713	38	15	12	3
Controls	706	45	15	11	4
Odds ratio (95% CI)	1·00	0·84 (0·53–1·31)	0·98 (0·47–2·06)	1·07 (0·45–2·53)	0·75 (0·17–3·35)
Adjusted odds ratio (95% CI)	1·00	0·81 (0·52–1·28)	0·97 (0·46–2·05)	1·08 (0·45–2·56)	0·71 (0·16–3·19)
Total malignant disease					
Cases	2067	120	39	31	8
Controls	2054	128	44	35	9
Odds ratio (95% CI)	1·00	0·93 (0·72–1·20)	0·88 (0·57–1·36)	0·88 (0·54–1·43)	0·89 (0·34–2·29)
Adjusted odds ratio (95% CI)	1·00	0·93 (0·72–1·19)	0·87 (0·56–1·35)	0·87 (0·53–1·42)	0·89 (0·34–2·32)

Table 4: **Odds ratios for acute lymphoblastic leukaemia, all leukaemia, cancers of the central nervous system, and other malignant disease by exposure**

were used in the analysis when available for a case and the corresponding control. If a phase II measurement was available for only one of a case-control pair, we used phase I measurements for both. For the remaining 80% of case-control pairs, the average annual exposure based on the phase I measurement was used. The repeatability of the phase I and phase II measurements is described elsewhere.[11]

The validity of the phase I and phase II estimates, compared with average exposure over a year was assessed in a study done by the National Radiological Protection Board, which will be reported elsewhere.

Statistical analysis

The primary analysis used the estimated arithmetic mean EMF exposure in the year preceding date of diagnosis, confined to matched pairs on whom measurements had been made. The same type of exposure estimate, (ie, whether or not incorporating the phase II measurement) was always used for the cases and controls of each pair. Exposure was divided into four categories (<0·100 μT, 0·100–0·199 μT, 0·200–0·399 μT, and >0·400 μT), based on previously reported results,[6–8] with the primary analysis combining the top two categories. The analysis preserved case and control matching through use of conditional logistic regression. Treatment of confounding variables was based on the definition of a confounder, that it should be associated with both disease and exposure. Variables that may be associated with exposure but for which there is no evidence of relation to disease, causally or through differential selection into the study, were not included as confounding variables. Some selection into the full study based on socioeconomic variables differed between cases and controls.[11] In addition, a weak relation between socioeconomic status and EMF exposure is seen in the control group. We therefore included a measure of socioeconomic status. We based the measure on a census-derived deprivation index.[11] for the census enumeration district containing the child's address at the date of diagnosis or pseudo-diagnosis. The measure is based on unemployment, overcrowding, and car ownership. Danesh and colleagues[15] and Townsend and colleagues[16] have described the usefulness in the UK of small-area-based measures of socioeconomic status instead of measures based on individuals.

We obtained information on proximity to powerlines and the associated line-load information for cases and controls included in the main study for whom no EMF measurements were available, and for some first-choice controls not included in the main study. We analysed this information to find out whether our results, based on measurement, could have been affected by selection bias.

Results

87% of all eligible cases diagnosed in the UKCCS in England, Scotland, and Wales in the defined periods were included, with at least one of the parents interviewed. The corresponding response rate among controls was 64% (figure), with evidence of under-representation of those living in the most deprived census areas. 2226 case-control pairs were eligible for analysis (58% of interviewed case-control sets, 50% of all eligible cases). The main reason for non-inclusion in the EMF part of the study was change of residence in the time between date of diagnosis or pseudo-diagnosis and measurements being taken. The most deprived category, from census-based small-area deprivation indices, was strikingly under-represented, compared with the full set of first-choice controls. Distribution of deprivation classification differed little, however, between the cases and controls with EMF measurements, which showed only slight relative under-representation among controls in the most deprived

Measurements alone	After adjustment				
	<0·1 μT	0·1–<0·2 μT	0·2–<0·4 μT	⩾0·4 μT	Total
Cases					
<0·1 μT	24	0	0	0	24
0·1–<0·2 μT	1	2	0	0	3
0·2–<0·4 μT	0	0	3	0	3
⩾0·4 μT	0	0	1	0	1
Total	25	2	4	0	31
Controls					
<0·1 μT	11	0	0	0	11
0·1–<0·2 μT	1	1	1	0	3
0·2–<0·4 μT	0	0	2	0	2
⩾0·4 μT	0	0	0	1	1
Total	12	1	3	1	17

Table 5: **Estimated exposure before and after adjustment for historical line-load data, among those with relevant external-source questionnaires, for cases and controls**

categories (table 1). Table 2 gives the age and deprivation index distribution by diagnostic category and table 3 the distribution of exposure by age and deprivation index. Exposure seemed not to be age-related, but was moderately associated with deprivation (table 3).

