2. Studies of Cancer in Humans

2.1 Exposure assessment in epidemiological studies

2.1.1 *Considerations in assessment of exposure to electric and magnetic fields relevant to epidemiology*

Electric and magnetic fields are complex and many different parameters are necessary to characterize them completely. These parameters are discussed more fully in section 1. In general, they include transients, harmonic content, resonance conditions, peak values and time above thresholds, as well as average levels. It is not known which of these parameters or what combination of parameters, if any, are relevant for carcinogenesis. If there were a known biophysical mechanism of interaction for carcinogenesis, it would be possible to identify the critical parameters of exposure, including relevant timing of exposure. However, in the absence of a generally accepted mechanism for carcinogenesis, most exposure assessments in epidemiological studies are based on a time-weighted average of the field, a measure that is also related to many other characteristics of the fields (Zaffanella & Kalton, 1998).

Exposure to electric and magnetic fields and approaches for exposure assessment have been described in detail in section 1. Some of the characteristics of exposure to electric and magnetic fields which make exposure assessment for the purposes of epidemiological studies particularly difficult are listed below:

- *Prevalence of exposure*. Everyone in the population is exposed to some degree to ELF electric and magnetic fields and therefore exposure assessment has to separate the more from the less exposed individuals, as opposed to the easier task of separating individuals who are exposed from those who are not.
- *Inability of subjects to identify exposure.* Exposure to electric and magnetic fields, whilst ubiquitous, is neither detectable by the exposed person nor memorable, and hence epidemiological studies cannot rely solely on questionnaire data to characterize past exposures adequately.
- *Lack of clear contrast between 'high' and 'low' exposure*. The difference between the electric and magnetic fields to which 'highly exposed' and 'less highly exposed' individuals in a population are subjected is not great. The typical average magnetic fields in homes appear to be about 0.05–0.1 μT. Pooled analyses of childhood leukaemia and magnetic fields, such as that by Ahlbom

et al. (2000), have used ≥ 0.4 μT as a high-exposure category. Therefore, an exposure assessment method has to separate reliably exposures which may differ by factors of only 2 or 4. Even in most of the occupational settings considered to entail 'high exposures' the average fields measured are only one order of magnitude higher than those measured in residential settings (Kheifets *et al.*, 1995).

- *Variability of exposure over time*: *short-term*. Fields (particularly magnetic fields) vary over time-scales of seconds or longer. Assessing a person's exposure over any period involves using a single summary figure for a highly variable quantity.
- *Variability of exposure over time: long-term*. Fields are also likely to vary over time-scales of seasons and years. With the exception of historical data on loads carried by high-voltage power lines, data on such variation are rare. Therefore, when a person's exposure at some period in the past is assessed from data collected later, an assumption has to be made. The usual assumption is that the exposure has not changed. Some authors (e.g. Jackson, 1992; Petridou *et al.*, 1993; Swanson, 1996) have estimated the variations of exposure over time from available data, for example, on electricity consumption. These apply to population averages and are unlikely to be accurate for individuals.
- *Variability of exposure over space*. Magnetic fields vary over the volume of, for example, a building so that, as people move around, they may experience fields of varying intensity. Personal exposure monitoring captures this, but other assessment methods generally do not.

People accumulate exposure to fields in different settings, such as at home, at school, at work, while travelling and outdoors, and there can be great variability of fields between these environments. Current understanding of the contributions to exposure from different sources and in different settings is limited. Most studies make exposure assessments within a single environment, typically at home for residential studies and at work for occupational studies. Some recent studies have included measures of exposure from more than one setting (e.g. Feychting *et al*., 1997; UK Childhood Cancer Study Investigators, 1999; Forssén, 2000).

In epidemiological studies, the distribution of exposures in a population has consequences for the statistical power of the study. Most populations are characterized by an approximately log-normal distribution with a heavy preponderance of low-level exposure and much less high-level exposure. Pilot studies of exposure distribution are important for developing effective study designs.

2.1.2 *Assessing residential exposure to magnetic fields*

(*a*) *Methods not involving measurement*

(i) *Distance*

The simplest possible way of assessing exposure is to record proximity to a facility (such as a power line or a substation) which is likely to be a source of field. This does provide a very crude measure of exposure to both electric and magnetic fields from that source, but takes no account of other sources or of how the fields vary with distance from the source (which is different for different sources). Distances reported by study subjects rather than measured by the investigators tend to be unreliable.

(ii) *Wire code*

Wire coding is a non-intrusive method of classifying dwellings on the basis of their distance from visible electrical installations and the characteristics of these installations. This method does not take account of exposure from sources within the home.

Wertheimer and Leeper (1979) devised a simple set of rules to classify residences with respect to their potential for having a higher than usual exposure to magnetic fields. Their assumptions were simple:

— the field strength decreases with distance from the source;
— current flowing in power lines decreases at every pole from which 'service drop' wires deliver power to houses;
— if both thick and thin conductors are used for lines carrying power at a given voltage, and more than one conductor is present, it is reasonable to assume that more and thicker conductors are required to carry greater currents; and
— when lines are buried in a conduit or a trench, their contribution to exposure can be neglected. This is because buried cables are placed close together and the fields produced by currents flowing from and back to the source cancel each other much more effectively than when they are spaced apart on a cross beam on a pole.

Wertheimer and Leeper (1979) used these four criteria to define two and later four (Wertheimer & Leeper, 1982) then five (Savitz *et al*., 1988) classes of home: VHCC (very high current configuration), OHCC (ordinary high current configuration), OLCC (ordinary low current configuration), VLCC (very low current configuration) and UG (underground, i.e. buried). The houses with the higher classifications were assumed to have stronger background fields than those with lower classifications.

Wire coding, in the original form developed by Wertheimer and Leeper, has been used in a number of studies. Although some relationship between measured magnetic fields and the wire-coding classification is seen in all studies (see for example Table 17 for studies of childhood leukaemia), wiring codes generally misclassify many homes although they do differentiate between high-field homes and others (Kheifets *et al*., 1997a).

Table 17. Typical mean values of time-weighted average magnetic fields (μT) — and percentage of houses > 0.2 μT — associated with wire-code exposure classes from childhood leukaemia studies

Reference, country	Classification	Underground (UG)	Very low (VLCC)	Low (LCC)	High (HCC)	Very high (VHCC)
Savitz *et al.* (1988) [a] USA	No. of observations	133	27	174	88	12
	mean (μT)	0.05	0.05	0.07	0.12	0.21
	% > 0.2 μT	3	0	6	21	60
Tarone *et al.* (1998)[b] USA	No. of homes	150	221	262	170	55
	mean (μT)	0.06	0.08	0.12	0.14	0.2
	% > 0.2 μT	3	6	15	20	40
McBride *et al.* (1999)[c] Canada	No. of residences	127	137	131	164	43
	mean (μT)	0.09	0.08	0.11	0.17	0.26
Green *et al.* (1999a)[d] Canada	No. of measurements	66	9	25	19	6
	mean (μT)	0.07	0.04	0.14	0.18	0.38
	SD	0.06	0.02	0.1	0.2	0.3
London *et al.* (1991) [e] USA	No. of measurements	19	20	94	108	50
	mean (μT)	0.05	0.05	0.07	0.07	0.12
	% > 0.25 μT	0.3	3.7	11.6	6.4	16.6

[a] Childhood cancer. Magnetic fields measured under low power use conditions
[b] 24-h magnetic field measurements in the bedroom
[c] 24-h magnetic field measurements (child's bedroom); % > 0.2 μT not reported
[d] Personal monitoring of controls; SD, standard deviation
[e] 24-h measurements

The concept of wire coding, that is, assessing residential exposure on the basis of the observable characteristics of nearby electrical installations, has been shown to be a usable surrogate when tailored to local wiring practices. However, the so-called Wertheimer and Leeper wire code may not be an adequate surrogate in every environment (see Table 17). In general, wire codes have been used only in North American studies, as their applicability is limited in other countries where power drops to homes are mostly underground.

(iii) *Calculated historical fields*

Feychting and Ahlbom (1993) carried out a case–control study nested in a cohort of residents living in homes within 300 m of power lines in Sweden. The geometry of the conductors on the power line, the distance of the houses from the power lines and historical records of currents, were all available. This special situation allowed the investigators to calculate the fields to which the subjects' homes were exposed at various times (e.g. prior to diagnosis) (Kheifets *et al.*, 1997a).

The common elements between wire coding and the calculation model used by Feychting and Ahlbom (1993) are: the reliance on the basic physical principles that the field increases with the current and decreases with the distance from the power line, and the fact that both neglect magnetic-field sources other than visible power lines. There is, however, one important difference: in the Wertheimer and Leeper code, the line type and thickness are a measure of the *potential* current carrying capacity of the line. In the Feychting and Ahlbom (1993) study, the approximate yearly average current was obtained from utility records; thus the question of temporal stability of the estimated fields did not even arise: assessment carried out for different times, using different load figures, yielded different estimates.

The approach of Feychting and Ahlbom (1993) has been used in various Nordic countries and elsewhere, although the likely accuracy of the calculations has varied depending in part on the completeness and precision of the available information on historical load. The necessary assumption that other sources of field are negligible is reasonable only for subjects relatively close to high-voltage power lines. The validity of the assumption also depends on details such as the definition of the population chosen for the study and the size of average fields from other sources to which the relevant population is exposed.

There is some evidence from Feychting and Ahlbom (1993) that their approach may work better for single-family homes than for apartments. When Feychting and Ahlbom (1993) validated their method by comparing calculations of present-day fields with present-day measurements, they found that virtually all homes with a measured field < 0.2 μT, whether single-family or apartments, were correctly classified by their calculations. However, for homes with a measured field > 0.2 μT, the calculations were able to classify correctly [85%] of single-family homes, but nearly half of the apartments were misclassified.

The difference between historical calculations and contemporary measurements was also evaluated by Feychting and Ahlbom (1993) who found that calculations using contemporary current loads resulted in a [45%] increase in the fraction of single-family homes estimated to have a field > 0.2 μT, compared with calculations based on historical data. If these calculations of historical fields do accurately reflect exposure, this implies that present-day spot measurements overestimate the number of exposed homes in the past.

(*b*) *Methods involving measurement*

Following the publication of the Wertheimer and Leeper (1979, 1982) studies, doubt was cast on the reported association between cancer and electrical wiring configurations on the grounds that exposure had not been 'measured'. Consequently, many of the later studies included measurements of various types.

All measurements have the advantage that they capture exposure from whatever sources are present, and do not depend on prior identification of sources, as wire codes and calculated fields do. Furthermore, because measurements can classify fields on a continuous scale rather than in a limited number of categories, they provide greater scope for investigating different thresholds and exposure–response relationships.

(i) *Spot measurements in the home*

The simplest form of measurement is a reading made at a point in time at one place in a home. To capture spatial variations of field, some studies have made multiple spot measurements at different places in or around the home. In an attempt to differentiate between fields arising from sources inside and outside the home, some studies have made spot measurements under 'low-power' (all appliances turned off) and 'high-power' (all appliances turned on) conditions. Neither of these alternatives truly represents the usual exposure conditions in a home, although the low-power conditions are closer to the typical conditions.

The major drawback of spot measurements is their inability to capture temporal variations. As with all measurements, spot measurements can assess only contemporary exposure, and can yield no information about historical exposure, which is an intrinsic requirement for retrospective studies of cancer risk. An additional problem of spot measurements is that they give only an approximation even for the contemporary field, because of short-term temporal variation of fields, and unless repeated throughout the year do not reflect seasonal variations.

A number of authors have compared the time-stability of spot measurements over periods of up to five years (reviewed in Kheifets *et al*., 1997a; UK Childhood Cancer Study Investigators, 2000a). The correlation coefficients reported were from 0.7–0.9, but even correlation coefficients this high may result in significant misclassification (Neutra & DelPizzo, 1996).

(ii) *Longer-term measurements in homes*

Because spot measurements capture short-term temporal variability poorly, many studies have measured fields at one or more locations for longer periods, usually 24–48 h, most commonly in a child's bedroom, which is an improvement on spot measurements. Comparisons of measurements have found only a poor-to-fair agreement between long-term and short-term measurements. This was mainly because short-term increases in fields caused by appliances or indoor wiring do not affect the average field measured over many hours (Schüz *et al*., 2000).

Measurements over 24–48 h cannot account for longer-term temporal variations. One study (UK Childhood Cancer Study Investigators, 1999) attempted to adjust for longer-term variation by making 48-h measurements, and then, for subjects close to high-voltage power lines, modifying the measurements by calculating the fields using historical load data. In a study in Germany, Schüz *et al*. (2001a) identified the source of elevated fields by multiple measurements, and attempted to classify these sources as to the likelihood of their being stable over time. Before beginning the largest study in the USA (Linet *et al*., 1997), a pilot study was conducted (Friedman *et al*., 1996) to establish the proportion of their time children of various ages spent in different parts of the home. These estimates were used to weight the individual room measurements in the main study (Linet *et al*., 1997) for the time-weighted average measure. In addition, the pilot study documented that magnetic fields in dwellings rather than schools accounted for most of the variability in children's exposure to magnetic fields.

(iii) *Personal exposure monitoring*

Monitoring the personal exposure of a subject by a meter worn on the body is attractive because it captures exposure to fields from all sources. Because all sources are included, the average fields measured tend to be higher than those derived from spot or long-term measurements. However, the use of personal exposure monitoring in case–control studies could be problematic, due to age- or disease-related changes in behaviour. The latter could introduce differential misclassification in exposure estimates. However, personal exposure monitoring can be used to validate other types of measurements or estimates.

(*c*) *Assessment of exposure to ELF electric and magnetic fields from appliances*

The contribution to overall exposure by appliances depends, among other things, on the type of appliance, its age, its distance from the person using it, and the pattern and duration of use. Epidemiological studies have generally relied on questionnaires, sometimes answered by proxies such as other household members (Mills *et al.*, 2000). These questionnaires ascertain some (but not usually all) of these facts, and are subject to recall bias. It is not known how well data from even the best questionnaire approximate to the actual exposure. Mezei *et al*. (2001) reported that questionnaire-based information on appliance use, even when focused on use within the last year, has limited value in estimating personal exposure to magnetic fields. Some limited attempts have been made (e.g. UK Childhood Cancer Study Investigators, 1999) to include some measurements as well as questionnaire data.

Because exposure to magnetic fields from appliances tends to be short-term and intermittent, the appropriate method for combining assessments of exposure from different appliances and chronic exposure from other sources would be particularly dependent on assumptions made about exposure metrics. Such methods have yet to be developed.

2.1.3 *Assessing occupational exposure to magnetic fields*

Following Wertheimer and Leeper's report of an association between residential magnetic fields and childhood leukaemia, Milham (1982, 1985a,b) noted an association between cancer and some occupations (often subsequently called the 'electrical occupations') intuitively expected to involve proximity to sources of electric and magnetic fields. However, classification based on job title is a very coarse surrogate. Critics (Loomis & Savitz, 1990; Guénel *et al.*, 1993a; Thériault *et al.*, 1994) have pointed out that, for example, many electrical engineers are basically office workers and that many electricians work on disconnected wiring.

Intuitive classification of occupations by investigators can be improved upon by taking account of judgements made by appropriate experts (e.g. Loomis *et al*., 1994a), and by making measurements in occupational groups (e.g. Bowman *et al*., 1988).

A further improvement is a systematic measurement programme to characterize exposure in a range of jobs corresponding as closely as possible to those of the subjects in a study, thus creating a 'job–exposure matrix', which links measurement data to job titles.

Despite the improvements in exposure assessment, the ability to explain exposure variability in complex occupational environments remains poor. Job titles alone explain only a small proportion of exposure variability. A consideration of the work environment and of the tasks undertaken by workers in a specific occupation leads to a more precise estimate (Kelsh *et al.*, 2000). Harrington *et al*. (2001) have taken this approach one stage further by combining job information with historical information not only on the environment in general but on specific power stations and substations. The within-worker and between-worker variability which account for most of the variation are not captured using these assessments.

It should be noted that even the limited information that is available on occupational exposure is confined almost entirely to the so-called electrical occupations and the power utility workforce. There is evidence (Zaffanella & Kalton, 1998) that workers in some non-electrical occupations are among those most heavily exposed to magnetic fields.

In addition to the need for correct classification of jobs, the quality of occupational exposure assessment depends on the details of work history available to the investigators. The crudest assessments are based on a single job (e.g. as mentioned on a death certificate). This assessment can be improved by identifying the job held for the longest period, or even better, by obtaining a complete job history which would allow for the calculation of the subject's cumulative exposure often expressed in μT–years.

2.1.4 *Assessing exposure to electric fields*

Assessment of exposure to electric fields is generally even more difficult and less well developed than the assessment of exposure to magnetic fields. All of the difficulties encountered in assessment of exposure to magnetic fields discussed above also apply to electric fields. In addition, electric fields are easily perturbed by any conducting object, including the human body. Therefore, the very presence of subjects in an environment means that they are not being exposed to an 'unperturbed field' although most studies that have assessed electric fields have attempted to assess the unperturbed field.

2.2 Cancer in children

2.2.1 *Residential exposure*

(*a*) *Descriptive studies*

In an ecological study in Taiwan, Lin and Lee (1994) observed a higher than expected incidence of childhood leukaemia in five districts in the Taipei Metropolitan Area where a high-voltage power line passed over at least one elementary school campus (standardized incidence ratio [SIR], 1.5; 95% CI, 1.2–1.9; based on 67 cases) for the period 1979–88. In a re-analysis, Li *et al*. (1998) focused on the three districts densely scattered with high-voltage power lines during the period 1987–92 and found an SIR of 2.7 (95% CI, 1.1–5.6) on the basis of seven observed cases versus 2.6 expected cases in all children in Taiwan, living within a distance of 100 m from an overhead power line.

Milham and Ossiander (2001) hypothesized that the emergence of the peak in incidence of acute lymphoblastic leukaemia in children aged 3–4 years may be due to exposure to ELF electric and magnetic fields. The authors examined state mortality rates in the USA during the years 1928–32 and 1949–51 and related this to the percentage of residences within each state with an electricity supply. The peak incidence of acute lymphoblastic leukaemia in children appeared to have developed earlier in those states in which more homes were connected earlier to the electricity supply.

(*b*) *Cohort study*

The only cohort study of childhood cancer and magnetic fields (see Table 18) was conducted by Verkasalo *et al*. (1993) in Finland. The study examined the risk of cancer in children living at any time from 1970–89 within 500 m of overhead high-voltage power lines (110–400 kV), where average magnetic fields were calculated to be ≥ 0.01 μT. The cohort comprised 68 300 boys and 66 500 girls under the age of 20 (contributing 978 100 person–years). During the observation period of 17 years, a total of 140 patients with childhood cancer (35 children with leukaemia, 39 with a tumour of the central nervous system, 15 with a lymphoma and 51 with other malignant tumours) were identified by the Finnish Cancer Registry. Historical magnetic fields were estimated for each year from 1970–89 by the Finnish power company. The dwellings of each child were ascertained from the central population registry and the shortest distance to nearby power lines was calculated by using exact coordinates of homes and power lines. Additional variables used in the calculation of the magnetic field strength were the current flow and the location of phase conductors of each power line. Point estimates of average annual currents for 1984–89 were generated by a power system simulator; information on existing line load was available for 1977–83; and data on power consumption from 1977, corrected for year of construction of power lines, were used to estimate current flow for the years 1970–76. Cumulative exposure was defined as the average exposure per year multiplied by the number of years of exposure (μT–years).

Table 18. Cohort study of childhood cancer and exposure to ELF magnetic fields

Study size, number of cases	Exposure	SIR (95% CI) by cancer site									
		Leukaemia	No. of cases	CNS	No. of cases	Lymphoma	No. of cases	Other sites	No. of cases	All cancers	No. of cases
68 300 boys, 66 500 girls, aged 0–19 years; 140 incident cancer cases diagnosed 1970–89	**Calculated historical magnetic fields**										
	< 0.01 µT (baseline)	1.0		1.0		1.0		1.0		1.0	
	0.01–0.19 µT	0.89 (0.61–1.3)	32	0.85 (0.59–1.2)	34	0.91 (0.51–1.5)	15	1.1 (0.79–1.4)	48	0.94 (0.79–1.1)	129
	≥ 0.2 µT	1.6 (0.32–4.5)	3	2.3 (0.75–5.4)	5	0 (0.0–4.2)	0	1.2 (0.26–3.6)	3	1.5 (0.74–2.7)	11
	Calculated cumulative magnetic fields (µT–years)										
	< 0.01 (baseline)	1.0		1.0		1.0		1.0		1.0	
	0.01–0.39	0.90 (0.62–1.3)	32	0.82 (0.56–1.2)	32	0.88 (0.48–1.5)	14	1.1 (0.80–1.4)	47	0.93 (0.78–1.1)	125
	≥ 0.4	1.2 (0.26–3.6)	3	2.3 (0.94–4.8)	7	0.64 (0.02–3.6)	1	1.0 (0.27–2.6)	4	1.4 (0.77–2.3)	15

From Verkasalo *et al.* (1993), Finland
SIR, standardized incidence ratio; CI, confidence interval; CNS, central nervous system
Expected numbers calculated in sex-specific five-year age groups; no further adjustments. SIRs for highest exposure categories for CNS tumours are questionable, since one boy with three primary tumours was counted three times.

The cut-points chosen to indicate high exposure were ≥ 0.2 μT for average exposure and ≥ 0.4 μT–years for cumulative exposure. The expected number of cases was calculated in five-year age groups by multiplying the stratum-specific number of person–years by the corresponding cancer incidence in Finland. No effect modifiers were considered. Standardized incidence ratios for children exposed to magnetic fields of ≥ 0.2 μT were 1.6 (95% CI, 0.32–4.5) for leukaemia, 2.3 (95% CI, 0.75–5.4) for tumours of the central nervous system (all in boys) and 1.5 (95% CI, 0.74–2.7) for all cancers combined. No child exposed to magnetic fields was diagnosed with lymphoma versus 0.88 expected. The corresponding SIRs with cumulative exposure of ≥ 0.4 μT–years were 1.2 (95% CI, 0.26–3.6) for leukaemia, 2.3 (95% CI, 0.94–4.8) for tumours of the central nervous system, 0.64 (95% CI, 0.02–3.6) for lymphoma and 1.4 (95% CI, 0.77–2.3) for all cancers, respectively. The SIRs in the intermediate category for each metric (0.01–< 0.2 μT, average exposure; 0.01–< 0.4 μT–years, cumulative exposure) were below unity. The SIRs for tumours of the central nervous system require careful interpretation, since one 18-year-old boy with three primary brain tumours and neurofibromatosis type 2 was counted as three cases. If this child were considered as one case, the number of cases of tumours of the central nervous system in exposed children would be reduced from five to three.

(*c*) *Case–control studies*

A number of case–control studies of childhood leukaemia and ELF electric and magnetic fields have been published.