Adjustment for deprivation index had only a small effect on odds ratios for acute lymphoblastic leukaemia, leukaemia, tumours of the central nervous system, other malignant disease, and all malignant disease (table 4). Some participation bias not captured by this index is possible, but that it would have concealed a substantial positive association seems implausible. We did trend tests for the odds ratios for each sub-table; p values ranged from 0·33 to 0·80. There was no evidence, for any category of malignant disease, supporting either of the hypotheses of the EMF study. Compared with the baseline group, who had exposures of less than 0·1 μT, there was no excess among children with exposures of more than 0·2 μT, nor was there any evidence of increasing risk with increasing dose.

The data were examined for children aged 5 years or younger and children aged 6 or older for total leukaemia and for all other malignant disease. Risk did not differ by age.

We made line-load data adjustments for 48 children (80% of requests for load data), and only on one occasion (for a control) was an exposure estimate increased sufficiently, based on line-load data, to cause an upward change in exposure category (table 5). Only eight of 83 children (four cases, four controls) with substantial external-source exposure had exposures of more than 0·2 μT. More cases than controls were included through their proximity to high-voltage power lines (p=0·04, table 5). The entire excess, however, is in the exposure category of less than 0·1 μT. If this difference is true, it does not seem to be related to average exposure.

Of the 170 individuals who had an appliance of interest in the home, only two (one case and one control) changed exposure category when the estimated field from the appliance (electric blanket) was included in the assessment (from lowest to second lowest category). Only three individuals (all controls) were in one of the two highest exposure categories because of exposure at school. All three moved from the lowest category to the second highest.

Among the interviewed cases and first-choice controls for whom EMF measurements were not taken but external-source questionnaires were completed to assess possible bias (2525), only three (two cases and one control) had calculated exposures of more than than 0·2 μT. 970 first-choice controls who refused to participate in the main UKCCS had external-source quesionnaires completed for them, and none had calculated exposures of more than 0·2 μT.

Discussion

We found no evidence that magnetic fields associated with the electricity supply increase risk of childhood leukaemia, malignant brain (or other central nervous system) tumours, or any other childhood cancer.

Of the total number of cases eligible for inclusion in the main UKCCS study, only 50% had EMF measurements, as did only 40% of first-choice controls. Although there was some under-representation of individuals living in more deprived areas among controls compared with cases, the association between deprivation and EMF exposure suggests the observed odds ratios would be even smaller if this category of children had not been under-represented.

We took a stringent approach to the inclusion of confounding variables. Inclusion of many variables, for which there is no good evidence of association with disease, on the basis of algorithms such as stepwise regression, can lead to ambiguity and increase uncertainty.[17] If the number of individuals who have exposures at levels thought to be of interest is small, such effects can be heightened. Given the strength of association that would be required both with EMF exposure and with disease risk, that adjustment by an additional variable could lead to odds ratio significantly greater than 1·00 seems implausible.

The results seen did not seem to depend on the values chosen as cut-off points. For all malignant disease, the adjusted risk for the category 0·050–0·099 μT relative to less than 0·050 μT was 0·89 (0·76–1·03), and for acute lymphoblastic leukaemia it was 0·83 (0·66–1·05). For an exposure category of 0·3 μT or more, the adjusted risk relative to exposure of less than 0·01 μT was 0·79 (0·40–1·56) for all malignant disease and 0·93 (0·30–2·91) for acute lymphoblastic leukaemia.

The degrees of exposure were low compared with those in studies reported from North America, probably because of differences in the operating characteristics of the electricity supply and wiring practices.[18] In the USA,[6] and five Canadian provinces,[8] 11·4% and 15·4% of controls, respectively, had exposures higher than 0·2 μT. In the UKCCS for the total control group, the proportion was 2·3%. In the study reported from Germany, the proportion was 2·0%[7] and in New Zealand,[10] 2·5% of controls had exposures of more than 0·2 μT for bedroom measurements. Consequently, although the UKCCS included more individuals with EMF measurements than other studies, it did not have more individuals in the high-exposure categories than the North American studies did. UKCCS has little power to detect increases in risk at exposures of 0·4 μT or higher. The 95% CI for the adjusted odds ratio for acute lymphoblastic leukaemia in this exposure category was 0·25–9·18; this interval includes all values that could plausibly be true. Only 0·4% of our study population with measurements had exposure at this level.

We focused on the 12 months before diagnosis. If periods earlier in a child's life were important, our results would reflect this association only indirectly. There is no biological evidence, however, to support the view that EMF could have an initiating effect and our results are of direct relevance for effects on the promotion or progression of malignant disease.

The measurements were residence based, rather than based on individual monitoring, and were taken some time after the time period of interest. Both repeatability and validation studies were done. The correlation between repeated phase I measurements was in the range 0·6–0·7 for up to 4 years between measurements. The correlation between phase I and phase II measurements was 0·76 for measurements taken less than 1 year apart, falling to 0·66 for those taken more than 2 years apart.[11] We have assessed the association of phase I and phase II measurements with individual exposure in a study of 100 children who each wore a personal monitor for three 1-week periods over 1 year. The results will be presented elsewhere, but good overall correlation was seen between mean annual personal exposure and phase I and phase II

measurements (T J Mee, National Radiological Protection Board, personal communication). The measurement protocol used in the UKCCS should, therefore, provide adequate surrogate measures of individual exposures in the year preceding diagnosis or pseudo-diagnosis.

Our results are consistent with those of larger studies on childhood leukaemia that used measured fields,[6,8] and population-based studies from Scandinavia of calculated fields.[19–22] Those studies, as well as this study, are consistent with the idea that exposures higher than 0·2 μT do not increase the risk of childhood leukaemia, but there is uncertainty from the other studies as to whether exposures higher than 0·4 μT increase the risk, and our study contributes little evidence. An overview of all available data from studies of childhood leukaemia with measured exposures is underway, based on individual records of residential exposure.

For childhood malignant disease other than leukaemia, data from other studies based on measured fields are sparse. For cancers of the central nervous system, and other malignant disease combined, the UKCCS provides no support for the hypothesis that power-frequency magnetic fields increase the risk of childhood cancer.

A scientific question may still remain about the effect of exposures higher than 0·4 μT. For the vast majority of children in the UK, however, there is now a large body of evidence that the EMF levels to which they are exposed do not increase the risk of leukaemia or other malignant disease.

UKCCS

Management committee—K K Cheng, Central region; N Day, East Anglia region; R Cartwright, A Craft, North East region; J M Birch, O B Eden, North West region; P A McKinney, Scotland; J Peto, South East region; V Beral, E Roman, South Midlands region; P Elwood, South Wales region; F E Alexander, South West region; C E D Chilvers, Trent region; R Doll, Epidemiological Studies Unit, University of Oxford, Oxford; C M Taylor Immunogenetics Laboratory, University of Manchester, Manchester; M Greaves, Leukaemia Research Fund Centre, Institute of Cancer Research; D Goodhead, Radiation and Genome Stability Unit, Medical Research Council, Harwell; F A Fry, Naitonal Radiological Protection Board; G Adams, UK Coordinating Committee for Cancer Research.

Writing Committee—N Day, J Skinner East Anglia region;E Roman, South Midlands region; S G Allen, M P Maslanyj, T J Mee, National Radiological Protection Board.

Regional Investigators—K K Cheng, E Gilman Central region; N Day, J Skinner, D Williams, East Anglia region; R Carwright, A Craft, North East region; J M Birch, O B Eden, North West region; P A McKinney, Scotland; J Deacon, J Peto, South East region; V Beral, E Roman, South Midlands region; P Elwood, South Wales region; F E Alexander, M Mott, South West region; C E D Chilvers, K Muir, Trent region.

Leukaemia Research Fund Data Management Processing Group—R Cartwright, G Law, J Simpson, E Roman.

A complete list of investigators is given in: The United Kingdom Childhood Cancer Study: objectives, material, and methods. *Br J Cancer* (in press).

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