The results of these studies by tumour type (leukaemia and central nervous system) and by magnetic and electric fields are shown in Tables 19–21. The tables show only studies that contributed substantially to the overall summary and only the results of a-priori hypotheses are presented.

The first study of ELF electric and magnetic fields and childhood cancer was conducted in Denver, CO, USA (Wertheimer & Leeper, 1979). The population base consisted of children born in Colorado who resided in the greater Denver area between 1946 and 1973. The cases were all children aged less than 19 years who had died from cancer between 1950 and 1973 (n = 344), including 155 children with leukaemias and 66 with brain tumours, 44 with lymphomas and 63 with cancers of other sites. The controls (n = 344) were selected from two sources: Denver-area birth certificates and listings of all births in Colorado during the time period. Exposure was assessed by using diagrams to characterize electrical wiring configurations near the dwelling occupied by the child at birth and that occupied two years prior to death, or the corresponding dates for matched controls. The wiring was classified as having a high or low current configuration (HCC or LCC). Potential confounding was evaluated by examining the results within strata by age, birth order, social class, urban versus suburban, and heavy traffic areas versus lighter traffic areas. Point estimates were not reported, but p values calculated from chi-square tests were given. The percentage of children living in HCC homes two years before death was 41%, 41% and 46% for

Table 19. Case–control studies of childhood leukaemia and exposure to ELF magnetic fields[a]

Reference, area	Study size (for analyses)	Exposure	No. of cases	Risk estimates: odds ratio (95% CI)	Comments
Wertheimer & Leeper (1979), Denver, CO, USA	155 deceased cases, 155 controls, aged 0–19 years	**Wire code**			No risk estimates presented; lack of blinding for the exposure assessment; hypothesis-generating study
		LCC	92 (126 controls)		
		HCC	63 (29 controls)		
London *et al*. (1991), Los Angeles County, CA, USA	*Wire code*: 211 cases, 205 controls; *24-h measurements*: 164 cases, 144 controls, aged 0–10 years	**Wire code**			Matched analysis, no further adjustments; low response rates for measurements; no wire coding of subjects who refused to participate
		UG/VLCC (baseline)	31	1.0	
		OLCC	58	0.95 (0.53–1.7)	
		OHCC	80	1.4 (0.81–2.6)	
		VHCC	42	2.2 (1.1–4.3)	
		Mean magnetic fields (24-h bedroom measurement)			
		< 0.067 μT (baseline)	85	1.0	
		0.068–0.118 μT	35	0.68 (0.39–1.2)	
		0.119–0.267 μT	24	0.89 (0.46–1.7)	
		≥ 0.268 μT	20	1.5 (0.66–3.3)	
Feychting & Ahlbom (1993), Sweden (corridors along power lines)	39 cases, 558 controls, aged 0–15 years	**Calculated historical magnetic fields**			Adjusted for sex, age, year of diagnosis, type of house, Stockholm county (yes/no); in subsequent analysis also for socioeconomic status and air pollution from traffic; no contact with subjects required
		< 0.1 μT (baseline)	27	1.0	
		0.1–0.19 μT	4	2.1 (0.6–6.1)	
		≥ 0.2 μT	7	2.7 (1.0–6.3)	

Table 19 (contd)

Reference, area	Study size (for analyses)	Exposure	No. of cases	Risk estimates: odds ratio (95% CI)	Comments
Olsen *et al*. (1993), Denmark	833 cases, 1666 controls, aged 0–14 years	**Calculated historical magnetic fields**			Adjusted for sex and age at diagnosis; socioeconomic status, distribution similar between cases and controls; no contact with subjects required
		< 0.1 μT (baseline)	829	1.0	
		0.1–0.24 μT	1	0.5 (0.1–4.3)	
		≥ 0.25 μT	3	1.5 (0.3–6.7)	
Tynes & Haldorsen (1997), Norway (census wards crossed by power lines)	148 cases, 579 controls, aged 0–14 years	**Calculated historical magnetic fields**			Adjusted for sex, age and municipality, also for socioeconomic status, type of house, and number of dwellings; no contact with subjects required
		< 0.05 μT (baseline)	139	1.0	
		0.05–< 0.14 μT	8	1.8 (0.7–4.2)	
		≥ 0.14 μT	1	0.3 (0.0–2.1)	
Michaelis *et al*. (1998), Lower Saxony and Berlin (Germany)	176 cases, 414 controls, aged 0–14 years	**Median magnetic fields (bedroom 24-h measurement)**			Adjusted for sex, age and part of Germany (East, West), socioeconomic status and degree of urbanization; information on a variety of potential confounders was available; low response rates
		< 0.2 μT (baseline)	167	1.0	
		≥ 0.2 μT	9	2.3 (0.8–6.7)	

Table 19 (contd)

Reference, area	Study size (for analyses)	Exposure	No. of cases	Risk estimates: odds ratio (95% CI)	Comments
McBride *et al.* (1999), five Canadian provinces, subjects living within 100 km of major cities, Canada	*Personal monitoring*: 293 cases, 339 controls, aged 0–14 years	**Personal monitoring (48-h)**			Adjusted for age, sex, province, maternal age at birth of child, maternal education, family income, ethnicity and number of residences since birth; information on a variety of potential confounding factors was available; relatively low response rates for the personal monitoring portion; children with Down syndrome excluded from this study
		< 0.08 µT (baseline)	149	1.0	
		0.08–< 0.15 µT	67	0.57 (0.37–0.87)	
		0.15–< 0.27 µT	45	1.1 (0.61–1.8)	
		≥ 0.27 µT	32	0.68 (0.37–1.3)	
	Wire code: 351 cases, 362 controls	**Wire code**			
		UG (baseline)	79	1.0	
		VLCC	73	0.70 (0.41–1.2)	
		OLCC	77	0.76 (0.45–1.3)	
		OHCC	83	0.64 (0.38–1.1)	
		VHCC	39	1.2 (0.58–2.3)	
UKCCSI (1999), England, Wales and Scotland	1073 cases, 1073 controls, aged 0–14 years	**Time-weighted average magnetic fields (1.5–48-h measurement)**			Adjusted for sex, date of birth and region, also for socioeconomic status; information on a variety of potential confounders was available; low reponse rates
		< 0.1 µT (baseline)	995	1.0	
		0.1–< 0.2 µT	57	0.78 (0.55–1.1)	
		≥ 0.2 µT	21	0.90 (0.49–1.6)	
		0.2–< 0.4 µT	16	0.78 (0.40–1.5)	
		≥ 0.4 µT	5	1.7 (0.40–7.1)	

Table 19 (contd)

Reference, area	Study size (for analyses)	Exposure	No. of cases	Risk estimates: odds ratio (95% CI)	Comments
Schüz *et al*. (2001a), West Germany	514 cases, 1301 controls, aged 0–14 years	**Median magnetic fields (24-h bedroom measurement)**			Adjusted for sex, age, year of birth, socioeconomic status and degree of urbanization; information on a variety of potential confounders was available; low response rates; relatively long time lag between date of diagnosis and date of the measurement
		< 0.1 μT (baseline)	472	1.0	
		0.1–< 0.2 μT	33	1.2 (0.73–1.8)	
		0.2–< 0.4 μT	6	1.2 (0.43–3.1)	
		≥ 0.4 μT	3	5.8 (0.78–43)	
		Night-time magnetic fields			
		< 0.1 μT (baseline)	468	1.0	
		0.1–< 0.2 μT	34	1.4 (0.90–2.2)	
		0.2–< 0.4 μT	7	2.5 (0.86–7.5)	
		≥ 0.4 μT	5	5.5 (1.2–27)	

Table 19 (contd)

Reference, area	Study size (for analyses)	Exposure	No. of cases	Risk estimates: odds ratio (95% CI)	No. of cases	Risk estimates: odds ratio (95% CI)	Comments
Linet *et al*. (1997), nine mid-western and mid-Atlantic states, USA	*Wire code*: 408 cases, 408 controls, aged 0–14 years; *24-h measurements*: 638 cases, 620 controls	**Time-weighted average (24-h bedroom measurement plus spot measurements in two rooms)**		Unmatched		Matched	Unmatched analysis additionally adjusted for age, sex, mother's education and family income; information on a variety of potential confounding factors was available; wire coding of subjects who refused to participate; relatively low response rates for the measurements in controls; only acute lymphoblastic leukaemia; children with Down syndrome excluded from this study (Schüz *et al*., 2001a)
		< 0.065 μT (baseline)	267	1.0	206	1.0	
		0.065–0.099 μT	123	1.1 (0.81–1.5)	92	0.96 (0.65–1.4)	
		0.100–0.199 μT	151	1.1 (0.83–1.5)	107	1.2 (0.79–1.7)	
		≥ 0.200 μT	83	1.2 (0.86–1.8)	58	1.5 (0.91–2.6)	
		Wire code					
		UG/VLCC (baseline)			175	1.0	
		OLCC			116	1.1 (0.74–1.5)	
		OHCC			87	0.99 (0.67–1.5)	
		VHCC			24	0.88 (0.48–1.6)	

UG, underground wires; VLCC, very low current configuration; OLCC, ordinary low current configuration; OHCC, ordinary high current configuration; VHCC, very high current configuration; LCC, low current configuration; HCC, high current configuration; UKCCSI, UK Childhood Cancer Study Investigators

[a] In these tables, only studies that contributed substantially to the overall summary were considered; only results that were part of the analysis strategy defined above are presented; exposure metrics and cut-points vary across studies, for a better comparison, please refer to Table 23.

Table 20. Case–control studies of childhood tumours of the central nervous system and exposure to ELF magnetic fields

Reference, area	Study size	Exposure	No. of cases	Risk estimates: odds ratio (95% CI)	Comments
Wertheimer & Leeper (1979), Denver, CO, USA	66 deceased cases, 66 controls, aged 0–19 years	**Wire code**			No risk estimates presented; lack of blinding for the exposure assessment; hypothesis-generating study
		LCC	36 (49 controls)		
		HCC	30 (17 controls)		
Feychting & Ahlbom (1993), Sweden (corridors along power lines)	33 cases, 558 controls, aged 0–15 years	**Calculated historical magnetic fields**			Adjusted for sex, age, year of diagnosis, type of house, Stockholm county (yes/no); in subsequent analysis also for socioeconomic status and air pollution from traffic; no contact with subjects required
		< 0.1 μT (baseline)	29	1.0	
		0.1–0.19 μT	2	1.0 (0.2–3.8)	
		≥ 0.2 μT	2	0.7 (0.1–2.7)	
Olsen *et al*. (1993), Denmark	624 cases, 1872 controls, aged 0–14 years	**Calculated historical magnetic fields**			Adjusted for sex and age at diagnosis; socioeconomic distribution similar among cases and controls; no contact with subjects required
		< 0.1 μT (baseline)	621	1.0	
		0.1–0.24 μT	1	1.0 (0.1–9.6)	
		≥ 0.25 μT	2	1.0 (0.2–5.0)	
Preston-Martin *et al*. (1996a), Los Angeles County, CA, USA	298 cases, 298 controls, aged 0–19 years	**Mean magnetic fields (24-h bedroom)**			Adjusted for age, sex, birth year, socioeconomic status, maternal waterbed use; low response rates for measurements
		0.010–0.058 μT (baseline)	48	1.0	
		0.059–0.106 μT	29	1.5 (0.7–3.0)	
		0.107–0.248 μT	16	1.2 (0.5–2.8)	
		0.249–0.960 μT	13	1.6 (0.6–4.5)	
		Wire code			
		UG	39	2.3 (1.2–4.3)	
		VLCC/OLCC (baseline)	114	1.0	
		OHCC	97	0.8 (0.6–1.2)	
		VHCC	31	1.2 (0.6–2.2)	

Table 20 (contd)

Reference, area	Study size	Exposure	No. of cases	Risk estimates: odds ratio (95% CI)	Comments
Gurney *et al*. (1996), Seattle, WA, USA	133 cases, 270 controls, aged 0–19 years	**Wire code**			Unadjusted, but evaluated for confounding by age, sex, race, county, reference year, mother's education, family history of brain tumours, passive smoking, farm residence, history of head injury, X-rays, epilepsy
		UG (baseline)	47	1.0	
		VLCC	39	1.3 (0.7–2.1)	
		OLCC	11	0.7 (0.3–1.6)	
		OHCC	19	1.1 (0.6–2.1)	
		VHCC	4	0.5 (0.2–1.6)	
Tynes & Haldorsen (1997), Norway (census wards crossed by power lines)	156 cases, 639 controls, aged 0–14 years	**Historical calculated magnetic fields**			Adjusted for sex, age and municipality, also for socioeconomic status, type of house, and number of dwellings; no contact with subjects required
		< 0.05 μT (baseline)	144	1.0	
		0.05–< 0.14 μT	8	1.9 (0.8–4.6)	
		≥ 0.14 μT	4	0.7 (0.2–2.1)	
UKCCSI (1999), England, Wales and Scotland	387 cases, 387 controls, aged 0–14 years	**Time-weighted average magnetic fields (1.5–48-h measurement)**			Adjusted for sex, date of birth, and region, also for socioeconomic status; information on a variety of potential confounders was available; low reponse rates; no exposure to magnetic fields ≥ 0.4 μT
		< 0.1 μT (baseline)	359	1.0	
		0.1–< 0.2 μT	25	2.4 (1.2–5.1)	
		≥ 0.2 μT	3	0.46 (0.11–1.9)	
		0.2–< 0.4 μT	3	0.70 (0.16–3.2)	
Schüz *et al*. (2001b), Lower Saxony and Berlin (Germany)	64 cases, 414 controls, aged 0–14 years	**Median magnetic fields (24-h bedroom measurement)**			Adjusted for sex, age, part of Germany (East, West), socioeconomic status and degree of urbanization; information on a variety of potential confounders was available; low response rates; same control group as for leukaemia cases (Michaelis *et al*., 1998)
		< 0.2 μT (baseline)	62	1.0	
		≥ 0.2 μT	2	1.7 (0.32–8.8)	

UG, underground wires; VLCC, very low current configuration; OLCC, ordinary low current configuration; OHCC, ordinary high current configuration; VHCC, very high current configuration; UKCCSI, UK Childhood Cancer Study Investigators

Table 21. Case–control studies of childhood leukaemia and exposure to ELF electric fields

Reference, area	Study size (for analyses)	Exposure	No. of cases	Risk estimates: odds ratio (95% CI)	Comments
London *et al*. (1991), Los Angeles County, CA, USA	**Spot measurements (child's bedroom)** 136 cases, 108 controls, aged 0–10 years	< 50th percentile (baseline) 50–74th percentile (baseline) 75–89th percentile (baseline) ≥ 90th percentile (baseline)	NR	1.0 0.66 (0.36–1.2) 1.1 (0.58–2.6) 0.44 (0.19–1.0)	Matched analysis, no further adjustments; low response rates for measurements; no wire coding of subjects who refused to participate
McBride *et al*. (1999), five Canadian provinces, subjects living within 100 km of major cities, Canada	**Personal monitoring** 274 cases, 331 controls, aged 0–14 years	< 12.2 V/m (baseline) 12.2–< 17.2 V/m 17.2–< 24.6 V/m 24.6–64.7 V/m	143 64 39 28	1.0 0.79 (0.51–1.2) 0.76 (0.45–1.2) 0.82 (0.45–1.5)	Adjusted for age, sex, province, maternal age at birth of child, maternal education, family income, ethnicity and number of dwellings since birth; children with Down syndrome excluded from this study

NR, not reported

children with leukaemia, lymphoma and brain tumours, respectively, compared with 19%, 25% and 26% in the controls. Forty-four per cent of 109 cases and 20.3% of 128 controls with stable dwellings had HCC wiring configurations ($p < 0.001$). The results were similar when birth addresses were used. When exposure was further subdivided into the categories of substation (highest exposure), other HCC, LCC except end poles and end poles, the percentage of children with cancer declined with lower wiring configuration. The results also appeared to be fairly consistent within broad categories of potential confounding variables. [The Working Group noted that the wire-coding technicians in this study were not blinded as to the status of cases or controls leading to potential bias in exposure assessment.]

Fulton *et al*. (1980) conducted a case–control study in Rhode Island, USA. Patients with leukaemia aged between 0 and 20 years were identified from the records of the Rhode Island Hospital from 1964–78. Out of 155 cases, a total of 119 were selected and 36 cases who had resided out of the state for part of the eight years preceding diagnosis were excluded. The analysis was based on dwellings, not individuals, and 209 case dwellings were included. Two hundred and forty control addresses were selected from Rhode Island birth certificates. Two controls were matched to each case on year of birth. The authors obtained complete address histories for cases, but not for controls. Exposure assessment consisted of mapping the power lines situated within 50 yards (45.72 m) of each residence and categorizing the expected current according to a method of wire coding. A total of 95% of case and 94% of control addresses were successfully mapped. The association between exposure category and childhood leukaemia was tested by means of chi-square tests. The analysis showed no relationship between childhood leukaemia and exposure category. [The Working Group noted that the shortcomings of this study include lack of comparability of cases and controls, analysis by dwelling as opposed to by individual and the lack of control for confounding.]

The first European study on childhood leukaemia and exposure to magnetic fields was carried out in Sweden (Tomenius, 1986). The study included children aged between 0 and 18 years with benign and malignant tumours. The children had been born and diagnosed in the county of Stockholm and were registered with the Swedish Cancer Registry during the years 1958–73. A total of 716 children of whom 660 had a malignant tumour were included. For each case, a control matched for sex, age and church district of birth was selected from birth registration records held in the same parish office. The controls had been born just before or after the child with a tumour and still lived in Stockholm county at the date of diagnosis of the corresponding case. The analysis was based on dwellings rather than individuals. A total of 1172 dwellings were included for cases and 1015 dwellings for controls. Almost all (96%) dwellings were visited to determine their proximity to different types of electrical installation (200-kV power lines, 6–< 200-kV power lines, substations, transformers, electric railways, underground railways). Spot measurements of peak magnetic field were conducted outside the entrance door. From magnetic field measurements, the odds ratios in those children exposed to magnetic fields of ≥ 0.3 μT were 0.3 for leukaemia, 1.8 for lymphoma, 3.7 for cancer of the central nervous system ($p < 0.05$) and 2.1 for all tumours combined ($p < 0.05$). An excess tumour risk was also reported for children living less than 150 m from a 200-kV power line, but this was because the observed number of case dwellings located 100–150 m from a power line was higher than expected, while the number of case dwellings located within 100 m from a power line was as expected. [The Working Group noted that outdoor spot measurements, sometimes made more than 30 years after the etiologically relevant time period, are a poor proxy for an individual's exposure to magnetic fields. Another limitation is that the analyses are based on dwellings rather than individuals, and that the numbers of dwellings were different for cases and controls.]

Savitz *et al*. (1988) carried out a second study in the Denver, CO, area during the 1980s. The population base consisted of all children < 15 years of age residing in the 1970 Denver Standard Metropolitan Statistical Area. A total of 356 cases of childhood cancers diagnosed from 1976–1983 were identified from the Colorado Central Cancer Registry and from records of area hospitals. A total of 278 potential controls were identified through random digit dialling and were matched to the cases by age (± 3 years), sex and telephone exchange. The cases had been diagnosed up to nine years prior to selection, so controls had to be restricted to those who still lived in the same residence as they had done at the time the case was diagnosed. Exposure to electric fields was assessed by means of spot measurements under 'high-power' conditions (when selected appliances and lights were turned on) and exposure to magnetic fields by means of spot measurements under both 'high-power' and 'low-power' conditions (when most appliances and lights were turned off). The measurements were made in the current dwelling of the case if it was also the dwelling occupied prior to diagnosis, and homes were classified by Wertheimer-Leeper wire codes. A total of 252 (70.8%) of the cases were interviewed; spot measurements of fields were made for 128 cases (36%) and wire coding was completed for 319 (89.6%). Two hundred and twenty-two controls were interviewed, giving a final response rate from the random-digit dialling phase of 63%; a total of 207 (74.5%) of the controls had spot measurements made in their homes and the homes of 259 (93.2%) were wire coded. Potential confounding variables included year of diagnosis and residential stability; electric load at the time of measurement; parental age, race, education and income; traffic density, and various in-utero exposures. For low-power conditions, the odds ratios for magnetic field measurements of ≥ 0.2 μT versus < 0.2 μT were 1.4 (95% CI, 0.63–2.9) for all cancers combined, 1.9 (95% CI, 0.67–5.6) for leukaemia, 2.2 (95% CI, 0.46–10) for lymphoma and 1.0 (95% CI, 0.22–4.8) for brain cancer. The odds ratios for high-power conditions were near unity for most cancer sites, and those for high electric fields were mostly below unity. For assessment of the influence of wire codes, underground wires were considered to have the lowest magnetic fields. The odds ratios for 'high' (HCC and VHCC) versus 'low' (underground, VLCC and LCC) wire codes were 1.5 (95% CI, 1.0–2.3) for all cancers combined, 1.5 (95% CI, 0.90–2.6) for leukaemia, 0.8 (95% CI, 0.29–2.2) for lymphoma and 2.0 (95% CI, 1.1–3.8) for brain cancer. For VHCC versus buried wires, the odds ratios were 2.2 (95% CI, 0.98–5.2) for all cancers, 2.8 (95% CI, 0.94–8.0) for leukaemia, 3.3 (95% CI, 0.80–14) for lymphoma and 1.9 (95% CI, 0.47–8.0) for brain cancer. [The Working Group noted the differential residential requirements for controls compared with cases, leading to a possible selection bias. Spot measurements were taken only in dwellings that were still occupied by the cases, although many years might have elapsed since the date of diagnosis (measurements were made for only 36% of the eligible cases) and in many instances, measurements were made years after the etiological time period of interest.]

Coleman *et al*. (1989) conducted a registry (Thames Cancer Registry)-based case–control study in the United Kingdom. The study included leukaemia patients of all ages diagnosed between 1965 and 1980 and resident in one of four adjacent London boroughs. Two tumour controls were selected randomly from the same registry and matched to each case for sex, age and year of diagnosis. The childhood study population comprised 84 leukaemia cases and 141 cancer controls under the age of 18. Only one case and one control lived within 100 m of an overhead power line; thus, no risk estimates were presented for proximity to power lines. No clear pattern was seen for children living within 100 m of a substation.

The second case–control study in the United Kingdom was carried out by Myers *et al*. (1990) on children born within the boundaries of the Yorkshire Health Region and registered in the period 1970–79. A total of 419 cases and 656 controls were identified, but some could not be located, and 374 cases (89%) and 588 (90%) controls were finally analysed. Exposure was assessed by calculations of historical magnetic fields due to the load currents of overhead power lines at the birth addresses of the children, on the basis of line-network maps and load records. Risk estimates were presented for all cancers, and separately for non-solid tumours (mostly leukaemia and lymphoma) and solid tumours (all brain tumours, neuroblastomas and tumours of other sites). For all cancers combined, for children in the group calculated to have the highest exposure to magnetic fields, i.e. ≥ 0.1 μT, the resulting odds ratio was 0.4 (95% CI, 0.04–4.3). For the two diagnostic subgroups, non-solid tumours and solid tumours, a cut-point of ≥ 0.03 μT was chosen and the respective odds ratios were 1.4 (95% CI, 0.41–5.0) and 3.1 (95% CI, 0.31–32). The distance analysis with a cut-point of < 25 m gave an odds ratio of 1.1 (95% CI, 0.47–2.6) for all cancers combined.

The first North American study to include long-term measurements of ELF magnetic fields was carried out by London *et al*. (1991, 1993) in Los Angeles, CA. The study population consisted of children from birth to the age of 10 years who had resided in Los Angeles County. A total of 331 cases of childhood leukaemia were identified by the Los Angeles County Cancer Surveillance Program from 1980–87. A total of 257 controls were identified, using a combination of friends of the patients and random digit dialling. The cases and controls were individually matched on age, sex and ethnicity. Exposure assessment consisted of spot measurements of electric and magnetic fields in three or four locations inside the home and three locations outside, a 24-h magnetic field measurement made in the child's bedroom and wire coding. Lifetime residential histories were obtained, and measurements were sought for at least one dwelling per subject. Spot measurements were made in multiple residences when possible. Latency was considered in the design phase by defining an 'etiological time-period' that extended from birth up to a reference date that depended upon the child's age at diagnosis. The same reference date was used for each matched control. The response rates for cases for the various parts of the study were approximately 51% for the 24-h measurement and about 66% for wire coding. [The Working Group noted that it was not possible to calculate accurate response rates for the controls.] Twenty-four-hour measurements for both cases and controls were analysed according to percentile cut-points (< 50th (< 0.07 μT), 50–74th, 75–89th and ≥ 90th (≥ 0.27 μT)). When compared with the referent group of < 50th percentile, the odds ratios for each category were 0.68 (95% CI, 0.39–1.2), 0.89 (95% CI, 0.46–1.7) and 1.5 (95% CI, 0.66–3.3) in relation to the arithmetic mean of 24-h measurements of magnetic field in the child's bedroom. When compared with a referent group with VLCC and underground wire codes, the odds ratios for OLCC, OHCC and VHCC were 0.95 (95% CI, 0.53–1.7), 1.4 (95% CI, 0.81–2.6) and 2.2 (95% CI, 1.1–4.3). Adjustment for confounding variables reduced the estimate for VHCC from 2.2 to 1.7 (95% CI, 0.82–3.7), but the trend was still statistically significant. There was no significant association of childhood leukaemia with spot measurements of magnetic or electric fields. [The Working Group considered that the limitations of this study include somewhat low response rates for the measurement component of the study.]

Ebi *et al.* (1999) re-analysed the Savitz *et al*. (1988) and London *et al*. (1991) studies using the 'case-specular method'. This method compared the wire codes of subjects' homes with those of 'specular residences': imaginary homes constructed as a mirror image of the true home, symmetrical with respect to the centre of the street. This method is intended to discriminate between the 'neighbourhood variables', which are normally the same for the true home and its mirror image, and the effects of power lines that are normally not placed symmetrically in the centre of the street. The study confirmed the association reported in the original studies. [The Working Group noted that this study did not correct for limitations noted for the original studies and did not address selection bias.]

Feychting and Ahlbom (1993) conducted a population-based nested case–control study in Sweden. The study base consisted of all children aged less than 16 years who had lived on a property at least partially located within 300 m of any 220- or 400-kV power lines from 1960–85. They were followed from the time they moved into the corridor until the end of the study period. The Swedish population registry was used to identify individuals who had lived on the respective properties, and record linkage to the Swedish Cancer Registry was performed to identify patients with childhood cancer among this group. A total of 142 children with cancer were identified within the power-line corridors, 39 of whom were diagnosed as having leukaemia, 33 as having a tumour of the central nervous system, 19 as having a lymphoma and 51 as having some other type of cancer. Approximately four controls per case, matched according to age, sex, parish of residence during the year of diagnosis or during the last year before the case moved to a new home, and proximity to the same power line, were selected randomly from the study base, providing a total of 558 controls. Exposure to magnetic fields was assessed by calculated historical fields, calculated contemporary fields and spot measurements under low-power conditions within the dwelling. To calculate historical fields, information on the average power load on each power line was obtained for each year. Spot measurements were made with a meter, constructed specifically for the purpose of this study, in the home within the power-line corridor where the child lived at the time closest to diagnosis. Spot measurements were conducted 5–31 years after diagnosis [the participation rate was 63% among cases and 62% among controls]. In the analysis, the authors placed most emphasis on calculated historical fields using a three-level exposure scale with categories of < 0.1 μT, 0.1–< 0.2 μT and ≥ 0.2 μT. The relative risks were calculated by using a logistic regression model stratified according to age, sex, year of diagnosis, type of house (single-family house or apartment), and whether or not the subject lived within the county of Stockholm. Other potential effect modifiers considered in the analysis were socioeconomic status taken from the population censuses made closest to the year of birth and closest to the year of diagnosis of cancer, and air pollution from traffic estimated by the Swedish Environmental Protection Board. Cancer risk in relation to calculated magnetic fields closest in time to diagnosis at ≥ 0.2 μT compared with < 0.1 μT was elevated for childhood leukaemia (odds ratio, 2.7; 95% CI, 1.0–6.3; 7 cases) but not for tumours of the central nervous system (odds ratio, 0.7; 95% CI, 0.1–2.7; 2 cases), lymphoma (odds ratio, 1.3; 95% CI, 0.2–5.1; 2 cases) or all cancers combined (odds ratio, 1.1; 95% CI, 0.5–2.1; 12 cases). At ≥ 0.3 μT compared with < 0.1 μT, the increased risk for leukaemia was more pronounced with an odds ratio of 3.8 (95% CI, 1.4–9.3; 7 cases), while the risks for the other types of cancer were only slightly altered. Subgroup analysis revealed the highest odds ratios for children aged 5–9 years at date of diagnosis and for children living in single-family homes. Spot measurements showed a good agreement with calculated contemporary fields, demonstrating that calculated fields could predict residential magnetic fields, but agreement with calculated historical fields was poor. Based on a distance of ≤ 50 m compared with > 100 m to nearby power lines, the odds ratio was 2.9 (95% CI, 1.0–7.3; 6 exposed cases, 34 controls) for leukaemia, 1.0 (95% CI, 0.5–2.2; 9 cases, 34 controls) for all cancers and 0.5 (95% CI, 0.0–2.8; 1 case, 34 controls) for tumours of the central nervous system.

The results of a similar population-based case–control study were published in the same year by Olsen *et al.* (1993). The study population included all Danish children under the age of 15 years who had been diagnosed as having leukaemia, a tumour of the central nervous system or malignant lymphoma during the period 1968–86. A total of 1707 patients was identified from the Danish Cancer Registry, of whom 833 had a leukaemia, 624 had a tumour of the central nervous system and 250 had a malignant lymphoma. Two controls for each patient with leukaemia, three controls for each patient with a tumour of the central nervous system and five controls for each patient with a lymphoma were drawn at random from the files of the Danish central population registry. The matching criteria chosen were sex and date of birth within one year. The total number of controls was 4788. The residential histories of each family were ascertained restrospectively from the date of diagnosis to nine months before the child's birth. Each address was checked against maps of existing or former 50–400-kV power lines, and areas of potential exposure to magnetic fields ≥ 0.1 μT were defined. For all dwellings outside the potential exposure areas, the magnetic fields were assumed to be zero. For other dwellings, historical fields were calculated taking into account the annual average current flow of the line, the type of pylon, the category of the line, the ordering of the phases and any reconstructions. The basic measure of exposure was the average magnetic field generated from a power line to which the child was ever exposed. Exposure was categorized into the groups < 0.1 μT, 0.1–< 0.25 μT and ≥ 0.25 μT. The cumulative dose of magnetic fields was obtained by multiplying the number of months of exposure by the average magnetic field at the dwelling (μT–months). Odds ratios were derived from logistic regression models adjusted for sex and age at diagnosis. The distribution of cases and controls according to socio-economic group did not differ. Odds ratios at calculated field levels of ≥ 0.25 μT compared with < 0.1 μT were 1.5 (95% CI, 0.3–6.7) for leukaemia based on three exposed cases and four exposed controls, 1.0 (95% CI, 0.2–5.0) for tumours of the central nervous system (2 cases, 6 controls) and 5.0 (0.3–82) for malignant lymphoma (1 case, 1 control). In a post-hoc analysis comparing calculated field levels of ≥ 0.4 μT with the same baseline, the respective odds ratios were 6.0 (95% CI, 0.8–44; 3 cases) for leukaemia, 6.0 (95% CI, 0.7–44; 2 cases) for tumours of the central nervous system, 5.0 (95% CI, 0.3–82; 1 case) for malignant lymphoma and 5.6 (95% CI, 1.6–19) for the combined groups based on only six exposed cases and three exposed controls. The distribution functions of cumulative doses of magnetic fields for cases and controls showed that doses were generally higher among cases; but there was never any significant association with an increase in risk.

Coghill *et al*. (1996) conducted a small case–control study in the United Kingdom involving 56 patients with leukaemia and 56 controls. Patients with leukaemia diagnosed between 1985 and 1995 were recruited by media advertising, personal introduction and with the support of the Wessex Health Authority and various self-help groups. Controls of the same age and sex were suggested by the parents of the patients (friend controls). Measurements of the magnetic field (mean, 0.070 μT for the cases, 0.057 μT for the controls) were conducted in the child's bedroom between 20:00 and 08:00. The main result of a conditional logistic regression analysis was an association between leukaemia and electric fields of ≥ 20 V/m with an odds ratio of 4.7 (95% CI, 1.2–28) and somewhat weaker associations in groups with intermediate exposures of 10–19 V/m (odds ratio, 2.4; 95% CI, 0.79–8.1) and of 5–9 V/m (odds ratio, 1.5; 95% CI, 0.47–5.1), suggesting a dose–response relationship. No association was seen between leukaemia and magnetic fields. [The Working Group noted the potential lack of comparability of cases and controls.]

A study of 298 children with brain tumours (ICD-9 191, 192) and 298 control children was carried out in Los Angeles, CA, by Preston-Martin *et al*. (1996a). The study subjects were aged 19 years or younger, resident in Los Angeles County and diagnosed between 1984 and 1991. Controls were identified by random digit dialling and matched on age and sex. The response rates were about 70% for both cases (298/437) and controls (298/433). Cases and controls were accrued prospectively from 1989 onwards, but retrospectively from 1984 to 1988. The authors attempted to obtain exterior spot measurements and wire codes for all the homes occupied by subjects from conception until diagnosis of brain tumour. The 596 (298 cases, 298 controls) study subjects reported living in a total of 2000 homes; of these, some measurements were made or wire codes were assigned for 1131. No measurements or wire coding were attempted if the former home was outside Los Angeles County. Interior 24-h measurements were made in the child's bedroom and one other room if at the time of interview the child still occupied a home lived in prior to diagnosis. Interior measurements were available for 110 cases (37% of those interviewed) and 101 controls (34% of those interviewed). Wire codes were available for at least one residence for 292 cases (98%) and 269 controls (90%) and exterior spot measurements, made at the front door, were available for 255 cases (86%) and 208 controls (70%). There was no association between living in a home with a wire code of VHCC at diagnosis and childhood brain tumours (odds ratio for VHCC versus VLCC and OLCC, 1.2; 95% CI , 0.6–2.2; 31 cases), adjusted for age, sex, year of birth, socio-economic status and maternal use of a water bed during pregnancy. The data showed an increased risk for subjects living in homes with underground wiring (odds ratio, 2.3; 95% CI, 1.2–4.3; 39 cases); but this increased risk was apparent only in cases diagnosed before 1989 (odds ratio, 4.3; 95% CI, 1.6–11; 28 cases). There was no increased risk associated with the measurements of magnetic field taken outside the home occupied at the time of diagnosis. The odds ratio was 0.7 (95% CI, 0.3–1.5) for front door measurements > 0.2 μT (13 cases) and 0.9 (95% CI, 0.3–3.2) for fields over 0.3 μT (7 cases). For 24-h means over 0.2 μT in the child's bedroom, the odds ratio was 1.2 (95% CI, 0.5–2.8; 16 cases) and, for fields over 0.3 μT, the odds ratio was 1.7 (95% CI, 0.6–5.0; 12 cases). [The Working Group considered that the limitations of this study included relatively low response rates for both cases and controls, in particular for the interior measurement portion of the study. There is also some indication of bias in the control selection process, as manifested by the different results for underground wiring between cases diagnosed before and after 1989.]

Gurney *et al*. (1996) studied childhood brain tumours in relation to ELF magnetic fields in the Seattle, WA, area of the USA. Patients under 20 years of age were identified through a population-based registry. One hundred and thirty-three of a total of 179 identified cases (74%), and 270 of 343 controls (79%), identified through random digit dialling, participated in the study. Magnetic field exposure was assessed by wire coding of homes occupied by cases and controls at the diagnosis or reference date. There was no evidence of an association between risk for brain tumour and wire codes. The odds ratio for VHCC homes was 0.5 (95% CI, 0.2–1.6; 4 cases) and, when wire codes were classified into high and low exposure categories, the odds ratio was 0.9 (95% CI, 0.5–1.5; 23 cases). When wire codes for the homes of eligible non-participants were included in the calculations, the odds ratios were similar. [The Working Group noted that cases had lived in their homes for an average of 12 months longer than controls, suggesting the possibility of selection bias.]

In a hospital-based case–control study on childhood leukaemia in Greece, the possible relationship between childhood leukaemia and residential proximity to power lines was investigated (Petridou *et al*., 1997). The study population comprised 117 out of 153 (76%) incident leukaemia cases in children under the age of 15 years diagnosed in 1993–94 and identified by a nationwide network of paediatric oncologists, and two controls per case (202/306; 66%). For every study participant, the Public Power Cooperation of Greece specified the distance between the centre of the dwelling and the two closest power lines between 0.4 and 400 kV (blindly as to status as case or control). From this information, the voltage of each of the two closest power lines was divided by the distance (V/m) and the maximum of the two values was taken as the subject's exposure (modified distance measure). The same procedure was performed by dividing the voltage level of each power line by the square of the distance (V/m^2) and the cube of the distance (V/m^3). Compared with the first quintile, odds ratios for V/m^2 were 0.58 (95% CI, 0.24–1.4), 0.65 (95% CI, 0.26–1.6), 1.5 (95% CI, 0.58–3.8) and 1.7 (95% CI, 0.67–4.1) for the 2nd, 3rd, 4th and 5th quintile, respectively (*p* value for trend = 0.08). The Wertheimer-Leeper wire code was adapted to conditions in Greece. The odds ratios for the four levels in ascending order of magnetic field strength were 0.99 (95% CI, 0.54–1.8), 1.8 (95% CI, 0.26–13), 4.3 (95% CI, 0.94–19) and 1.6 (95% CI, 0.26–9.4); *p* value for trend = 0.17). [The Working Group noted that the main limitation of the study was the crude exposure assessment.]

Tynes and Haldorsen (1997) reported the results from a nested case–control study in Norway. The cohort comprised children under the age of 15 years who had lived in a census ward crossed by a power line (45 kV or greater in urban areas, 100 kV or greater in rural areas) during at least one of the years 1960, 1970, 1980, 1985, 1987 or 1989. Cancer cases occurring in the study area between 1965 and 1989 were identified by record linkage with the Cancer Registry of Norway. Out of 532 children with cancer, 500 were included in the study, of whom 148 had a leukaemia, 156 had a brain tumour, 30 had a lymphoma and 166 had cancer at another site. For each case, one to five controls (depending on eligibility) matched for sex, year of birth and municipality were selected at random from the cohort, resulting in a total of 2004 controls. Exposure was assessed by calculating historical magnetic fields based on the historical current load on the line, the height of the towers and ordering and distance between phases for every power line of 11 kV or greater. The exposure metric was validated by comparing calculated contemporary fields with magnetic fields measured for 65 schoolchildren who wore personal dosimeters for 24 h. The validation study showed a good agreement between the measured and the calculated magnetic fields. Time-weighted average (TWA) exposure to calculated magnetic fields as well as calculated magnetic fields closest in time to diagnosis were categorized into the groups < 0.05 μT, 0.05–< 0.14 μT and ≥ 0.14 μT. The odds ratio was computed by conditional logistic regression models for matched sets. Effect modifiers considered in additional analyses included socioeconomic status based on the occupation of the father (from the National Central Bureau of Statistics), type of building and number of dwellings. The risk for all cancers combined at TWA exposure ≥ 0.14 μT was estimated to be 0.9 (95% CI, 0.5–1.8) based on 12 exposed cases and 51 exposed controls. The odds ratios for the different types of cancer were 0.3 (95% CI, 0.0–2.1; 1 case) for leukaemia, 0.7 (95% CI, 0.2–2.1; 4 cases) for brain tumour, 2.5 (95% CI, 0.4–16; 2 cases) for lymphoma and 1.9 (95% CI, 0.6–6.0; 5 cases) for cancers at other sites. At a TWA exposure of ≥ 0.2 μT, the odds ratio for children with leukaemia was 0.5 (95% CI, 0.1–2.2; 2 cases). On the basis of the magnetic field exposure closest in time to diagnosis, the odds ratios at ≥ 0.14 μT were generally close to unity (brain tumour, 1.1 (95% CI, 0.5–2.5; 9 cases), lymphoma, 1.2 (95% CI, 0.2–6.4; 2 cases), leukaemia, 0.8 (95% CI, 0.3–2.4; 4 cases), all cancers combined, 1.3 (95% CI, 0.8–2.2; 24 cases), with the exception of cancers at other sites where the odds ratio was 2.5 (95% CI, 1.1–5.9; 9 cases). The cancer risk in relation to calculated magnetic fields of ≥ 0.14 μT during the first year of a child's life was 0.8 (95% CI, 0.1–7.1; 1 case) for leukaemia, 2.3 (0.8–6.6; 7 cases) for tumours of the central nervous system and 2.0 (0.9–4.2; 12 cases) for all cancers combined. A distance from nearby power lines of ≤ 50 m was associated with a significantly enhanced odds ratio of 2.8 (95% CI, 1.5–5.0; 23 cases) for tumours at other sites, but the odds ratio was not significantly different for leukaemia (0.6; 95% CI, 0.3–1.3; 9 cases), brain tumour (0.8; 95% CI, 0.4–1.6; 14 cases) or lymphoma (1.9; 95% CI, 0.6–6.4; 5 cases). The exposure to electric fields was also calculated, but since shielding between houses and power lines was not accounted for, the figures were not used in the risk analysis.

Linet *et al*. (1997) conducted a large study of acute lymphoblastic leukaemia in children in nine mid-western and mid-Atlantic states in the USA between 1989 and 1994 (the NCI (National Cancer Institute)/CCG (Children's Cancer Group) study). The eligible patients were less than 15 years of age and resided in one of the nine states at the time of diagnosis. Controls were selected by random-digit dialling and matched to the cases on age, ethnicity and telephone exchange. Exposure assessment consisted of spot measurements of magnetic fields in three rooms under normal and low-power conditions and outside the front door, and a 24-h measurement made under the child's bed. Wire codes were also noted. For children under the age of five years, measurements were taken in homes that they had occupied for at least six months, if the residences available for measurements collectively accounted for at least 70% of the child's lifetime from conception to the date of diagnosis. For children over the age of five years, measurements were made for a maximum of two homes occupied during the five years prior to diagnosis, and these homes had to account for at least 70% of the five-year ‘etiological time period’. For the wire-coding portion of the study, one dwelling was selected that accounted for at least 70% of the child’s lifetime (children < 5 years) or at least 70% of the five years prior to diagnosis for children ≥ 5 years. Thus, this study focused on residentially stable children, particularly for the wire-code part of the study. Measurements were made in the homes of 638 cases and 620 controls (78% and 63% response rates, respectively, according to the eligibility criteria described by Kleinerman *et al.*, 1997). The homes of 408 matched pairs were wire coded. Subjects who refused to participate further in the study after the telephone interview that collected data on residential history were included in the wire-coding portion of the study if they had an eligible current or former dwelling. The main exposure metric consisted of a TWA summary measure based on the 24-h measurement and the indoor spot measurements taken in multiple residences, if applicable. The measurements were weighted by an estimate of the time spent in each room, made in a separate personal dosimetry study (Friedman *et al*., 1996). The metric was divided into four a-priori cut-points based on the distribution of measurements in the control group. When compared with children who were exposed to magnetic fields < 0.065 μT, the odds ratios for exposure to 0.065–0.099 μT, 0.10–0.199 μT and ≥ 0.2 μT were 1.1 (95% CI, 0.81–1.5; 123 cases), 1.1 (95% CI, 0.83–1.5; 151 cases) and 1.2 (95% CI, 0.86–1.8; 83 cases), respectively, using unmatched analyses. Matched analyses resulted in a slightly higher estimate for the highest exposure category (odds ratio, 1.5; 95% CI, 0.91–2.6; 58 cases). The risk was elevated when the category of magnetic fields of 0.3 μT and above was considered (odds ratio, 1.7; 95% CI, 1.0–2.9; 45 cases), but the trend was not statistically significant, and the odds ratio for magnetic fields of ≥ 0.5 μT was near unity in the matched analysis. There were no significantly elevated risks when exposure during pregnancy was considered. Measurements in the homes that were occupied during pregnancy were made for 257 cases and 239 controls. There was no positive association between wire codes and childhood leukaemia (odds ratio for VHCC versus underground and VLCC, 0.88; 95% CI, 0.48–1.6; 24 cases). [The Working Group noted that the low response rate of the controls was a limitation of this study.]

Hatch *et al.* (2000) conducted a re-analysis of the National Cancer Institute/ Children’s Cancer Group study to evaluate internal evidence for selection bias. Certain characteristics of the subjects who did not allow in-home measurements or interviews (partial participants) were compared with those of subjects who did allow a data collector inside their homes (complete participants). The partial participants were found to be more likely to have annual incomes of < $ 20 000 (23% versus 12%), mothers who were unmarried (25% versus 10%), a lower education level (46% versus 38%) and were less likely to live in a single-family home (58% versus 83%) than complete participants. When partial participants were excluded from the analysis of measured fields, the odds ratios for magnetic fields of ≥ 0.3 μT increased from 1.6

(95% CI, 0.98–2.6) to 1.9 (95% CI, 1.1–3.3). When partial participants were excluded from the wire-code analysis, the odds ratios for VHCC (versus UG/VLCC) increased from 1.0 (95% CI, 0.62–1.6) to 1.2 (95% CI, 0.74–2.0). If the non-participants had similar characteristics to partial participants, the National Cancer Institute/Children's Cancer Group study may have overestimated risk estimates due to selection bias. [The Working Group noted that this publication included both complete and partial participants. The risk estimates differed slightly due to small differences in the study populations included and to differences in the variables adjusted for.]

Auvinen *et al.* (2000) carried out an exploratory analysis of the National Cancer Institute/Children's Cancer Group study data using alternative magnetic field exposure metrics. The analysis was restricted to 515 cases of acute lymphoblastic leukaemia and 516 controls who had lived in one home for at least 70% of the time-period of interest. Subjects with Down syndrome were excluded. Measures of the central tendency, peak values, the percentage of time above various thresholds and the short-term variability of the 24-h bedroom measurements were also assessed. A weak positive association was found between acute lymphoblastic leukaemia and measures of the central tendency, particularly when night-time exposure was assessed. For example, when the 30th percentile values of the 24-h measurements were examined, the odds ratios for the highest versus the lowest category (90th% versus < 50th%) were 1.4 (95% CI, 0.87–2.2) for the 24-h measurements and 1.7 (95% CI, 1.1–2.7) for the night-time measurements. Little evidence for any association with peak exposure, thresholds or variability was found.

Kleinerman *et al.* (2000) examined data from the National Cancer Institute/ Children's Cancer Group study in relation to distance from power lines and an exposure index which took into account both distance and relative load for high-voltage and three-phase primary power lines. Most of the subjects (601/816; 74%) had lived more than 40 m from a high-voltage or three-phase primary power line. The odds ratio for living within 14 m of a potentially high-exposure line was 0.79 (95% CI, 0.46–1.3) and that for the highest category of the exposure index (mean magnetic field in homes, 0.213 μT), described above, was 0.98 (95% CI, 0.59–1.6).

Measurements of magnetic fields were included in a population-based case–control study of leukaemia in children under the age of 15 years in Germany. The study area was at first restricted to north-western Germany (i.e. Lower Saxony) (Michaelis *et al.*, 1997), but was extended to include the metropolitan area of Berlin (Michaelis *et al.*, 1998), before the first part was completed. Patients in whom leukaemia was diagnosed between 1988 and 1993 (for Lower Saxony) or 1991 and 1994 (for Berlin) were identified by the nationwide German Childhood Cancer Registry. In the Lower Saxony part of the study, two controls per case were selected randomly from the files for registration of residents. One control was matched for sex, date of birth and community; a second control was matched only for sex and date of birth, but drawn at random from any community in Lower Saxony, taking the population size of each community into account. In the Berlin part of the study, one control per case matched according to sex, date of birth and district within the city was randomly selected from the Berlin population registry. Measurements of the magnetic field were also made for patients with tumours of the central nervous system (Schüz *et al*., 2001b), but no controls were selected specifically for this diagnostic group. A total of 176 children with leukaemia, 64 with tumours of the central nervous system and 414 controls participated in the study (Michaelis *et al.*, 1998; Schüz *et al.*, 2001b). The response rates were 62% (176/283) for cases and 45% (414/919) for controls. In both parts of the study, measurements of the magnetic field over 24 h were performed in the child's bedroom and in the living room of the dwelling where the child had lived for longest before the date of diagnosis. Additional spot measurements were made in all dwellings where the child had lived for more than one year. All measurements were made between 1992 and 1996. The main analysis was based on the median magnetic field in the child's bedroom, with 0.2 μT as a cut-point. Post-hoc exposure metrics included the mean of the spot measurements, and the magnetic field during the night (22:00 to 06:00, extracted from the 24-h measurement). The odds ratios were derived from a logistic regression analysis stratified for age, sex and part of Germany (East-Berlin versus West-Berlin and Lower Saxony) and were adjusted for socioeconomic status and degree of urbanization. For the analysis of tumours of the central nervous system, the sample of controls selected for the leukaemia cases was used in unconditional logistic regression models adjusted for age, sex, socioeconomic status and degree of urbanization. Information on a variety of potential confounders was available. The odds ratio for median magnetic fields ≥ 0.2 μT compared with fields of < 0.2 μT was 2.3 (95% CI, 0.8–6.7; 9 exposed cases and 8 exposed controls) for leukaemia and 1.7 (95% CI, 0.3–8.8); 2 exposed cases) for tumours of the central nervous system. The association with leukaemia was more pronounced for children aged four years or younger (odds ratio, 7.1 (95% CI, 1.4–37; 7 cases, 2 controls) and for all children exposed to median magnetic fields ≥ 0.2 μT during the night (odds ratio, 3.8; 95% CI, 1.2–12; 9 cases, 5 controls). No association was seen with spot measurements; spot measurements and 24-h measurements showed a poor agreement. It is also of interest that more of the stronger magnetic fields were caused by low-voltage field sources than by overhead power lines. [The Working Group noted that selection bias is a cause for concern due to the high proportion of non-participants.]

To assess the risk of childhood cancer from exposure to ELF electric and magnetic fields, Dockerty *et al*. (1998) conducted a population-based case–control study in New Zealand. The study base consisted of children under the age of 15 years diagnosed from 1990–1993 with leukaemia or a solid tumour. Children with cancer were identified from the New Zealand Cancer Registry, the New Zealand Children's Cancer Registry or the computerized records of admissions and discharges from public hospitals. The controls were selected at random from national birth records and one control was matched to each case on age (same quarter of the birth year) and sex. Only cases and controls resident in New Zealand and not adopted were included. Altogether, 344 children with cancer were eligible for inclusion in this study, 131 of whom had leukaemia. Household measurements were made for 115 leukaemia patients and 117 controls, resulting in 113 matched pairs (86%). The response rate among first-choice controls was 69%. Measurements of the magnetic field and the electrical field were conducted over 24 h in two rooms of the dwelling; one was the room in which the child slept at night and one was the room in which the child spent most of his or her day. The two measurements were taken on subsequent days so that the parents had to move the measurement instrument from one room to another. A log sheet was used to record the times and dates on which the instrument was started and moved. Analyses using conditional logistic regression models were performed for thirds of the empirical distributions of the exposure metrics for electric fields and, for magnetic field measurements, for categories 0.1–< 0.2 μT and ≥ 0.2 μT compared with < 0.1 μT. The confounders considered in the analyses included mother's education, maternal smoking during pregnancy, residence of the child on a farm, home ownership status, number of people in the household, residential mobility, mother's marital status and season of the measurement. Risk estimates were presented for a subset of 40 matched pairs for which, two years before the date of diagnosis, both the leukaemia case and the matched control lived in the same house in which the measurements were subsequently made. For leukaemia, the adjusted odds ratios for magnetic fields ≥ 0.2 μT compared with < 0.1 μT were 16 (95% CI, 1.1–224; based on 5 exposed cases and 1 exposed control) for the bedroom measurement and 5.2 (95% CI, 0.9–31; based on 7 exposed cases and 3 exposed controls) for the daytime room measurement. The respective odds ratios for the highest third electric field (≥ 10.75 V/m) compared with the lowest third (< 3.64 V/m) were 2.3 (95% CI, 0.4–13) and 2.5 (95% CI, 0.3–18). Dockerty *et al*. (1999) re-analysed the above data by combining daytime and night-time magnetic fields to produce TWA magnetic fields. The odds ratio for magnetic fields ≥ 0.2 μT decreased to 3.3 (95% CI, 0.5–24) based on the same 40 matched pairs. The analyses of all 113 matched pairs showed no association with exposure to magnetic fields ≥ 0.2 μT (odds ratio, 1.4; 95% CI, 0.3–6.3). [The Working Group noted that risk estimates for leukaemia were presented for only 35% of the matched pairs included in the study.]

McBride *et al*. (1999) conducted a prospective case–control study of childhood leukaemia in five Canadian provinces (Alberta, British Columbia, Manitoba, Quebec and Saskatchewan) from 1990–95. Cases were identified through paediatric oncology treatment centres in each province and provincial cancer registries for all provinces except Quebec. Children under 15 years of age in whom leukaemia had been diagnosed and who resided in census tracts within 100 km of major cities were eligible for the study. A total of 445 potentially eligible cases were identified, and 399 of them were interviewed (90%). In-home measurements were made for 67% of the total eligible cases. The controls were identified from health insurance rolls (and family allowance rolls for the first two years of the study period in Quebec) and were matched by age, sex and area to cases. Of the 526 eligible controls, 399 were interviewed (76%) and in-home measurements were made for 65% of the total. Exposure was assessed by personal monitoring for 48 h as well as by 24-h stationary measurements in the child's bedroom if the home lived in before diagnosis was still occupied by the child at the date of interview. Wire codes were assigned and outdoor measurements at current and former dwellings (except for apartments more than four storeys high) were made. The personal exposure of subjects in their former dwellings was assessed from outdoor (perimeter) measurements in conjunction with wire codes. The model was based on analyses from currently occupied residences. For children under three years of age, homes occupied for at least three months, and for children over three years of age, homes lived in for six months or more were eligible for exposure assessment. Cases were ascertained retrospectively for one year, and prospectively thereafter; thus, most of the measurements were taken relatively close in time to the diagnosis or reference date. The potential confounding variables that were assessed included outdoor temperature at the time of measurement, family history of cancer, occupational and recreational exposure of parents, exposure to ionizing radiation and socioeconomic factors. The results of personal monitoring gave no indication of a positive association between risk for leukaemia and increasing exposure to magnetic fields, whether based on contemporaneous measures, a measure of estimated exposure two years before the reference date, or estimated lifetime exposure. For the highest exposure category of the contemporary measures (≥ 90th percentile or ≥ 0.27 μT versus < 50th percentile or < 0.08 μT), the unadjusted odds ratio was 0.78 (95% CI, 0.46–1.3), based on 32 exposed cases and 37 exposed controls. Similar results were found when estimated exposure from former residences was included in the exposure assessment. For the 24-h bedroom measurements, the odds ratio for ≥ 90th percentile was 1.3 (95% CI, 0.69–2.3) compared to < 50th percentile. For wire codes, when VHCC was compared with UG and VLCC, the adjusted odds ratio was 1.2 (95% CI, 0.58–2.3), using the residence at the reference date. There was also no association found between childhood leukaemia and measured electric fields. [The Working Group considered that the limitations of this study include relatively low response rates for controls and a higher proportion of controls than of cases who had not moved home since diagnosis.]

Green *et al*. (1999b) carried out a case–control study of childhood leukaemia in the greater Toronto area of Ontario, Canada. Eligible children were under 15 years of age at diagnosis, treated at the Hospital for Sick Children (the only children's hospital in the greater Toronto area) between 1985 and 1993 and still resident in the study catchment area when the study was conducted (1992–95). Patients were identified through a paediatric oncology registry in Ontario. All subjects had to have lived in the study area at the diagnosis or reference date, to ensure comparability in terms of residential stability. A total of 298 children were identified of whom 256 were approached and 203 [68%] interviewed. Controls were selected from a random sample of 10 000 published telephone numbers. A total of 4180 numbers were called and 1133 households were found to have eligible children and be willing to participate. [The number of eligible persons who refused at this stage was not stated.] Of the 1133 potential controls, 645 (two controls per case) were randomly selected and matched by age and sex. A total of 419 (65%) of the 645 controls approached were interviewed. The assessment of exposure to magnetic fields included spot measurements made in the child's bedroom under normal-power conditions and in two other rooms frequently used by the child, outside measurements around the perimeter of the house, personal monitoring and wire codes. Personal monitoring and in-home measurements were used only if the current residence was occupied before diagnosis or the comparable reference date for the controls. Bedroom measurements were taken for 152 cases [51% of those originally identified] and 300 controls (47% of those approached). The results were analysed using conditional logistic regression and measurements were divided into quartiles according to the distribution among the controls. For bedroom measurements, the adjusted odds ratio for all leukaemias for the highest quartile (≥ 0.13 μT versus < 0.03 μT) was 1.1 (95% CI, 0.31–4.1). Similarly, for the average of interior measurements, the odds ratio was 1.5 (95% CI, 0.44–4.9) for the highest versus lowest quartile. For the exterior measurements, which were taken for a greater number of residences (183 cases and 375 controls), the odds ratios for the second quartile (4.1; 95% CI, 1.3–13 for 0.03–0.07 μT) and for the fourth quartile (3.5; 95% CI, 1.1–11 for ≥ 0.15 μT) were elevated compared with the lowest quartile. There was no association between wire-code and leukaemia incidence. The results for the personal exposure monitoring, based on only 88 cases (34%) and 113 controls (18%) were published separately (Green *et al.*, 1999a). There was a significantly increased risk for all childhood leukaemias for the third (0.07 μT–0.14 μT) and fourth (≥ 0.14 μT) quartiles of magnetic field exposure, compared with the lowest quartile (< 0.03 μT). The odds ratios were 4.0 (95% CI, 1.1–14) and 4.5 (95% CI, 1.3–16) for the third and fourth quartile, respectively, after adjustment for average power consumption, family income, residential mobility, exposure of the child to chemicals and birth order. The odds ratios for electric fields measured by personal dosimetry were mostly below unity. [The Working Group noted that the limitations of the study include the low response rates, especially for the personal monitoring part of the study, and that measurements were taken many years after the time period of interest. The use of published telephone listings raises concern about the comparability of cases and controls.]

The United Kingdom Childhood Cancer Study (UKCCS) was a population-based case–control study covering the whole of England, Wales and Scotland (UK Childhood Cancer Study Investigators, 1999). The study population was defined as children under the age of 15, registered with one of the Family Health Service Authorities (England and Wales) or with one of the Health Boards (Scotland). The prospective collection of cases with a pathologically confirmed malignant disease began in 1992 (except in Scotland where it began in 1991) and ended in 1994 (except in England and Wales, where cases with leukaemia were collected throughout 1996 and cases with non-Hodgkin lymphoma throughout 1995). For each case, two controls, matched for sex and date of birth, were selected randomly from the list of the same Family Health Service Authorities or Health Board as the case. For the study of electric and magnetic fields, only one control per case was chosen. At first, the family of the control with the lower identification number of the two controls was approached and, in case of non-participation or ineligibility, a second control family was chosen. Case and control families were ineligible for the electric and magnetic field part of the study if they had moved house during the year before diagnosis or lived in a mobile home. A total of 3838 cases (87% of all eligible cases in the UK Childhood Cancer Study) were included, and at least one of the parents was interviewed. A total of 7629 controls were included and the participation rate was 64%. Measurements were made for 2423 cases and 2416 controls; 2226 matched pairs (50% of all cases [37% of half of the controls]) were available for analysis. Of the 2226 cases, 1073 had leukaemia, 387 had cancer of the central nervous system and 766 had another malignant disease. The protocol for exposure assessment was specifically designed to estimate the average magnetic fields to which the subjects had been exposed in the year before diagnosis and measurements were made in the homes of all participants during the first phase of exposure assessment. These first-phase measurements comprised a 1.5-h stationary measurement in the centre of the main family room and three spot measurements at different places in the child's bedroom, which were repeated after the 1.5-h measurement. During the household visits, the parents were asked about potential sources of exposure, e.g. night storage heaters, and about the amounts of time the child spent in his or her room and at school. An exposure assessment was carried out in the child's school where relevant. In the second phase of exposure assessment, a measurement over a period of 48 h was conducted in homes where the first measurement had indicated magnetic fields ≥ 0.1 μT, where a potential source of exposure had been identified during the first visit or where an external source of exposure had been reported on a questionnaire that had been completed by the regional electricity companies. If the potential field source was assumed to have a seasonal variability, the dwelling was revisited during the winter months. The dwellings of the families of matched cases or controls where there were potential sources of exposure were also revisited in the second phase. An algorithm was developed to calculate the TWA exposure to magnetic fields on an individual basis, including the magnetic field strengths measured in the bedroom, in other rooms of the dwelling and at school, but with different weightings for each child according to the amount of time he or she had spent in each place. For participants for whom only first-phase measurements had been made, exposure in the bedroom was estimated from the spot measurements and exposure outside the bedroom was estimated from the 1.5-h measurement made in the main family room. For participants for whom long-term measurements had been made, exposure in the bedroom was estimated from the 48-h measurement and exposure outside the bedroom from the 1.5-h measurement conducted during the first visit. To allow for changes in line-loading and circuit configuration between the year of diagnosis and the time of measurement, the exposure measurements were adjusted to take into account calculated historical magnetic fields. Exposure was divided into four groups (< 0.1 μT, 0.1–< 0.2 μT, 0.2–< 0.4 μT and ≥ 0.4 μT) and into three categories with cut-points at 0.1 μT and 0.2 μT, respectively. Additional adjustments were performed for a census-derived deprivation index based on unemployment, overcrowding and car ownership in the appropriate district. The odds ratios were presented separately for leukaemia, cancers of the central nervous system, other malignant diseases and all cancers combined. At magnetic fields ≥ 0.2 μT, all the adjusted odds ratios were below unity (leukaemia, odds ratio, 0.90 (95% CI, 0.49–1.6), cancer of the central nervous system, odds ratio, 0.46 (95% CI, 0.11–1.9), other types of cancer, odds ratio, 0.97 (95% CI, 0.46–2.1), all cancers combined, odds ratio, 0.87 (95% CI, 0.56–1.4)). At ≥ 0.4 μT, the odds ratio for leukaemia was slightly elevated (1.7; 95% CI, 0.40–7.1), based on five exposed cases and three exposed controls. No association with magnetic fields of ≥ 0.4 μT was seen for cancer of the central nervous system (no exposed cases) or other malignant diseases (odds ratio, 0.71; 95% CI, 0.16–3.2; three exposed cases). For the intermediate category 0.2–< 0.4 μT, all odds ratios were below unity or, in the case of other malignant diseases, very close to unity (leukaemia, odds ratio, 0.78 (95% CI, 0.40–1.5), cancer of the central nervous system, odds ratio, 0.70 (95% CI, 0.16–3.2), other malignant disease, odds ratio, 1.1 (95% CI, 0.45–2.6)). Adjustment for deprivation index had only a small effect on the risks and risk did not vary according to age. [The Working Group considered that the main limitation of this study was the low proportion of subjects for whom fields were measured.]

In a second approach, the study examined distance from external sources of electric and magnetic fields (UK Childhood Cancer Study Investigators, 2000a). These data were available for nearly 90% of the children eligible for the study of electric and magnetic fields. Separate odds ratios were calculated for different types of overhead power line (11- and 20-kV, 33-kV, 66-kV, 132-kV, 275-kV and 400-kV) and for different types of underground high-voltage cable (33-kV, 132-kV and 275-kV), substations and low-voltage circuits. The only association seen was between leukaemia and 66-kV overhead power lines (odds ratio, 3.2; 95% CI, 1.0–9.7; 5 cases), although associations with other sources of field, including stronger ones, were close to unity. The magnetic fields associated with power lines were also calculated for all dwellings on the basis of line-load data for the period of interest. For magnetic fields of ≥ 0.4 μT, the odds ratio was decreased for leukaemia (0.27; 95% CI, 0.03–2.2), but only one case and eight controls were classified as being exposed. No excess risk for any type of malignancy was seen with exposure to magnetic fields ≥ 0.2 μT.

Bianchi *et al*. (2000) conducted a small case–control study in Italy. The study areas were the municipalities within the Province of Varese that were crossed by high-voltage power lines. A total of 103 children under the age of 15 years diagnosed with leukaemia between 1976 and 1992 were identified by the Lombardy Cancer Registry and four healthy controls per case were selected randomly from the 1996 lists of Health Service Archives. A total of 101 cases and 412 controls were available for analysis. The average magnetic fields for subjects living within 150 m of a power line were calculated from data on the power load for the year 1998. In addition, spot measurements at the entrance of the dwelling were conducted in a validation study.

Odds ratios obtained from logistic regression analysis stratified for age and sex, revealed considerable increases in leukaemia risk from exposure to magnetic fields in the ranges 0.001–0.1 μT (odds ratio, 3.3; 95% CI, 1.1–9.7, 6 cases) and > 0.1 μT (odds ratio, 4.5; 95% CI, 0.88–23, 3 cases), compared to exposure to fields < 0.001 μT (92 cases). [The Working Group noted that current data on power load were used to estimate historical magnetic fields up to 22 years in the past. The highest exposure group was defined at a very low cut-point (> 0.1 μT) and even then comprised only a few subjects. Furthermore, cases and controls were enrolled from two different recruitment periods.]

Schüz *et al.* (2001a) reported the results of a large-scale population-based case–control study covering the whole of the former West Germany. A total of 514 patients with acute leukaemia aged less than 15 years were identified from the German Childhood Cancer Registry from 1990–94, and 1301 controls from population registration files were included. Measurements of magnetic fields were made in 1997–99. [Overall participation rates were 51% among cases and 41% among controls]. Of those families who were asked for permission to conduct measurements, 66% (520/783) responded. The exposure assessment was similar to that of the first German study (Michaelis *et al.*, 1998; see above), except that spot measurements were conducted only to identify the source of strong magnetic fields and were not part of the risk analysis. The main exposure metrics were the median magnetic field over 24 h and the median magnetic field during the night. Odds ratios were calculated using logistic regression models adjusted for sex, age, year of birth, social class and degree of urbanization. The odds ratio for 24-h median magnetic fields ≥ 0.2 μT was 1.6 (95% CI, 0.65–3.7; 9 exposed cases and 18 exposed controls). An elevated risk for leukaemia was observed for night-time exposure with an odds ratio of 3.2 (95% CI, 1.3–7.8; 12 exposed cases and 12 exposed controls). At a cut-point of ≥ 0.4 μT, the odds ratio for median magnetic fields increased to 5.8 (95% CI, 0.78–43), but was based on only three exposed cases and three exposed controls. Odds ratios were altered only slightly when the analyses were restricted to residentially stable children. The association was strongest for children aged four years or younger. Two exposed children with Down syndrome had median and night-time exposure > 0.2 μT. The exclusion of children with Down syndrome from the analyses led to a decrease in the odds ratio at ≥ 0.2 μT to 1.3 (95% CI, 0.49–3.2) (7 exposed cases) for median magnetic fields and to 2.8 (95% CI, 1.1–7.0) (10 exposed cases) for night-time exposure, the increase in the latter was still statistically significant. [The Working Group noted that the study had two limitations, the low participation rate and the very long time lag between date of diagnosis and date of measurement.]

A pooled analysis of the two German studies (Michaelis *et al.*, 1998; Schüz *et al.*, 2001a) resulted in an increase in the odds ratios for leukaemia in children exposed to 24-h median magnetic fields ≥ 0.4 μT to 3.5 (95% CI, 1.0–12; 7 cases). No associations were seen for the intermediate exposure categories of 0.1–< 0.2 μT (odds ratio, 1.1; 95% CI, 0.73–1.6; 43 cases) and 0.2–< 0.4 μT (odds ratio, 1.2; 95% CI, 0.55–2.6;

11 cases), compared with the baseline < 0.1 μT (629 cases). A dose–response relationship was observed for median magnetic fields during the night, with respective odds ratios of 1.3 (95% CI, 0.90–2.0; 44 cases), 2.4 (95% CI, 1.1–5.4; 14 cases) and 4.3 (95% CI, 1.3–15; 7 cases) for the exposure categories 0.1–< 0.2 μT, 0.2–< 0.4 μT and ≥ 0.4 μT, respectively (*p* value for trend < 0.01) (Schüz *et al.*, 2001a).

The study also examined exposure to 16 $^{2}/_{3}$-Hz magnetic fields, which is the frequency used by the German railway system (Schüz *et al.*, 2001c). Magnetic fields ≥ 0.2 μT at this frequency were measured in less than 1% of all dwellings. Considering this additional exposure in the main analysis changed the results only marginally, thus, neglecting magnetic fields at this frequency is not likely to affect studies of residential electric and magnetic fields.

(*d*) *Pooled analyses*

(i) Ahlbom *et al*. (2000) reported a pooled analysis of studies that examined the relation between childhood leukaemia and residential magnetic fields (Table 22). They included all studies except one (London *et al*., 1991) in which long-term indoor measurements had been reported and that were completed before 2000 (Linet *et al*., 1997; Michaelis *et al*., 1998; Dockerty *et al*., 1998; 1999; McBride *et al*., 1999; UK Childhood Cancer Study Investigators, 1999) and all studies that reported calculations of historical exposure to ELF magnetic fields (Feychting & Ahlbom, 1993; Olsen *et al*., 1993; Verkasalo *et al*., 1993; Tynes & Haldorsen, 1997). The analysis strategy was defined *a priori*. The greatest emphasis was placed on the geometric mean of the child's exposure measured in the bedroom in the most recent home inhabited before or at diagnosis. Exposure was categorized into the groups < 0.1 μT, 0.1–< 0.2 μT, 0.2–< 0.4 μT and ≥ 0.4 μT. The potential effect modifiers that were considered in an additional analysis included type of house, residential mobility, social group (or mother's education or family income), degree of urbanization and exposure to car exhaust. The study population comprised 3247 children with leukaemia, of whom 2704 had acute lymphoblastic leukaemia, and 10 400 controls, all under the age of 15 years. Due to the study protocol described above, the results for the single studies within this pooled analysis sometimes differed from the results originally reported for the same study. These differences were greatest for the US study (Linet *et al.*, 1997), the Canadian study (McBride *et al.*, 1999) and the United Kingdom study (UK Childhood Cancer Study Investigators, 1999). The pooled analysis modified the data of Linet *et al*. (1997) as follows: homes in which 24-h measurements had not been made were excluded; exposure measured in the year prior to diagnosis, rather than five years immediately prior to diagnosis were used, and arithmetic means were replaced by geometric means. The changes to the original Canadian results (McBride *et al*., 1999) made for the pooled analysis meant that exposure assessments from fixed-location in-home measurements were used instead of measures of exposure recorded with personal dosimeters. The original United Kingdom results (UK Childhood Cancer Study Investigators, 1999) modified for the pooled analysis used the geometric mean from the 1.5/48-h

Table 22. Pooled analysis of total leukaemia in children

Type of study	0.1–< 0.2 µT	0.2–< 0.4 µT	≥ 0.4 µT	O	E	Continuous analysis
Measurement studies						
Canada (McBride *et al.*, 1999)	1.3 (0.84–2.0)	1.4 (0.78–2.5)	1.6 (0.65–3.7)	13	10.3	1.2 (0.96–1.5)
Germany (Michaelis *et al.*, 1998)	1.2 (0.58–2.6)	1.7 (0.48–5.8)	2.0 (0.26–15)	2	0.9	1.3 (0.76–2.3)
New Zealand (Dockerty *et al.*, 1998, 1999)	0.67 (0.20–2.2)	4 cases/0 controls	0 cases/0 controls	0	0	1.4 (0.40–4.6)
United Kingdom (UKCCSI, 1999)	0.84 (0.57–1.2)	0.98 (0.50–1.9)	1.0 (0.30–3.4)	4	4.4	0.93 (0.69–1.3)
USA (Linet *et al.*, 1997)	1.1 (0.81–1.5)	1.0 (0.65–1.6)	3.4 (1.2–9.5)	17	4.7	1.3 (1.0–1.7)
Calculated field studies						
Denmark (Olsen *et al.*, 1993)	2.7 (0.24–31)	0 cases/8 controls	2 cases/0 controls	2	0	1.5 (0.85–2.7)
Finland (Verkasalo *et al.*, 1993)	0 cases/19 controls	4.1 (0.48–35)	6.2 (0.68–57)	1	0.2	1.2 (0.79–1.7)
Norway (Tynes & Haldorsen, 1997)	1.8 (0.65–4.7)	1.1 (0.21–5.2)	0 cases/10 controls	0	2.7	0.78 (0.50–1.2)
Sweden (Feychting & Ahlbom, 1993)	1.8 (0.48–6.4)	0.57 (0.07–4.7)	3.7 (1.2–11.4)	5	1.5	1.3 (0.98–1.7)
Summary						
Measurement studies	1.1 (0.86–1.3)	1.2 (0.85–1.5)	1.9 (1.1–3.2)	36	20.1	1.2 (1.0–1.3)
Calculated field studies	1.6 (0.77–3.3)	0.79 (0.27–2.3)	2.1 (0.93–4.9)	8	4.4	1.1 (0.94–1.3)
All studies	1.1 (0.89–1.3)	1.1 (0.84–1.5)	2.0 (1.3–3.1)	44	24.2	1.2 (1.0–1.3)

From Ahlbom *et al*. (2000)
The results of the pooled analysis show relative risks (95% CI) by exposure level and with exposure as continuous variable (relative risk per 0.2 µT) with adjustment for age, sex and socioeconomic status (measurement studies) and residence (in East or West Germany). The reference level is < 0.1 µT. Observed (O) and expected (E) case numbers at ≥ 0.4 µT are shown, with expected numbers given by modelling the probability of membership of each exposure category based on distribution of controls including covariates.
UKCCSI, UK Childhood Cancer Study Investigators

measurements rather than the TWA of the measurement protocol. The investigators of the Finnish cohort study (Verkasalo *et al*., 1993) provided a sample of 1027 controls drawn from the cohort.

To estimate a summary relative risk across centres in this pooled analysis, a logistic regression model was applied to the raw data, with study centres represented as effect modifiers. This was performed separately for measurement studies and studies of calculated fields, but also across all studies. Across the measurement studies, the summary relative risk was estimated at 1.9 (95% CI, 1.1–3.2) in the highest exposure category (≥ 0.4 μT). The two intermediate categories had relative risks close to unity (0.1–< 0.2 μT: relative risk, 1.1; 95% CI, 0.86–1.3; 0.2–< 0.4 μT: relative risk, 1.2; 95% CI, 0.85–1.5). The corresponding summary relative risks for the studies of calculated fields were 1.6 (95% CI, 0.77–3.3) in the category 0.1–< 0.2 μT, 0.79 (95% CI, 0.27–2.3) in the category 0.2–< 0.4 μT, and 2.1 (95% CI, 0.93–4.9) in the category ≥ 0.4 μT. The summary relative risks across all studies were also close to unity (0.1–< 0.2 μT: relative risk, 1.1; 95% CI, 0.89–1.3; 0.2–< 0.4 μT: relative risk, 1.1; 95% CI, 0.84–1.5), but in the highest category (≥ 0.4 μT), the summary relative risk was 2.0 (95% CI, 1.3–3.1) with a respective p value < 0.01. A similar analysis was conducted on continuous exposure, and the resulting relative risk per 0.2 μT interval was 1.2 (95% CI, 1.0–1.3). A homogeneity test based on the continuous analysis across all nine centres revealed that the variation in point estimates between the studies was not larger than would be expected from random variability. Subsequent sensitivity analysis confirmed that the observed association between leukaemia and stronger magnetic fields was not due to the choice of exposure metric (geometric mean) or the definition of cut-points, and was not strongly influenced by any of the studies. Consideration of potential confounders did not materially affect the risk estimates. The summary relative risks for acute lymphoblastic leukaemia only were similar to those obtained for total leukaemia. While the relative risks for the intermediate exposure categories were 1.1 (95% CI, 0.88–1.3) for the category 0.1–< 0.2 μT and 1.1 (95% CI, 0.84–1.5) for the 0.2–< 0.4 μT category, the relative risk for the highest exposure category (≥ 0.4 μT) showed a twofold increase (2.1; 95% CI, 1.3–3.3).

A comparison was made in the pooled analysis between the number of observed cases and the number of expected cases under the null hypothesis at ≥ 0.4 μT. In three studies, no excess leukaemia cases were observed; these were the United Kingdom study (4 observed, 4.4 expected cases), the Norwegian study (0 observed, 2.7 expected) and the New Zealand study (0 observed, 0 expected). The summary numbers across all studies were 44 observed cases compared with 24.2 expected cases.

Another finding of this pooled analysis related to the so-called wire code paradox. In earlier reviews, it had been observed that there was a stronger association between surrogates for exposure to ELF electric and magnetic fields and leukaemia risk than between direct measurements and leukaemia risk. The new studies did not support this. The summary relative risk of the US (Linet *et al*., 1997) and Canadian studies

(McBride *et al*., 1999) combined for the highest wire-code category was 1.2 (95% CI, 0.82–1.9) which was lower than that in the measurement or calculated field studies.

(ii) Greenland *et al*. (2000) reported a pooled analysis of 16 studies of childhood leukaemia and residential magnetic fields, based on either magnetic field measurements or wire codes. In contrast to the pooled analysis by Ahlbom *et al*. (2000), this analysis also included studies that relied only on wire codes for exposure assessment as well as some of the earlier studies which were smaller and less methodologically sound than more recent studies. The additional studies not included by Ahlbom *et al*. (2000) were those by Wertheimer and Leeper (1979), Fulton *et al*. (1980), Tomenius (1986), Savitz *et al*. (1988), London *et al*. (1991), Coghill *et al*. (1996), Fajardo-Gutiérrez *et al*. (1997) and Green *et al*. (1999a,b). The study carried out in the United Kingdom (UK Childhood Cancer Study Investigators, 1999) was not included in this pooled analysis, and from the study by Green *et al*. (1999a,b), only wire-code data were included. Eight of the studies (Coghill *et al.*, 1996; Linet *et al.*, 1997; London *et al.*, 1991; Michaelis *et al.*, 1998; Savitz *et al.*, 1988; Tomenius, 1986; Dockerty *et al.*, 1998; McBride *et al.*, 1999) provided some direct measurements of magnetic fields; four studies from the Nordic countries (Feychting & Ahlbom, 1993, Sweden; Olsen *et al.*, 1993, Denmark; Verkasalo *et al.*, 1993, Finland; Tynes & Haldorsen, 1997, Norway) were based upon calculated historical fields. Most studies provided multiple measurements. The a-priori measurement chosen for this pooled analysis was the best approximation of TWA exposure up to three months before diagnosis. Magnetic field strengths were categorized into groups ≤ 0.1 μT, > 0.1–≤ 0.2 μT, > 0.2–≤ 0.3 μT and > 0.3 μT. Data were analysed using maximum likelihood logistic regression and tabular methods. For the wire code analyses, the referent group consisted of low wire codes (underground [UG], VLCC and ordinary low current [OLCC] combined). For the measurement analysis, the combined results of the 12 studies gave relative risks of 1.01 (95% CI, 0.84–1.2), 1.06 (95% CI, 0.78–1.4) and 1.7 (95% CI, 1.2–2.3) for > 0.1–≤ 0.2, > 0.2–≤ 0.3 and > 0.3 μT compared with < 0.1 μT, respectively, using Mantel-Haenszel summary estimates and adjusting for study, age and sex. Restricting the studies to those with complete covariate data resulted in very similar estimates. The relative risks were 1.01 (95% CI, 0.82–1.3), 0.94 (95% CI, 0.65–1.4) and 2.1 (95% CI, 1.4–3.0) for > 0.1–≤ 0.2, > 0.2–≤ 0.3 and > 0.3 μT, respectively, using Mantel-Haenszel summary estimates, and adjusting for age, sex and socioeconomic variables. For the analysis of wire codes, summary estimates were not given for all of the studies, because of a great deal of heterogeneity within the study results, ranging in relative risks for VHCC of < 1 in three studies to > 2 in three studies (homogeneity $p = 0.005$). Eliminating the two earliest studies, which had extreme results, the summary relative risks were 1.02 (95% CI, 0.87–1.2) and 1.5 (95% CI, 1.2–1.9) for OHCC and VHCC, respectively, based on six studies with wire code data. Covariate adjustment had little effect on these results. As with the pooled analysis of Ahlbom *et al.* (2000), the 'wire-code paradox' was not evident, since measured fields showed stronger associations with childhood leukaemia than did wire codes. The two pooled analyses reached similar conclusions.

2.2.2 *Exposure to ELF electric and magnetic fields from electrical appliances* (Table 23)

Seven studies have examined the relationship between use of household electrical appliances and all childhood cancers, childhood leukaemia or tumours of the brain and nervous system. The first study, as described above (Savitz *et al*., 1988), was conducted in Denver, CO, USA (Savitz *et al*., 1990). A total of 252 children with cancer, identified through a tumour registry and area hospitals, and 222 controls, identified by random-digit dialling, were interviewed. The response rates were 70.8% for cases (252/356 eligible cases) and 79.9% for eligible controls (222/278). Maternal use of appliances during pregnancy and the use of appliances by the children in the study were assessed. Results for four appliances were presented: electric blankets, heated water beds, bedside electric clocks and bed-heating pads. For ever-use of electric blankets during pregnancy, the adjusted odds ratio was 1.7 (95% CI, 0.8–3.6; 13 exposed cases) for leukaemia and 2.5 (95% CI, 1.1–5.5; 11 exposed cases) for brain cancer in children. Slightly stronger effects were noted when use during the first trimester of pregnancy was considered (leukaemia, odds ratio, 2.3 (95% CI, 1.0–5.8), 9 cases; brain cancer, odds ratio, 4.0 (95% CI, 1.6–9.9), 9 cases) and for more hours of use, i.e. > 8 h versus < 8 h (leukaemia, odds ratio, 11 (95% CI, 1.8–67), 4 cases; brain cancer, odds ratio, 4.6 (95% CI, 0.5–39), 1 case). No significant associations were found for childhood use of electric appliances. Electric blankets had been used in childhood by only 13 cancer cases and eight control children; the odds ratio was 1.5 (95% CI, 0.5–5.1) for leukaemia and 1.2 (95% CI, 0.3–5.7) for brain cancer. Odds ratios for use of electrically heated water beds and hair dryers were mostly below one and those for bedside electric clocks were slightly elevated, but not significant (odds ratio for total cancer, 1.3; 95% CI, 0.8–2.2). [The Working Group noted that a potential problem of the study, in addition to the possible selection bias described previously, is that parents of cases and controls were interviewed many years after the time period of interest.]

The second study to include use of electric appliances as part of assessment of exposure to magnetic fields was conducted in Los Angeles, CA, USA (London *et al*., 1991, 1993). Two hundred and thirty-two children with leukaemia and 232 matched controls were interviewed. There was no indication of any important associations between maternal use of electrical appliances during pregnancy and risk for childhood leukaemia, but there were several significantly elevated odds ratios for use of appliances during childhood. Exposure during childhood was defined as use at least once per week in comparison to no use of the appliance. For black-and-white televisions, the odds ratio was 1.5 (95% CI, 1.0–2.2); that for use of hair dryers was 2.8 (95% CI, 1.4–6.3). Elevations in risk were also seen for use of electric dial clocks (odds ratio, 1.9; 95% CI, 0.97–3.8), curling irons (odds ratio, 6.0; 95% CI, 0.72–105), electric blankets (odds ratio, 7.0; 95% CI, 0.86–122) and video games (odds ratio, 1.6; 95% CI, 0.8–3.3). [The Working Group noted that because of the small numbers of appliance users, no attempt had been made to define high- or low-exposure groups.]

Table 23. Case–control studies of childhood cancer in relation to use of electrical appliances

Reference, area	Study size and cancer site		Exposure	No. of cases	Risk estimates: odds ratios (95% CI)	Comment
Savitz *et al*. (1990), Denver, CO, USA	252 cases, 222 controls, aged 0–14 years, diagnosed 1976–83		**Electric blankets**			Unadjusted odds ratios. Evidence of effect modification by income; no consistent evidence for increased risks with water beds, bedside electric clocks or heating pads; study vulnerable to selection bias due to differential residential restrictions placed on cases versus controls
	All cancers	(233 cases)	Prenatal use	38	1.1 (0.7–1.8)	
		(244 cases)	Postnatal use	13	1.5 (0.6–3.4)	
	Leukaemia	(70 cases)	Prenatal use	13	1.3 (0.7–2.6)	
		(73 cases)	Postnatal use	4	1.5 (0.5–5.1)	
	Brain cancer	(45 cases)	Prenatal use	11	1.8 (0.9–4.0)	
		(47 cases)	Postnatal use	2	1.2 (0.3–5.7)	
London *et al*. (1991), Los Angeles, CA, USA	232 cases of leukaemia, 232 controls, aged 0–10 years, diagnosed 1980–87		**Electric blankets**			No evaluation by frequency and/or duration of use of appliances; assessment of use made many years after etiological time-period
			Prenatal use	23	1.2 (0.66–2.3)	
			Postnatal use	7	7.0 (0.86–122)	
			Water beds			
			Prenatal use	14	0.67 (0.34–1.3)	
			Postnatal use	12	1.0 (0.45–2.3)	
			Television (black and white)			
			Postnatal use	64	1.5 (1.0–2.2)	
			Hair dryer			
			Postnatal use	31	2.8 (1.4–6.3)	
McCredie *et al*. (1994), Australia	82 cases of brain tumour, 164 controls, aged 0–14 years, diagnosed 1985–89		**Postnatal**			No assessment of dose–response and only two appliances considered
			Electric blankets	6	0.4 (0.2–1.2)	
			Water beds	1	0.2 (0–1.5)	

Table 23 (contd)

Reference, area	Study size and cancer site	Exposure	No. of cases	Risk estimates: odds ratios (95% CI)	Comment
Preston-Martin *et al.* (1996a), Los Angeles, CA	298 cases of brain tumour, 298 controls, aged 0–19 years, diagnosed 1984–91	**Electric blankets**			Slightly, non-significantly elevated risks for electric heat: prenatal (odds ratio, 1.6; 95% CI, 0.8–3.0), postnatal (odds ratio, 1.3; 95% CI, 0.7–2.4); some indication of higher risks among cases diagnosed in earlier time-period, suggesting possible control selection bias
		Prenatal use	20	1.2 (0.6–2.2)	
		Postnatal use	11	1.2 (0.5–3.0)	
		Water beds			
		Prenatal use	23	2.1 (1.0–4.2)	
		Postnatal use	8	2.0 (0.6–6.8)	
		Television (black and white)			
		Postnatal use	20	0.7 (0.4–1.4)	
		Hair dryer			
		Postnatal use	55	1.2 (0.7–2.1)	
Gurney *et al.* (1996), Seattle, WA	133 cases of brain tumour, 270 controls; aged 0–19 years, diagnosed 1984–90	Electric blankets			Some elevated odds ratios for childhood use of digital clocks, black-and-white television, incubators, and baby monitors; no association for electric heat
		Prenatal use	20	0.9 (0.5–1.6)	
		Postnatal use	6	0.5 (0.2–1.4)	
		Water beds			
		Prenatal use	20	0.7 (0.4–1.3)	
		Postnatal use	8	0.8 (0.3–1.9)	

Table 23 (contd)

Reference, area	Study size and cancer site	Exposure	No. of cases	Risk estimates: odds ratios (95% CI)	Comment
Hatch *et al*. (1998), 9 mid-western and mid-Atlantic states	651 cases of acute lymphoblastic leukaemia, 651 matched controls, aged 0–14 years, diagnosed 1989–93	**Electric blankets**			Dose–response trends by frequency and duration of use of appliances were not apparent; results may have been affected by recall bias
		Prenatal use	91	1.6 (1.1–2.3)	
		Postnatal use	45	2.8 (1.5–5.0)	
		Sewing machines			
		Prenatal use	198	0.76 (0.59–0.98)	
		Television			
		(< 4 ft vs ≥ 6 ft [1.2 vs ≥ 1.8 m] from TV)			
		Prenatal use	17	1.9 (0.79–4.5)	
		Postnatal use	166	1.6 (1.1–2.4)	
		≥ 6 h vs < 2 h/day			
		Postnatal use	178	2.4 (1.5–3.8)	
		Hair dryer			
		Postnatal use	266	1.6 (1.2–2.1)	
Dockerty *et al*. (1998), New Zealand	303 cancer cases, 303 controls, aged 0–14 years, diagnosed 1990–93				Adjusted odds ratios. No assessment of dose–response trends by amount of use
		Electric blankets			
	Leukaemia (121 cases)	Prenatal use	30	0.8 (0.4–1.6)	
		Postnatal use	17	2.2 (0.7–6.4)	
	Central nervous system cancer (58 cases)	Prenatal use	18	1.6 (0.6–4.3)	
		Postnatal use	8	1.6 (0.4–7.1)	
	Other solid tumours (124 cases)	Prenatal use	35	1.8 (0.9–3.5)	
		Postnatal use	26	2.4 (1.0–6.1)	

TV, television

McCredie *et al*. (1994) included an assessment of use of electric blankets and water beds in a study of childhood brain tumours (ICD-9, 191, 192) in New South Wales, Australia. A total of 97 eligible children aged 0–14 years and diagnosed with a brain tumour between 1985 and 1989, were identified from a population-based cancer registry for the areas of Sydney, Wollongong and Newcastle. Eighty-two (85%) of the mothers of children with cancer were interviewed. Potential control mothers were identified from electoral rolls in a two-phase selection process. Sixty per cent (400/672) of the mothers of eligible control children agreed to be interviewed and 164 of them were interviewed. Childhood use of electric blankets and water beds were the only potential sources of exposure to magnetic field assessed in this study. The odds ratio was 0.4 (95% CI, 0.2–1.2) for regular use of an electric blanket and 0.2 (95% CI, 0–1.5) for regular use of a water bed.

Preston-Martin *et al*. (1996b) studied the use of electrical appliances in relation to risk for childhood brain tumours (ICD-9 191, 192). Children aged 0–19 years, with brain tumours diagnosed between 1984 and 1991 were identified from three population-based cancer registries on the West Coast of the USA (Los Angeles County, five counties of the San Francisco area and 13 counties in Washington State including Seattle) for the years 1984–91. Controls were identified by random-digit dialling and were frequency-matched by age and sex to the case group. Mothers of a total of 540/739 cases (73%) and 801/1079 controls (74%) were interviewed about their use of electric blankets and electrically heated water beds during pregnancy and about use by the child after birth. No association of brain tumours with in-utero exposure to electric blankets (odds ratio, 0.9; 95% CI, 0.6–1.2) or use by the child (odds ratio, 1.0; 95% CI, 0.6–1.7) was found. There was also no effect of in-utero exposure resulting from use of water beds by the mother (odds ratio, 0.9; 95% CI, 0.6–1.3) or of use of water beds by children (odds ratio, 1.2; 95% CI, 0.7–2.0). When the analysis was restricted to the Los Angeles county (Preston-Martin *et al.* (1996a), the odds ratios for electric blankets were 1.2 (95% CI, 0.6–2.2) and 1.2 (95% CI, 0.5–3.0) for in-utero and postnatal exposure, respectively, and for water beds, the odds ratios were 2.1 (95% CI, 1.0–4.2) and 2.0 (95% CI, 0.6–6.8), respectively.

In a subset of the study population from the Seattle area (98 cases and 208 controls), Gurney *et al*. (1996) reported small, but non-significant elevations in risk for brain tumours associated with childhood use of portable black-and-white televisions (odds ratio, 1.6; 95% CI, 0.6–3.9), bedside digital clocks (odds ratio, 1.8; 95% CI, 0.9–3.3) and incubators (odds ratio, 1.5; 95% CI, 0.8–3.1), but no elevations in risk were associated with maternal use of appliances during pregnancy. In another subset of 133 cases and 270 controls, no association was seen for prenatal or postnatal exposure to electric blankets or water beds.

Hatch *et al*. (1998) examined both prenatal and postnatal use of appliances in the National Cancer Institute/Children's Cancer Group Study in the USA as described above. Interview data on the use of electrical appliances was available for 788 children, aged 0–14 years, with acute lymphoblastic leukaemia diagnosed between 1989 and 1993

[88% response] and 699 controls [64% response], providing 651 matched pairs. The use of several appliances during the prenatal period was significantly associated with the occurrence of acute lymphoblastic leukaemia, but there was no evidence of a dose–response effect. For ever- versus never-use by the mother during pregnancy, the odds ratios for the offspring were 1.6 (95% CI, 1.1–2.3) for electric blankets, 1.5 (95% CI, 1.0–2.1) for bed-heating pads, 1.4 (95% CI, 1.0–2.0) for humidifiers and 0.76 (95% CI, 0.59–0.98) for sewing machines. Some significant associations with childhood leukaemia were also found with use of electrical appliances during childhood, based on the mother's report. Ever-use of an electric blanket prior to the reference date was associated with an odds ratio of 2.8 (95% CI, 1.5–5.0), but the highest risk was found for the shortest duration of use in years (odds ratio for < 1 year of use, 5.5; 95% CI, 1.1–26). Similarly, the odds ratio for ever-use of a hair dryer was 1.6 (95% CI, 1.2–2.1), but the highest risk was for children who had used one hair dryer for less than one year (odds ratio, 2.5; 95% CI, 1.3–4.9). There was some suggestion of effects for video arcade games (odds ratio, 1.7; 95% CI, 1.2–2.3) and video games connected to televisions (odds ratio, 1.9; 95% CI, 1.4–2.7), but no indication of increased risks associated with use of a personal computer (odds ratio, 1.2; 95% CI, 0.83–1.7). The risk increased with increasing amount of time spent watching television (odds ratio for ≥ 6 h per day versus < 2 h per day, 2.4; 95% CI, 1.5–3.8), but these effects were seen regardless of the reported distance that the child sat from the television.

Dockerty *et al*. (1998) included assessment of exposure to electrical appliances in a nationwide study of childhood cancer in New Zealand (described above) (303 cases, 303 controls). There was little evidence for any relationship between maternal use of electrical appliances in pregnancy and childhood cancer. The odds ratios for use of electric blankets were 0.8 (95% CI, 0.4–1.6) for leukaemia, 1.6 (95% CI, 0.6–4.3) for cancers of the central nervous system and 1.8 (95% CI, 0.9–3.5) for other solid tumours. For childhood use of appliances, there was some suggestion of an increased risk associated with the use of an electric blanket. The odds ratios were 2.2 (95% CI, 0.7–6.4) for leukaemia, 1.6 (95% CI, 0.4–7.1) for tumours of the central nervous system and 2.4 (95% CI, 1.0–6.1) for other solid tumours. There was also the suggestion of an effect for electric heating, but only in the room occupied during the day (odds ratio, 1.8; 95% CI, 0.9–3.5), not in the child's bedroom (odds ratio, 1.0; 95% CI, 0.5–2.3).

2.2.3 *Parental exposure to ELF electric and magnetic fields*

(*a*) *Cohort study*

Feychting *et al*. (2000) conducted a cohort study on occupational exposure of parents to magnetic fields and cancer in offspring. Children born in Sweden in 1976, 1977, 1981 and 1982 were followed until 1993, and those who developed cancer before the age of 15 years were identified. A total of 522 children with cancer including 161 with leukaemias and 162 with cancer of the central nervous system were identified. The occupations of their mothers and fathers were taken from data recorded in the 1975 and

1980 censuses. The percentages of parents without a recorded job were 27.1% for mothers and 5.4% for fathers. The likelihood of occupational exposure to electric and magnetic fields was quantified through use of a job–exposure matrix. For children whose mothers had been exposed to magnetic fields ≥ 0.19 μT (third quartile) or ≥ 0.26 μT (90th percentile), the relative risks for all types of tumour were close to unity (relative risk, 1.1 (95% CI, 0.7–1.4) and relative risk, 1.1 (95% CI, 0.7–1.7), respectively). For children whose fathers had been exposed to magnetic fields ≥ 0.3 μT, the risk for leukaemia was elevated (relative risk, 2.0; 95% CI, 1.1–3.5) and the risk for cancers of the central nervous system was less than unity (relative risk, 0.5; 95% CI, 0.3–1.0).

(*b*) *Case–control studies*

In a case–control study of 157 children, less than 15 years of age, who had died of neuroblastoma during 1964–78 in Texas, USA, Spitz and Johnson (1985) reported an elevated risk for neuroblastoma (odds ratio, 2.1; 95% CI, 1.1–4.4) among the children of electrical workers. Data on parental occupation at birth of the child were abstracted from the birth certificate, and exposure was inferred from occupational title.

A subsequent hospital-based study on the incidence of neuroblastoma in Ohio, USA of 101 incident cases of neuroblastoma in children < 15 years old born during 1942–67 and 404 controls (Wilkins & Hundley, 1990) made use of information on paternal occupation from birth certificates to infer exposure, but found no association between employment of the father in an electrical occupation and risk of neuroblastoma in the offspring.

Bunin *et al*. (1990) conducted a small case–control study of neuroblastoma in 104 children diagnosed from 1970–79 at two hospital-based tumour registries in North-east USA. One hundred and four controls were selected by random-digit dialling. Data on parental occupation were obtained by telephone interview and exposure to electric and magnetic fields was classified using the same scheme as that used by Spitz and Johnson (1985). No association was seen between neuroblastoma in offspring, and exposure of fathers employed as electricians, insulation workers or power utility workers during the preconception period (odds ratio, 0.3; 95% CI, 0.1–1.2) or mother's exposure during pregnancy (same occupational groups as for fathers) (0.3; 95% CI, 0.1–1.3).

Nasca *et al.* (1988) conducted a case–control study of children with cancer and parental occupation. Three hundred and thirty-eight children (aged 0–14 years) with a primary tumour of the central nervous system diagnosed between 1968 and 1977 in 53 New York counties were included. Six hundred and seventy-six controls matched by age and geographical location were also selected. Parents were interviewed by telephone to obtain job information. Exposure was classified according to occupational title. No association was seen between cancer of the central nervous system in offspring and parental exposure to electric and magnetic fields before the birth of the child (odds ratio, 1.6; 95% CI, 0.83–3.1).

Wilkins and Koutras (1988) in Ohio, USA, conducted a case–control study of mortality from brain cancer during 1959–78. The study population included 491 offspring (< 20 years of age) of men whose job title suggested occupational exposure to electric and magnetic fields. An elevated risk of brain cancer was seen in the children of men involved in electrical assembly, installation and repairing occupations (odds ratio, 2.7; 95% CI, 1.2–6.1).

Johnson and Spitz (1989) conducted a mortality case–control study of all children under the age of 15 years who had died in Texas, USA from 1964–80 of intracranial and spinal cord tumours (499 cases, 998 controls). Data on parental occupation collected at birth of the children were used to infer exposure. For all occupational categories thought to involve potential exposure of parents to ELF electric and magnetic fields, the risk was marginally elevated (odds ratio, 1.6; 95% CI, 0.96–2.8) in the offspring.

Parental occupation as a risk factor for astrocytoma in children aged 0–14 was examined by Kuijten *et al*. (1992). The patients were identified through tumour registries in eight hospitals in Pennsylvania, New Jersey and Delaware (USA) and included all cases diagnosed from 1980–86. Controls were selected by random-digit dialling and were pair-matched to cases by age, race and telephone exchange. The mothers and fathers of the 158 case–control pairs were interviewed by telephone, and exposure to electric and magnetic fields was inferred from job title. In general no associations with childhood astrocytoma were seen; however, in a sub-analysis, men reported as being ‘electrical repairing workers’ during the preconception period had a significantly elevated risk of fathering a child who later developed astrocytoma (odds ratio, 8.0; 95% CI, 1.1–356).

Wilkins and Wellage (1996) identified 94 patients aged 20 years or less with tumours of the central nervous system who were diagnosed during the years 1975–82 through the Columbus Children’s Hospital Tumor Registry (USA). Random-digit dialling was used to select 166 controls from the 48-county referral area of the registry. For fathers who had occupations presumed to have resulted in exposure to electric and magnetic fields during the period before conception, no elevated risk of cancer of the central nervous system was noted in their offspring. However, exposure of the father working in welding-related jobs during preconception was associated with an elevated risk (odds ratio, 3.8; 95% CI, 0.95–16).

2.3 Cancer in adults

2.3.1 *Residential exposure to ELF electric and magnetic fields*

In addition to the many methodological considerations discussed in other sections, including the lack of studies that have included a comprehensive assessment of exposure, residential studies of adults present unique difficulties. These problems are:

— the contribution of occupational exposure — not considered in most studies;
— the lack of assessment of other sources of exposure likely to be important for adults who spend only a fraction of their time at home;

— the long latency period for most adult malignancies, often necessitating assessment (owing to residential mobility) in several residences;
— the need to use proxy response for deceased cases; and
— low participation rates.

The assessment of exposure in most of the following studies was based either on proximity to electrical installations or on simple questions regarding appliance use. Few studies included spot measurements in several locations. Even long-term residential measurements are unlikely to capture the strength or variability of daily exposure for working adults. In a 1000-person study, Zaffanella and Kalton (1998) found that occupational exposure was often significantly higher and more variable than other sources of exposure; the highest mean and median exposure occurs at work, followed by exposure at home and during travel. Since most people spend much of their time at home, ignoring exposure either at home or at work is likely to lead to a large misclassification. In a small study of the use of household appliances, Mezei *et al*. (2001) found that a large proportion of total exposure for most adults is accumulated at home. Similarly, the 1000-person study found exposure at home to be moderately predictive of 24-h average exposure or of time spent in magnetic fields above 0.4 μT, but completely uncorrelated with maximum fields or with field changes.

The long latency of cancers in adults and the unknown biological mechanism necessitate estimation of exposure over long time periods, an exceptionally difficult task owing to the mobility and behavioural changes likely to occur with time. The situation is even more difficult for rapidly fatal diseases such as brain cancer about which information is generally obtained from numerous proxies.

Following the publication of the study by Wertheimer and Leeper (1979) suggesting an association between residential exposure to ELF magnetic fields and cancer in children (see p. 105), many studies have investigated the possible carcinogenic effects of electric and magnetic fields. Most of the epidemiological studies have focused on cancer in children (see section 2.2). Studies of adults have looked primarily at occupational exposure, but some have investigated residential settings. As shown in Table 24, which lists studies of residential adult cancer by exposure category, several studies have investigated links between the use of electric blankets and breast cancer. Many studies have examined proximity to power lines and cancer, focusing particularly on leukaemia and brain cancer, but studies in which a sophisticated assessment of exposure has been made are few.

The first study on residential exposure to ELF magnetic fields and adult cancer was conducted by Wertheimer and Leeper (1982) in the USA. [The Working Group noted that this was a hypothesis-generating paper, but its usefulness for hypothesis testing was compromised because of unblinded exposure assessment, potential overmatching for the Denver cases and the unusual and complex method for selection of cases and controls.]

Table 24. Residential studies of adult cancer by exposure category

Outcome	Exposure					
	Electric blanket	Other appliances	Proximity	Calculated fields	Spot measurements	Combined occupational and residential
Leukaemia						
Wertheimer & Leeper (1987)	–	–	4	–	–	–
McDowall (1986)	–	–	4	–	–	–
Coleman *et al*. (1989)	–	–	4	–	–	–
Youngson *et al*. (1991)	–	–	4	4	–	–
Schreiber *et al*. (1993)	–	–	4	–	–	–
Severson *et al*. (1988)	4	–	4	–	4	–
Feychting & Ahlbom (1994)	–	–	4	4	4	–
Feychting *et al*. (1997)	–	–	–	–	–	4
Verkasalo *et al*. (1996)	–	–	–	4	–	–
Li *et al*. (1997)	–	–	4	4	–	–
Preston-Martin *et al*. (1988)	4	–	–	–	–	–
Lovely *et al*. (1994)	–	4	–	–	–	–
Sussman & Kheifets (1996)	–	4	–	–	–	–
Brain						
Wertheimer & Leeper (1982, 1987)	–	–	4	–	–	–
Schreiber *et al*. (1993)	–	–	4	–	–	–
Feychting & Ahlbom (1994)	–	–	4	4	–	–
Feychting *et al*. (1997)	–	–	–	–	–	4
Verkasalo *et al*. (1996)	–	–	–	4	–	–
Li *et al*. (1997)	–	–	4	4	–	–
Wrensch *et al*. (1999)	–	–	4	–	4	–
Ryan *et al*. (1992)	4	4	–	–	–	4
Mutnick & Muscat (1997)	4	4	–	–	–	–

Table 24 (contd)

Outcome	Exposure					
	Electric blanket	Other appliances	Proximity	Calculated fields	Spot measurements	Combined occupational and residential
Breast						
Wertheimer & Leeper (1982; 1987)	–	–	4	–	–	–
McDowall (1986)	–	–	4	–	–	–
Schreiber *et al* (1993)	–	–	4	–	–	–
Verkasalo *et al* (1996)	–	–	–	4	–	–
Li *et al*. (1997)	–	–	4	4	–	–
Coogan & Aschengrau (1998)	4	4	4	–	–	4
Feychting *et al*. (1998)	–	–	–	4	–	–
Forssén *et al*. (2000)	–	–	–	–	–	4
Vena *et al*. (1991, 1994, 1995)	4	–	–	–	–	–
Gammon *et al*. (1998)	4	–	–	–	–	–
Laden *et al*. (2000)	4	–	–	–	–	–
Zheng *et al*. (2000)	4	4	–	–	–	–
Other cancers						
Wertheimer & Leeper (1982, 1987)	–	–	4	–	–	–
Verkasalo *et al.* (1996)	–	–	–	4	–	–
Zhu *et al*. (1999)	4	–	–	–	–	–

(*a*) *Leukaemia*

Early studies of leukaemia focused mostly on the potential association between proximity to power lines and cancer development. From 1971–83, McDowall (1986) followed a cohort of 7631 people in East Anglia, England, who lived within 50 m of a substation or other electrical installation, or within 30 m of overhead power lines at the time of the 1971 census. Coleman *et al*. (1989) conducted a case–control study of leukaemia and residential proximity to electric power facilities in four London boroughs. Seven hundred and seventy-one leukaemia cases diagnosed between 1965 and 1980 were identified from a population-based cancer registry. In a matched case–control study, Youngson *et al*. (1991) investigated adult haematological malignancies in relation to overhead power lines; the study included 3144 adults with leukaemia identified from regional cancer registries in north-west England and Yorkshire; controls were selected from hospital discharge listings. Schreiber *et al*. (1993) investigated mortality and residence near electric power facilities in a retrospective cohort study of 3549 people who lived for five consecutive years between 1956 and 1981 in an urban quarter of Maastricht, The Netherlands. Koifman *et al*. (1998) investigated cancer clusters near power lines in Brazil; small numbers and other methodological problems make the study uninformative for evaluation, and it is mentioned here only for completeness. [The Working Group noted that although some of these studies indicated a small, non-significant elevation of risk, they are based on small numbers, low potential exposures and very crude exposure assessment methods. The overall results are non-informative.]

Several studies of adult leukaemia deserve special mention, including Severson *et al*. (1988), Feychting and Ahlbom (1994), with a follow-up study by Feychting *et al*. (1997), and studies by Verkasalo (1996), Verkasalo *et al*. (1996) and Li *et al*. (1997) (see Table 25).

Severson *et al*. (1988) conducted a case–control study of 164 adults, both living and deceased, diagnosed with acute non-lymphocytic leukaemia in the USA. The patients studied were aged from 20–79 years, diagnosed between 1981 and 1984 and recorded in a population-based cancer registry in western Washington State. The response rate was 70%. For controls, the response rate was 65%. One hundred and fourteen patients (or the next-of-kin if the patient had died) and 133 controls completed detailed questionnaires on residential history and use of electrical appliances. Three different methods were used to assess exposure. (1) The wire-coding scheme of Wertheimer and Leeper (1979) was used to classify all homes in the study area in which a subject had lived in the previous 15 years. Residential magnetic fields were also estimated according to a method developed by Kaune *et al*. (1987) using wiring configuration maps of dwellings. (2) Single measurements of indoor and outdoor magnetic fields were made at the time of the interview in a subject's home if the subject had lived there continuously for one year or longer immediately preceding the reference date (controls) or the date of diagnosis (cases). Measurements were made in the kitchen, the subject's bedroom and the family room, under both low-power (all possible appliances

Table 25. Design and results of epidemiological studies of residential exposure to ELF magnetic fields and adult leukaemia

Reference, country	Study base and subject identification	Exposure metrics	Results				Comments
Severson *et al.* (1988) USA	**Case selection**: ANLL cases aged 20–79 years, resident in western Washington state, from cancer registry (1981–84). 114 cases included in analyses (91 AML) **Control selection**: controls from random-digit dialling, matched on geographical area and frequency matched on age and sex. 133 controls included in analyses	Wertheimer and Leeper wire-coding. Estimation of magnetic fields from maps and wire coding — method of Kaune *et al.* (1987). Single measurements of 60-Hz magnetic fields inside (kitchen, bedroom, family room in HPC and LPC) and outside house; 24-h measurements in sample of houses. Electric appliance use from questionnaire	Mean exposure, low-power configuration				Refusal rate for measurements much higher among controls than cases. Single measurements made in only 56% of houses as many subjects had moved recently
				Ref.: ≤ 0.05 µT		OR (95% CI)	
			Single measurements	0.051–0.199 µT ≥ 0.2 µT		1.2 (0.52–2.6) 1.5 (0.48–4.7)	
			Weighted mean	0.051–0.199 µT ≥ 0.2 µT		1.2 (0.54–2.5) 1.0 (0.33–3.2)	
Feychting & Ahlbom (1994) Sweden	**Case selection**: All incident cancer cases from cancer registry (1960–85), from cohort of Swedish population aged ≥ 16 years, living on a property located within 300 m of any 220- or 400-kV power lines. 325 cases analysed (72 AML, 57 CML, 14 ALL and 132 CLL) **Control selection**: Two controls per case from same cohort. Matched on age, sex, parish and residence near same power line. 1091 controls in analysis	Distance to power lines from residence. In-home magnetic-field spot measurements under low- and high-power use conditions. Calculations were made of magnetic fields generated by power lines at the time of spot measurements (calculated contemporary fields) and for the year closest in time to diagnosis (calculated historical fields).	Calculated fields closest to time of diagnosis				Matched and unmatched analyses, adjusted or not for age and socioeconomic status were carried out. No information on other sources of residential exposure to electric and magnetic fields
				Ref.: ≤ 0.09 µT	No.	OR (95% CI)	
			All leukaemia	0.10–0.19 µT ≥ 0.2 µT	20 26	0.9 (0.5–1.5) 1.0 (0.7–1.7)	
			AML	0.10–0.19 µT ≥ 0.2 µT	5 9	1.0 (0.4–2.5) 1.7 (0.8–3.5))	
			CML	0.10–0.19 µT ≥ 0.2 µT	2 7	1.4 (0.5–3.3) 1.7 (0.7–3.8)	
			CLL	0.10–0.19 µT ≥ 0.2 µT	8 7	0.8 (0.4–1.7) 0.7 (0.3–1.4)	
Feychting *et al.* (1997) Sweden	Same as Feychting and Ahlbom (1994)	Same as above for residential. Occupational exposure from job–exposure matrix [developed from workday measurements made for another study] and information on occupation held in the year preceding the reference date	Subjects with both residential and occupational exposure				Same as above. Job–exposure matrix. Relevance especially for females unclear
			Ref.: ≤ 0.1 µT res. and < 0.13 µT occ.		No.	OR (95% CI)	
			All leukaemia	≥ 0.2 µT for both	9	3.7 (1.5–9.4)	
			AML	≥ 0.2 µT for both	3	6.3 (1.5–26)	
			CML	≥ 0.2 µT for both	3	6.3 (1.5–27)	
			CLL	≥ 0.2 µT for both	2	2.1 (0.4–10)	

Table 25 (contd)

Reference, country	Study base and subject identification	Exposure metrics	Results				Comments
Verkasalo *et al*. (1996) Finland	**Cohort** consisting of 383 700 persons (189 300 men) aged 20 years or older who contributed 2.5 million person–years of follow-up between 1970 and 1989 **Case selection**: All primary leukaemia cases (1974–89) living within 500 m of overhead power lines. 203 cases identified	Cumulative exposure. Estimates based on residential history, distance to 110–400 kV power line in 500 m corridor and calculated average annual magnetic fields for each building presumed to be ≥ 0.01μT. Took into account current, typical locations of phase conductors and distance.	Cumulative exposure				Cohort study, SIRs. No information on other sources of residential exposure to electric and magnetic fields. No direct information from study subjects
			Ref.: general population		No.	SIR (95% CI)	
			All leukaemia	< 0.20 μT	156	0.96 (0.82–1.1)	
				0.20–0.39 μT	23	1.1 (0.68–1.6)	
				0.40–0.99 μT	15	0.87 (0.49–1.4)	
				1.00–1.99 μT	5	0.81 (0.26–1.9)	
				≥ 2.0 μT	4	0.71 (0.19–1.8)	
Verkasalo (1996) Finland	**Case selection**: Same as Verkasalo *et al*. (1996): 196 leukaemia cases included (60 AML, 12 ALL, 30 CML, 73 CLL and 21 other or unknown subtype) **Control selection**: 10 controls per case from cohort. Matched on sex and age at diagnosis and alive in the year of diagnosis of the case	Cumulative exposure: total and within 0–4, 5–9 and ≥ 10 years of diagnosis. Annual average magnetic fields 1–20 years prior to diagnosis. Highest annual average magnetic field ever and in time windows before diagnosis. Age at first exposure to annual average magnetic field greater than a specific level. Duration and time since exposure to annual averages above that level	Cumulative exposure				
			Ref.: < 0.2 μT–years		No.	OR (95% CI)	
			All leukaemia	≥ 2.0 μT–years	4	0.77 (0.28–2.2)	
			ALL	≥ 2.0 μT–years	none		
			AML	≥ 2.0 μT–years	none		
			CML	≥ 2.0 μT–years	none		
			CLL	≥ 2.0 μT–years	3	1.7 (0.48–5.8)	
Li *et al*. (1997)	**Case selection**: Pathologically confirmed incident cases of leukaemia from northern Taiwan from cancer registry (1987–92). 870 cases included in analyses **Control selection**: One control per case from cancer registry excluding cancers of the brain and breast, haematopoietic and reticulo-endothelial system, skin, ovary, fallopian tube and broad ligament. Matched on date of birth, sex and date of diagnosis. 889 controls included in analyses	Distance from lines. Average and maximum magnetic fields assessed using distance from the lines, distance between wires, height of wires above the ground, annual and maximum loads along the lines from 1987–92, current phase and geographical resistivity of earth	Calculated exposure in year of diagnosis				Limited information on confounders because of restrictions on interview
			Ref.: < 0.1 μT		No.	OR (95% CI)	
			All leukaemia	0.1–0.2 μT	47	1.3 (0.8–1.9)	
				> 0.2 μT	97	1.4 (1.0–1.9)	
			ALL	0.1–0.2 μT	8	1.5 (0.7–3.2)	
				> 0.2 μT	17	1.7 (1.0–3.1)	
			AML	0.1–0.2 μT	28	1.5 (0.9–2.5)	
				> 0.2 μT	41	1.1 (0.7–1.7)	
			CML	0.1–0.2 μT	2	0.3 (0.1–1.2)	
				> 0.2 μT	22	1.5 (0.9–2.6)	
			CLL	0.1–0.2 μT	4	2.8 (0.9–9.3)	
				> 0.2 μT	3	0.6 (0.1–2.6)	

ANNL, acute non-lymphocytic leukaemia; AML, acute myeloid leukaemia; OR, odds ratio; CI, confidence interval; CML, chronic myeloid leukaemia; ALL, acute lymphoblastic leukaemia; CLL, chronic lymphocytic leukaemia; SIR, standardized incidence ratio; HPC, high-power configuration; LPC, low-power configuration; res., residential; occ., occupational; Ref.:, reference group with exposure level indicated turned off that could be (without overly disrupting the household) and high-power conditions (all such appliances switched on). (3) In a limited sample of dwellings, 24-h measurements were made. [However, neither details of the 24-h measurements nor the relevant results were given.] Cases tended to be of lower socioeconomic status than controls and were more likely to smoke or to have smoked in the past; these factors were adjusted for in subsequent analyses. No association was found between acute non-lymphocytic leukaemia and wire codes, either in the dwelling occupied for the longest period in the 3–10 years before the reference date or in the dwelling occupied closest to the reference date. There was also no association with TWA exposure to residential magnetic fields. For single measurements, available for only 56% of homes since many subjects had moved house after the reference date, a non-significant increase in odds ratio was found for mean exposures of ≥ 0.2 μT in both low-power (odds ratio, 1.5; 95% CI, 0.48–4.7) and high-power conditions (odds ratio, 1.6; 95% CI, 0.49–5.0). When weighted mean exposure was considered, the increase was no longer apparent in low-power conditions and was reduced in high-power conditions (odds ratio, 1.3; 95% CI, 0.35–4.5). [The Working Group noted that the participation rates in this study were low.]

Feychting and Ahlbom (1992a,b; 1994) conducted a nested case–control study of leukaemia and cancer of the central nervous system in a Swedish population who had lived for at least one year within 300 m of overhead 220- and 400-kV power lines between 1960 and 1985. The adult study population included 400 000 people ≥ 16 years of age, identified from the Population Registry, who lived on properties designated using maps from the Central Board for Real Estate Data, as being located within the power-line corridor. From this cohort, leukaemia cases were identified by record linkage with the Swedish Cancer Registry. Two controls for each case were selected at random from members of the cohort who had lived in the power-line corridor at least one year before the reference date (year of diagnosis of the case) and lived near the same power line as the corresponding case. Cases and controls were matched on age (within five years), sex, parish of residence and year of diagnosis. A total of 325 cases of leukaemia and 1091 controls were included in the analysis. Seventy-two of the cases had acute myeloid leukaemia, 57 chronic myeloid leukaemia, 14 acute lymphoblastic leukaemia, 132 chronic lymphocytic leukaemia and 50 had other types of leukaemia. In addition to spot measurements and distance from power lines, exposure metrics included estimated magnetic fields within residences as a function of their proximity to the lines. These fields were calculated from an engineering model that took into account past exposure (dating back to 1947, over more than three decades), physical dimensions of lines and their distance from a dwelling. The model served as the primary exposure index. Magnetic field strengths were estimated from calculations for the year of diagnosis, or the year closest to diagnosis if the subject had moved, as well as for one, five and 10 years before diagnosis. Cumulative exposure was also calculated by summing yearly averages for exposure to magnetic fields assigned to each of the 15 years before diagnosis. The study included information on age, sex, year of diagnosis, whether or not the subject resided in the county of Stockholm, type of housing and socioeconomic status. Some types of leukaemia were positively associated with fields calculated from the historical model and with proximity to the power line, but not with spot measurements. There was no association between the risk for all leukaemias and calculated exposure to magnetic fields closest to the time of diagnosis. For acute and chronic myeloid leukaemias, however, odds ratios were non-significantly increased for fields ≥ 0.2 μT compared with fields ≤ 0.09 μT. For acute myeloid leukaemia, the odds ratio, based on nine exposed cases, was 1.7 (95% CI, 0.8–3.5); for chronic myeloid leukaemia, the odds ratio, based on seven exposed cases, was 1.7 (95% CI, 0.7–3.8). For analyses based on calculated cumulative exposure during the 15 years preceding diagnosis, the odds ratios for all leukaemias were 1.0 (95% CI, 0.6–1.8) for cumulative exposures of 1.0–1.9 μT–years (16 cases), 1.5 (95% CI, 1.0–2.4) for ≥ 2.0 μT–years (29 cases) and 1.5 (95% CI, 0.9–2.6) for ≥ 3.0 μT–years (19 cases), in comparison with ≤ 0.99 μT–years. Odds ratios were increased for exposure ≥ 2.0 μT–years for acute myeloid leukaemia (odds ratio, 2.3; 95% CI, 1.0–4.6) (nine cases) and for exposure > 3.0 μT–years for chronic myeloid leukaemia (odds ratio, 2.7; 95% CI, 1.0–6.4) (6 cases). Adjustment for age and socioeconomic status had little effect on the results. Also, the results of matched analyses were similar to those of the unmatched analyses. For analyses based on spot measurements, odds ratios were close to unity for all categories of exposure and for all leukaemia subtypes, except for chronic myeloid leukaemia in the ≥ 0.2-μT category (odds ratio, 1.5; 95% CI, 0.7–3.2) (10 cases). [The Working Group noted that exposure assessment for leukaemia was complicated by the long time-period covered by the study, which necessitated estimation of field strengths going back 25 years or more.]

Feychting *et al*. (1997) conducted a follow-up study using the same study base together with information on occupation taken from censuses performed by Statistics Sweden every five years. For the occupation held in the year before the reference date, they assessed exposure based on a job–exposure matrix from a previous study (Floderus *et al*., 1993, 1996). In that study, workday measurements had been made for a large number of jobs held by a sample of the general male population; consequently, no information was available on the occupations of 43% of the women. Combined analysis of residential and occupational exposure showed that subjects who had only residential exposure in the highest category (compared with ‘unexposed’ subjects with residential exposure < 0.1 μT and occupational exposure < 0.13 μT) had the following odds ratios: for acute myeloid leukaemia, 1.3 (95% CI, 0.4–5.0) (3 cases), and for chronic myeloid leukaemia, 0.5 (95% CI, 0.1–3.9) (1 case). [The very small number of cases prevents any interpretation of these results.] The odds ratios for subjects who had both high occupational and high residential exposure were much higher: for acute myeloid leukaemia, the odds ratio was 6.3 (1.5–26) and for chronic myeloid leukaemia the odds ratio was 6.3 (95% CI, 1.5–27), based on three exposed cases of each subtype). [The Working Group noted that the limitations of the previous study also apply to this one. The information on occupational exposure was difficult to interpret because of the limited applicability of the job–exposure matrix to this population.]

In a nationwide cohort study of 383 700 adults in Finland, Verkasalo *et al*. (1996) investigated cancer risk and exposure to magnetic fields in homes near high-voltage power lines. The cohort included all adults who had lived within 500 m of overhead power lines in homes with calculated magnetic field strengths of ≥ 0.01 μT at any time between 1970 and 1989. Through record linkage between nationwide data files (from the Finnish Cancer Registry, the Central Population Register, the 1970 Population Census, and the five Finnish power companies), information was obtained on cancer cases, residential history and residential exposure to magnetic fields. Follow-up took place from January 1974 until December 1989. Verkasalo (1996) presented a detailed case–control analysis of leukaemia. Of a total of 196 patients with leukaemia included in the study, 60 had acute myeloid leukaemia, 12 acute lymphoblastic leukaemia, 30 chronic myeloid leukaemia, 73 chronic lymphocytic leukaemia and 21 other, or unknown, subtypes. For each case, 10 controls were selected from the cohort and matched on sex, age at diagnosis of the case (within one year) and whether they were alive in the year of diagnosis. Several exposure measures were used. These included cumulative exposure and exposure 0–4, 5–9 and ≥ 10 years before diagnosis; annual average magnetic fields 1–20 years before diagnosis; highest annual average magnetic field 0–4, 5–9 and ≥10 years before diagnosis; age at first exposure to an annual average magnetic field greater than a specified strength; and duration of exposure and time since exposure to annual averages above that strength. No association was seen between the risk for all leukaemias or for specific subtypes and cumulative exposure or highest annual average exposure. Adjustment for type of housing or for occupational exposure (none versus possible or probable, based on expert judgement) did not affect the results. On the basis of three exposed cases, the study showed a significant increase in risk for chronic lymphocytic leukaemia with dichotomized cumulative exposure of ≥ 0.2 μT–years and ≥ 0.4 μT–years for ≥ 10 years before diagnosis (odds ratios, 2.8 (95% CI, 1.1–7.4) (9 cases) and 4.6 (95% CI, 1.4–15) (6 cases), respectively) and for duration of exposure to fields of ≥ 0.1 μT for ≥ 12 years (odds ratio, 4.8; 95% CI, 1.5–15) (3 cases). No association was observed for other types of leukaemia. [The Working Group noted that no measurements were made to validate the calculated fields in this study, and that the lack of information on other sources of residential exposure to electric and magnetic fields might have resulted in substantial exposure misclassification.]

Li *et al*. (1997) conducted a case–control study of leukaemia and other cancers in adults living in northern Taiwan. Cases and controls were ≥ 15 years of age and diagnosed with leukaemia between 1987 and 1992 and were selected from the National Cancer Registry of Taiwan. Controls were adults with cancers other than those potentially related to exposure to magnetic fields. Each case was matched with one control based on age, sex and date of diagnosis. Maps showing the location of each dwelling were available for only 69% of the study area; the lack of such maps was the primary reason for exclusion from the study. Power-company maps showed that 121 high-voltage power lines (69–345 kV) were operating in the study area between 1987 and 1992. The distance between each dwelling occupied by a study subject at the time of diagnosis and the nearest power line was measured from the maps with a precision of 10 m. Residential exposure was calculated from data supplied by the Taiwan Power Company that included distance between wires, height of wires above the ground, annual average and maximum loads and current phase. Calculated magnetic fields were validated by indoor measurements made with an EMDEX meter under low-power conditions (household power turned off) for 30–40 min in 407 residences. Questionnaire data on age, weight, height, educational level, smoking habits and previous exposure to X-rays were available for approximately one-third of study subjects. Information was obtained on potential confounding factors including urbanization (which took into consideration local population density), age, mobility, economic activity and family income, educational level and sanitation facilities. Of 1135 initial cases 870 incident cases of leukaemia were included in the analysis. [Not enough detail was provided to estimate the participation rate for controls.] The numbers of controls for cases of leukaemia living within 100 m and 50 m from the power lines were 10.9% and 5.4%, respectively. Of the controls, 9.9% had a calculated exposure of ≥ 0.2 μT and 5.6% had a calculated exposure of ≥ 0.5 μT. When the results were grouped into three exposure categories (< 0.1 μT, 0.1–0.2 μT and > 0.2 μT), the agreement (κ) between arithmetic means for measured and calculated fields was 0.64 (95% CI, 0.50–0.78). Compared with subjects living ≥ 100 m from the power lines, subjects who lived within 50 m of the lines had an odds ratio for leukaemia of 2.0 (95% CI, 1.4–2.9). For subjects whose homes were 50–99 m from the lines, the odds ratio was 1.5 (95% CI, 1.1–2.3). For calculated magnetic fields, the odds ratios for leukaemia were moderately elevated in the middle and highest exposure categories in the year of diagnosis: odds ratio, 1.3 (95% CI, 0.8–1.9) for exposure to 0.1–0.2 μT and odds ratio, 1.4 (95% CI, 1.0–1.9) for > 0.2 μT, compared with < 0.1 μT. A test for trend with increased exposure to magnetic fields was statistically significant ($p = 0.04$). [The Working Group noted the use of other cancer cases as controls and the low participation rate. Information on the power distribution systems near the dwellings of the study subjects was apparently unavailable. The ± 10-m precision of distance could have had a significant impact on calculations for dwellings within 20 m of power lines, but would contribute less error for those further away. Because the study was based on the dwelling occupied at the time of diagnosis, cumulative estimates of exposure to magnetic fields could not be calculated. Although examination of potential confounders in a subset of control subjects indicated little confounding from education, smoking, exposure to X-rays and reproductive factors, the authors were unable to adequately adjust for these risk factors for leukaemia.]

— *Appliance use*

A case–control study of leukaemia and use of electric blankets in the USA conducted by Preston-Martin *et al*. (1988) included patients aged 20–69 years, identified through the population-based Los Angeles County cancer registry, who had been diagnosed with histologically confirmed acute or chronic myeloid leukaemia between July 1979 and June 1985. Of 858 eligible cases, 485 who were still living were chosen, and permission to contact 415 of them was obtained from their physicians. [The Working Group noted that inclusion of only living patients might lead to bias, if exposure influences survival.] Completed questionnaires were available for 295 of the 415 patients, resulting in a participation rate of 61%. Each case was matched with one neighbourhood control on sex, race and birth year (within five years). [The authors did not give the response rate for controls, but stated that controls could not be found in three neighbourhoods.] In all, 293 matched pairs, including 156 cases of acute myeloid leukaemia and 137 of chronic myeloid leukaemia, participated in the study. Because questions on use of electric blankets were added after the study had begun, information on their use was available for only 224 matched pairs. The results indicated that use of electric blankets was not related to risk of leukaemia. For acute myeloid leukaemia, the odds ratio was 0.9 (95% CI, 0.5–1.6) and that for chronic myeloid leukaemia was 0.8 (95% CI, 0.4–1.6). Cases and controls did not differ with regard to average duration of use, year of first regular use, or number of years since last use. Adjustment for other significant risk factors did not change the results. [The Working Group noted that the study did not indicate whether blankets had been used only for pre-warming the bed or continuously throughout the night.]

The study by Severson *et al*. (1988), described above, used questionnaires to obtain information on ownership and use of 32 [Lovely *et al.*, 1994] electrical domestic appliances. The study showed no association between risk of leukaemia and use of electric blankets, water-bed heaters or heated mattress pads. [The Working Group noted that participation rates in this study were low and limited information was available on use of electric blankets.]

The data from the study by Severson *et al*. (1988) were reanalysed by Lovely *et al*. (1994) and Sussman & Kheifets (1996). The bias due to the use of proxy respondents was noted by Sussman & Kheifets (1996) in the positive findings for the use of an electric razor (> 7.5 minutes/day) (odds ratio, 2.4; 95% CI, 1.1–5.5) reported by Severson *et al.* (1988).

(*b*) *Brain cancer*

Few studies, summarized in Table 26, have investigated the potential association between adult brain cancer and residential exposure to ELF magnetic fields. [Although several studies of adult cancers have examined cancer of the brain or nervous system as a subtype, results have been unremarkable (Wertheimer & Leeper, 1982; Schreiber *et al*., 1993)]. Studies by Feychting and Ahlbom (1992a,b, 1994), Feychting *et al*. (1997), Verkasalo *et al*. (1996) and Li *et al*. (1997), which are described in detail in section *(a)*, also analysed brain cancer risk.

The population-based, nested case–control study of Feychting and Ahlbom (1992a,b, 1994) investigated exposure to magnetic fields from high-voltage power lines

Table 26. Design and results of epidemiological studies of residential exposures to ELF magnetic fields and adult brain cancer

Reference, country	Study base and subject identification	Exposure metrics	Results				Comments
Feychting & Ahlbom (1994) Sweden	**Case selection**: All incident cancer cases from cancer registry (1960–85), from cohort of Swedish population aged ≥ 16 years, living on a property located within 300 m of any 220- or 400-kV power lines. 223 cases in analysis (66 astrocytoma I–II, 157 astrocytoma III–IV) **Control selection**: Two controls per case from same cohort. Matched on age, sex, parish and residence near same power line; 1091 controls in analysis	Distance to power lines from dwelling. In-home spot measurements of magnetic fields under low- and high-power use conditions. Calculations of the magnetic fields generated by the power lines at the time spot measurements were made (calculated contemporary fields), and for the year closest in time to diagnosis (calculated historical fields).	Calculated fields closest to time of diagnosis				Matched and unmatched analyses, adjusted or not for age and socioeconomic status were carried out. No information on other sources of residential exposure to electric and magnetic fields
				Ref.: ≤ 0.09 µT	No. of cases	OR (95% CI)	
			All CNS	0.10–0.19 µT ≥ 0.2 µT	18 12	1.1 (0.7–2.0) 0.7 (0.4–1.3)	
			Astrocytoma I–II	0.10–0.19 µT ≥ 0.2 µT	3 2	0.6 (0.1–1.8) 0.4 (0.1–1.3)	
			Astrocytoma III–IV	0.10–0.19 µT ≥ 0.2 µT	15 10	1.4 (0.8–2.5) 0.8 (0.4–1.7)	
Feychting *et al*. (1997) Sweden	Same as Feychting and Ahlbom (1994)	Same as above for residential. Occupational exposure from job–exposure matrix [developed from workday measurements made for another study] and information on occupation held in the year before the reference date	Subjects with both residential and occupational exposure				Same as above. Job–exposure matrix. Relevance especially for females unclear
			Ref.: ≤ 0.1 µT res. and < 0.13 µT occ.		No. of cases	RR (95% CI)	
			All CNS	≥ 0.2 µT for both	3	1.3 (0.3–4.8)	
			Astrocytoma I–II	≥ 0.2 µT for both	0		
			Astrocytoma III–IV	≥ 0.2 µT for both	3	2.2 (0.6–8.5)	
Verkasalo *et al*. (1996) Finland	**Cohort:** 383 700 persons (189 300 men) aged ≥ 20 who contributed 2.5 million person–years of follow-up between 1970 and 1989 **Case selection**: All primary brain cancer cases (1974–89) living within 500 m of overhead power lines; 301 cases identified	Cumulative exposure. Estimates based on residential history, distance to 110–400-kV power line in 500-m corridor and calculated average annual magnetic fields for each building presumed to be ≥ 0.01µT. Takes into account current, typical locations of phase conductors and distance.	Cumulative exposure				Cohort study, SIRs. No information on other sources of residential exposure to electric and magnetic fields. No direct information from study subjects. ICD-7 code 193
			Ref.: general population		No. of cases	SIR (95% CI)	
			Nervous system	< 0.20 µT 0.20–0.39 µT 0.40–0.99 µT 1.00–1.99 µT ≥ 2.0 µT	238 35 16 5 7	0.94 (0.82–1.1) 1.1 (0.77–1.5) 0.64 (0.37–1.0) 0.55 (0.18–1.3) 0.92 (0.37–1.9)	

Table 26 (contd)

Reference, country	Study base and subject identification	Exposure metrics	Results				Comments
Li *et al.* (1997)	**Case selection**: Pathologically confirmed incident cases of brain cancer from northern Taiwan from cancer registry (1987–92). 577 cases included in analyses. **Control selection**: One control per case from cancer registry excluding cancers of brain and breast, of the haematopoietic and reticulo-endothelial system, skin, ovary, fallopian tube, and broad ligament. Matched on date of birth, sex and date of diagnosis. 552 controls included in analyses	Distance from lines. Average and maximum magnetic fields assessed using distance from the lines, distance between wires, height of wires above the ground, annual and maximum loads along the lines from 1987–92, current phase and geographical resistivity of the earth	Calculated exposure in year of diagnosis				Limited information on confounders because of restrictions on interview
			Ref.: < 0.1 µT		No. of cases	OR (95% CI)	
			All brain tumours	0.1–0.2 µT	23	0.9 (0.5–1.7)	
				> 0.2 µT	71	1.1 (0.8–1.6)	
			Astrocytoma	0.1–0.2 µT	4	0.6 (0.2–1.8)	
				> 0.2 µT	16	0.8 (0.5–1.5)	
			Glioblastoma	0.1–0.2 µT	8	1.3 (0.5–2.9)	
				> 0.2 µT	19	1.1 (0.6–2.0)	
			Oligodendro-glioma	0.1–0.2 µT	3	2.8 (0.8–10.4)	
				> 0.2 µT	2	0.6 (0.1–2.5)	
Wrensch *et al.* (1999)	**Case selection** Study of adult glioma in the San Francisco Bay Area. 492 newly diagnosed cases between 1991 and 1994 identified through the Northern California Cancer Center. **Control selection** 462 controls identified through random-digit dialling. Controls were matched to cases on age, sex and ethnicity.	For current dwellings and for all other California dwellings occupied during the 7 years before the study, exposure was assessed through spot measurements, wire codes and characterization of electrical facilities located within 150 feet [46 m] of the dwelling	Calculated exposure in year of diagnosis				Information was obtained from a proxy for 47% of the cases. 85% of the gliomas were glioblastomas multiforme or astrocytomas.
			Ref.: < 0.1 µT		No. of cases	OR (95% CI)	
			Glioma	0.1–0.2 µT	62	0.97 (0.7–1.4)	
				0.2–0.3 µT	15	0.6 (0.3–1.1)	
				> 0.3 µT	20	1.7 (0.8–3.6)	

CNS, central nervous system; SIR, standardized incidence ratio; OR, odds ratio; ref., reference exposure; ICD, International Classification of Disease; res., residential; occ., occupational; Ref.:, reference group with exposure level indicated and risk for tumours of the central nervous system. The study examined 223 patients with brain tumours, including 66 with glioma (astrocytoma I and II) and 157 with glioblastoma (astrocytoma III and IV). There was no evidence of any association, whether exposure was assessed by spot measurements or by calculation of magnetic fields from power lines.

Feychting *et al*. (1997) combined residential and occupational exposure by incorporating estimates of occupational exposure to magnetic fields into their earlier residential study (Feychting & Ahlbom, 1994). They estimated residential exposure from calculated magnetic fields and occupational exposure from census information linked to a job–exposure matrix based on magnetic field measurements. Adults exposed to stronger magnetic fields both at home and at work showed no association between occupational or residential exposure and tumours of central nervous system. [The study also found no association for calculated residential exposure after exclusion of subjects who were not exposed at home but were exposed to field strengths ≥ 0.2 μT at work.] There was also no association when analyses were restricted to people who had only residential exposure (≥ 0.2 μT) (odds ratio, 0.7; 95% Cl, 0.3–1.7; 7 exposed cases). [The Working Group comments on the limitations of this study are given in section (*a*). However, this study is important in that it attempted to incorporate both residential and occupational exposure.]

Verkasalo *et al*. (1996), in their study of a cohort of 383 700 persons, investigated 301 cases of tumour of the nervous system and found no difference in incidence between members of the cohort and the general Finnish population. They also observed no association with calculated cumulative exposure to magnetic fields. The SIRs with respect to the general population were 0.94 (95% CI, 0.8–1.1; 238 cases) for exposures < 0.2 μT, 1.1 (95% CI, 0.77–1.5; 35 cases) for 0.2–0.39 μT, 0.64 (95% CI, 0.37–1.0; 16 cases) for 0.4–0.99 μT, 0.55 (95% CI, 0.18–1.3; 5 cases) for 1.00–1.99 μT and 0.92 (95% CI, 0.37–1.9; 7 cases) for ≥ 2.0 μT. Although the authors analysed gliomas and meningiomas separately, they reported only that the results were consistent with those for tumours of the nervous system as a whole. [See comments on the limitations of this study in section *(a)*.]

The case–control study of Li *et al*. (1997) described in section (*a*) examined 705 histologically confirmed incident cases of brain tumour (ICD[1]-9 191) in 45 districts of northern Taiwan. After exclusion of subjects residing in 14 of the districts because maps were not available, 577 cases and 552 controls remained. The study found no association between brain tumours and calculated exposure to magnetic fields in the year of diagnosis. Compared with the < 0.1 μT exposure category, the odds ratio for exposure of 0.1–0.2 μT was 0.9 (95% CI, 0.5–1.7; 23 cases) and that for exposure > 0.2 μT was 1.1 (95% CI, 0. 8–1.6; 71 cases). In analyses by tumour subtype, the odds ratios ranged from 0.6–2.8. [See comments on the limitations of this study in section *(a)*.]

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[1] International Classification of Diseases

A large study by Wrensch *et al.* (1999) investigated adult glioma and residential exposure to electric and magnetic fields in six San Francisco Bay Area counties. The eligible cases were all adults newly diagnosed with glioma between 1 August 1991 and 31 March 1994. The study included 492 cases (82% of 603 eligible) and 462 controls (63% of 732 eligible), identified through random-digit dialling. Controls were frequency-matched to cases on age, sex and ethnicity. The average age of subjects was 54 years; 83% were white and 57% were male. Interviews were conducted in person in the homes of consenting patients (or their proxies) and controls. The interviewers asked about all dwellings occupied by subjects for three months or more for 15 years before either diagnosis (for cases) or interview (for controls). They also enquired about the subject's family and personal medical history, occupation, diet, smoking habits and alcohol use. The original diagnosis for 85% of cases was glioblastoma multiforme or astrocytoma; the remainder had other types of glioma. Proxy interviews were conducted for 233 cases (47%): 50% of the proxies were spouses of the cases, 30% were their children, 9% were siblings, 4% were parents and 7% had other relationships to the cases. Questionnaires covered a 15-year exposure period, for which 954 subjects reported 2995 dwellings. Usable addresses for all dwellings occupied during the seven years prior to diagnosis or study entry were obtained for 81.7% of cases and 84.2% of controls giving 1723 dwellings in California. Exposure assessment for electric and magnetic fields was completed for 81% of case and 86% of control dwellings. Exposure was assessed using indoor and outdoor spot measurements; characterization of power lines, transformers and substations located within 150 feet [46 m] of the dwelling, and Wertheimer–Leeper and Kaune–Savitz wire codes. To determine wire-codes, trained field workers made standardized drawings of all power lines within 150 feet [46 m] of each dwelling. Within this distance, they categorized up to three lines as to highest current type. For houses, they determined the shortest distance from the lines to the house. For apartments, they measured the distance from the nearest power line to the nearest boundary wall of each unit. For index dwellings, defined as the current dwelling for controls or the dwelling at time of diagnosis for cases, spot measurements were made in the centre of the kitchen, family room and bedroom, at the front door, and at the four outdoor corners of the dwelling. In addition, each subject selected a room in which a meter ran during the in-home interview. Spot measurements were also made with EMDEX meters under up to three power lines within 150 feet [46 m] of both current and previous dwellings and at the front doors of previous dwellings. The odds ratio for the longest-occupied dwellings with high compared with low Kaune–Savitz wire codes was 0.9 (95% CI, 0.7–1.3). For spot measurements at the front door (longest-occupied dwelling), the odds ratios for exposures of 0.1–0.2 μT, 0.2–0.3 μT and > 0.3 μT compared with ≤ 0.1 μT were 1.0 (95% CI, 0.7–1.4), 0.6 (95% CI, 0.3–1.1) and 1.7 (95% CI, 0.8–3.6), respectively. Adjusting for age, sex, ethnicity and whether subjects owned their homes did not meaningfully change the results, nor did restricting analyses to the subjects' highest wire-coded or index dwellings, or to single-family homes. The authors pointed out that there was no difference between cases and controls in the cumulative distribution of average front door, average indoor or maximum EMDEX readings. [The Working Group noted that the use of random-digit dialling for control selection may have resulted in a control group that was not fully representative of the base population from which the cases arose. Information was obtained from proxies for 47% of the cases.]

— *Appliance use*

Two studies investigated whether the risk for adult brain tumours might be associated with the use of electric blankets and other domestic appliances. In an Australian brain tumour study, Ryan *et al*. (1992) used a questionnaire to obtain information on 110 incident cases of glioma and 60 of meningioma diagnosed in 1987–90, and 417 controls. The questionnaire was designed to examine the risk factors for brain tumour associated with the use of electric blankets and electrically heated water beds. Proxy or assisted interviews were necessary for 41% of cases and 7% of controls. [The data for direct and proxy interviews were not presented separately, but the authors stated that they found no important differences.] A non-significant excess risk (odds ratio, 1.5; 95% CI, 0.83–2.6) associated with the use of electric blankets was reported for glioma, but not for meningioma (odds ratio, 0.86; 95% CI, 0.39–1.9). The opposite was true for electrically-heated water beds (odds ratio, 0.67 (95% CI, 0.18–2.5) and 1.3 (95% CI, 0.25–6.4), for glioma and meningioma, respectively). [The power of the study for this exposure is not known, as the prevalence of use of electrically heated bedding was not given.] A second report (Mutnick & Muscat, 1997) presented a preliminary summary of the data collected so far in a hospital-based, case–control study of 328 patients with primary brain cancers (284 controls) in the USA (New York University Medical Center, Memorial Sloan-Kettering Cancer Center and Rhode Island Hospital). The authors reported no risk associated with regular use of a number of electrical appliances, including computers, electric blankets, hair dryers, razors, and bedside dial clocks. [The Working Group noted that aspects of the methodology (e.g. the low participation rate, the need for proxies, etc.) render this study uninformative.]

(*c*) *Breast cancer* (see Table 27)

The studies by Wertheimer and Leeper (1982, 1987), McDowall (1986) (in women) and Schreiber *et al*. (1993) (in women) also reported on breast cancer. The Working Group found the results of these studies uninformative.

Verkasalo *et al*. (1996) assessed the risk of breast cancer in their nationwide cohort study of Finnish adults described in the section on Leukaemia on p. 152. Of 194 400 women in the cohort, 1229 had been diagnosed with breast cancer. The SIRs were 1.1 (95% CI, 0.98–1.1; 945 cases) for exposure to fields of < 0.20 μT, 1.1 (95% CI, 0.88–1.3; 130 cases) for 0.20–0.39 μT, 0.89 (95% CI, 0.71–1.1; 87 cases) for 0.40–0.99 μT, 1.2 (95% CI, 0.89–1.6; 44 cases) for 1.00–1.99 μT and 0.75 (95% CI, 0.48–1.1; 23 cases) for ≥ 2.0 μT. [For comments on the limitations of this study, see section *(a)*.]

Table 27. Design and results of epidemiological studies of residential exposures to magnetic fields and breast cancer

Reference, country	Study base and subject identification	Exposure metrics	Results				Comments
Verkasalo *et al*. (1996) Finland (women)	**Cohort**: 383 700 persons (194 400 women) aged 20 or older who contributed 2.5 million person–years of follow-up between the years 1970 and 1989 **Case selection**: All primary breast cancer cases (1974–89) living within 500 m of overhead power lines: 1229 cases identified	Cumulative exposure. Estimates based on residential history, distance to 110–400-kV power line in 500-m corridor and calculated average annual magnetic fields for each building presumed to be ≥ 0.01µT. Took into account current, typical locations of phase conductors and distance.	Cumulative exposure				Cohort study, SIRs. No information on other sources of residential exposure to electric and magnetic fields. No direct information from study subjects.
			Ref.: general population		No. of cases	SIR (95% CI)	
			Breast cancer	> 0.20 µT	945	1.1 (0.98–1.1)	
				0.20–0.39 µT	130	1.1 (0.88–1.3)	
				0.40–0.99 µT	87	0.89 (0.7–1.1)	
				1.00–1.99 µT	44	1.2 (0.89–1.6)	
				≥ 2.0 µT	23	0.75 (0.48–1.1)	
Li *et al*. (1997) Taiwan (women)	**Case selection**: Pathologically confirmed incident cases of breast cancer from northern Taiwan from cancer registry (1990–92). 1980 cases included in analyses **Control selection**: One control per case from cancer registry excluding cancers of the brain and breast, of the haematopoietic and reticulo-endothelial system, skin, ovary, fallopian tube and broad ligament. Matched on date of birth, sex and date of diagnosis: 1880 controls included in analyses	Distance from lines. Average and maximum magnetic fields assessed using distance from the lines, distance between wires, height of wires above the ground, annual and maximum loads along the lines from 1987–92, current phase and geographical resistivity of earth	Calculated exposure in year of diagnosis				Limited information on confounders because of restrictions on interview
			Ref.: < 0.1 µT		No. of cases	OR (95% CI)	
			All breast cancers	0.1–0.2 µT	107	1.1 (0.8–1.5)	
				> 0.2 µT	224	1.1 (0.9–1.3)	
			Group I	0.1–0.2 µT	89	1.0 (0.8–1.4)	
				> 0.2 µT	193	1.0 (0.8–1.2)	
			Group II	0.1–0.2 µT	0	–	
				> 0.2 µT	7	0.9 (0.6–1.3)	
			Group III	0.1–0.2 µT	3	1.3 (0.4–4.2)	
				> 0.2 µT	8	1.5 (0.7–3.2)	
Coogan & Aschengrau (1998) USA (women)	**Case selection**: Cases diagnosed between 1983 and 1986 in Cape Cod. Of 334 cases reported, 259 were included in the analysis. **Control selection**: Controls identified from three sources — random-digit dialling, lists of Medicare beneficiaries and death certificates. The 738 controls were matched on age, vital status (and if deceased, on year of death).	Use of electrically heated bedding, occupational history since age 18 years and residential history from 1943. Residential exposure was determined from proximity (within 152 m) to power lines and substations for dwellings on Cape Cod. Occupations were assigned to one of three categories (high, medium and no exposure).	Proximity to power lines/substations				Adjusted OR. No measurement data are presented, no sources are cited. The grouping of occupations differs from that used by most other investigators.
				Years	No. of cases	OR (95% CI)	
			Breast cancer	1–5	7	1.3 (0.5–3.6)	
				> 5	4	1.7 (0.4–6.3)	

Table 27 (contd)

Reference, country	Study base and subject identification	Exposure metrics	Results				Comments
Feychting *et al.* (1998a) Sweden (men and women)	**Case selection**: All incident cancer cases from cancer registry (1960–85), from cohort of Swedish population aged ≥ 16 years, living in single family homes, located within 300 m of any 220- or 400- kV power lines: 699 women, 9 men **Control selection**: One control per case from same cohort. Matched on age, sex, parish and residence near same power line: 699 controls	Distance to power lines from dwelling. Calculations of the magnetic fields generated by the power lines	Calculated fields closest to time at diagnosis				Highest OR, 7.4 (1.0–178) for ER+ and less than 50 years of age
				Ref.: ≤ 0.09 µT	No. of cases	OR (95% CI)	
			Women				
			All ages	0.10–0.19 µT	57	1.2 (0.8–1.8)	
				≥ 0.2 µT	54	1.0 (0.7–1.5)	
			< 50 years	0.10–0.19 µT	14	1.2 (0.6–2.8)	
				≥ 0.2 µT	15	1.8 (0.7–4.3)	
			≥ 50 years	0.10–0.19 µT	43	1.2 (0.7–1.9)	
				≥ 0.2 µT	39	0.9 (0.5–1.4)	
			Men	≥ 0.2 µT	2	2.1 (0.3–14)	
Forssén *et al.* (2000) Sweden (women)	Same as Feychting *et al.* (1998a), but expanded to include apartments; 1767 cases and 1766 controls	Same as above for residential. Occupational exposure from job–exposure matrix [developed from workday measurements made for another study] and information on occupation held in the year before the reference date	Subjects with both residential and occupational exposure				Number of cases with ER– is zero.
			Ref.: < 0.1 µT res. and < 0.12 µT occ.		No.	OR (95% CI)	
			All ages	≥ 0.1 µT res., ≥ 0.12 µT	8	0.9 (0.3–2.7)	
			< 50 years	occ.	4	7.3 (0.7–78.3)	
			≥ 50 years	≥ 0.1 µT res., ≥ 0.12 µT	4	0.4 (0.1–1.4)	
			ER+	occ.	6	1.6 (0.3–9.9)	
				≥ 0.1 µT res., ≥ 0.12 µT occ.			

OR, odds ratio; CI, confidence interval; SIR, standardized incidence ratio; res., residential; occ., occupational; ER+, estrogen-receptor-positive; ER–, estrogen-receptor-negative; Ref., reference group with exposure level indicated

The case–control study of residential exposure to magnetic fields and adult cancer in Taiwan (Li *et al.*, 1997) included 2407 histologically confirmed, incident cases of breast cancer in women, of which 1980 were included in the analysis. No association was found between breast cancer and residence less than 50 m from power lines, compared to residence ≥ 100 m from the lines (odds ratio, 1.0; 95% CI, 0.8–1.3; 156 cases). For calculated exposure to magnetic fields, there was no increase in risk among the highest exposure group (> 0.2 μT) (odds ratio, 1.1; 95% CI, 0.9–1.3; 224 cases). [For comments on the limitations of this study see section *(a)*.]

Electric and magnetic fields were considered among a wide variety of environmental and behavioural factors evaluated in a large study seeking reasons for the higher-than-expected breast cancer rates in women resident in the Cape Cod, MA, area in the USA (Coogan & Aschengrau, 1998). The study found a small, non-significant association between breast cancer risk and exposure to magnetic fields. [The Working Group noted that the poor exposure assessment, together with other design flaws, render this study largely uninformative.]

In a population-based case–control study on the effects of exposure to magnetic fields from high-voltage power lines in Sweden, Feychting *et al.* (1998a) also investigated the risk for breast cancer. Men and women who lived within 300 m of a 220- or 400-kV power line for at least one year between 1960 and 1985 were eligible for the study. All male breast cancer cases were included, but only women living in single-family homes were included. Cases were identified from the Swedish National Cancer Registry. A total of 699 female patients matched 1:1 with controls and nine male patients matched 1:8 with controls were included in the analysis. Controls who lived near the same power line as the case with whom they were matched were selected at random from the study base from people who had lived in the power-line corridor for at least one year before the reference date. Controls were matched to cases on age (within five years), sex and parish of residence in the year of the diagnosis. Information from medical records on the estrogen-receptor status of tumours was available for only 102 of the 699 cases. The study showed no overall increase in risk for female breast cancer with increasing estimates of magnetic field exposure; adjusting for socio-economic status did not change this result. When exposure was defined as the average calculated exposure during the year closest in time to the diagnosis date, with categories of < 0.1 μT, 0.1–0.19 μT and > 0.2 μT, the odds ratio for the highest exposure group was 1.0 (95% CI, 0.7–1.5) for all women. For women aged 50 years or younger, the odds ratio was 1.8 (95% CI, 0.7–4.3); for older women the odds ratio was 0.9 (95% CI, 0.5–1.4). Analyses of cumulative exposure showed a non-significantly elevated risk among women with cumulative exposure ≥ 3.0 μT–years in the six years immediately preceding diagnosis (odds ratio, 1.6; 95% CI, 0.8–3.2; 25 cases). Among estrogen-receptor-positive women, the odds ratio for exposure to ≥ 0.1 μT was 1.6 (95% CI, 0.6–4.1; 17 cases). For estrogen-receptor-positive women aged under 50 years, the odds ratio was 7.4 (95% CI, 1.0–178), based on six exposed cases and one control. For men, a non-significant increase in risk (odds ratio, 2.1; 95% CI, 0.3–14) was observed for calculated exposure to magnetic fields of ≥ 0.2 μT during the year closest in time to the diagnosis, based on two exposed cases. [The Working Group reiterated the limitations of this study as described in section *(a)*. Additionally, because all the data were obtained from registry and hospital files, no information was available on important risk factors for breast cancer and information on estrogen-receptor status was available for only a few cases.]

The study by Feychting *et al*. (1998a) of breast cancer in Sweden was expanded to combine assessments of residential and occupational exposure (Forssén *et al*., 2000). Unlike the previous breast cancer analysis, which had been limited to single-family homes, this study included all types of dwelling. Cases of breast cancer were identified from the national cancer registry, and one matched control per case was selected at random from the general population. The assessment of occupational exposure was based on census-derived information about occupation that was linked to a job–exposure matrix developed for another study (Floderus *et al*., 1993). For residential exposure to magnetic fields ≥ 0.10 μT for the year closest in time to diagnosis, and occupational exposure < 0.12 μT, the estimated odds ratio was 0.5 (95% CI, 0.1–2.9; 5 cases) and women aged less than 50 years at diagnosis had an odds ratio of 2.4 (95% CI, 0.1–50; 1 case). The highest risk (odds ratio, 7.3; 95% CI, 0.7–78; 4 cases) was for younger women (< 50 years) with higher occupational (≥ 0.12 μT) and residential (≥ 0.1 μT) exposures. [The Working Group noted the very small number of subjects in some subgroups. Occupational exposure was estimated for only 43% of subjects. The study included no information on reproductive risk factors for breast cancer.]

— *Use of electric blankets*

Because of the potential for prolonged exposure to increased electric and magnetic fields, the use of electric blankets has been examined as a risk factor for breast cancer in several recent investigations (Table 28). Vena *et al*. (1991) reported a case–control study that examined the use of electric blankets among 382 women with breast cancer and 439 randomly selected community controls in western New York state in the USA from 1987–89. The study was limited to postmenopausal women and included newly diagnosed, histologically confirmed cases aged 41–85 years admitted to hospitals in the study area between 1987 and 1989. Controls living in the study area were randomly selected from New York drivers' licence records if they were aged under 65 years and from Health Care Financing Administration rosters if they were older. Cases and controls were matched on age. The participation rate was 56% among cases and 46% among controls. The histories of use of electric blankets were obtained through home interviews, using a questionnaire. Information sought included any use of electric blankets in the past 10 years, seasonal pattern of use and mode of use. The study found no significant association with any level of exposure and no dose–response effect. When the results were adjusted for age and education, the odds ratio for breast cancer with use of electric blankets was 0.89 (95% CI, 0.66–12). Further adjustment for risk factors for postmenopausal breast cancer (body mass index, age at first pregnancy,

Table 28. Use of electric blankets and risk for breast cancer in women

Study	Subjects	No. of cases/ controls	Ever use[a]			Daily use			Use through the night[b]			Long-term use[c]		
			OR	No. of cases	95% CI	OR	No. of cases	95% CI	OR	No. of cases	95% CI	OR	No. of cases	95% CI
Vena *et al*. (1991)	Postmenopausal	382/439	0.89	126	0.66–1.2	0.97	NR	0.70–1.4	1.5	68	0.96–2.2	1.4	32	0.77–2.4
Vena *et al*. (1994)	Premenopausal	290/289	1.2	115	0.83–1.7	1.3	84	0.86–1.9	1.4	75	0.94–2.2	1.1	24	0.59–2.1
Vena *et al*. (1995)	Pre- and post-menopausal	672/728	1.1	242	0.85–1.4	1.2	179	0.90–1.5	1.5	143	1.1–1.9	1.2	56	0.81–1.9
Coogan & Aschengrau (1998)[d]	Mostly post-menopausal	259/738	NR	NR	NR	1.0	112	0.7–1.4	NR	112	NR	1.2	23	0.7–2.2
Gammon *et al*. (1998)[e]	< 45 years	1645/1498	1.01	780	0.86–1.2	NR	NR	NR	1.0	630	0.88–1.2	0.96	155	0.74-1.3
	Postmenopausal (45–54 years)	261/250	0.97	143	0.67–1.4	NR	NR	NR	NR	NR	NR	NR	NR	NR
Laden *et al*. (2000)[f]	Premenopausal	95 cases; 41 585 person–years	1.1	42	0.71–1.7	NR	NR	NR	NR	NR	NR	0.88	15	0.49–1.6
	Postmenopausal	797 cases; 233 130 person–years	1.1	354	0.92–1.2	NR	NR	NR	NR	NR	NR	1.1	82	0.85–1.4
Zheng *et al*. (2000)	Pre- and postmenopausal	608/609	0.90	241	0.7–1.1	NR	NR	NR	0.9	147	0.7–1.2	0.8	96	0.6–1.1

OR, odds ratio; CI, confidence interval; NR, not reported
[a] Defined as any use during the last 10 years by Vena; ever use by Gammon
[b] Defined as use through the night by Vena and Zheng; on most of the time by Gammon
[c] Defined as use through the night in-season for 10 years by Vena; longer than 8 years for women aged < 45 years by Gammon; ≥ 20 years by Coogan; longer than 3 years by Zheng; ≥ 10 years for premenopausal women, ≥ 20 years for postmenopausal women by Laden
[d] Sleep with 'electric heating device'
[e] Women aged < 45 years included women from New Jersey, Washington and Atlanta; women aged 45–54 years were from Atlanta only.
[f] Prospective follow-up

number of pregnancies, age at menarche, family history of breast cancer and history of benign breast disease) resulted in an odds ratio of 1.0. There was no trend with increasing number of years of use or with frequency of use. A slightly increased risk was observed for women who reported using electric blankets continuously throughout the night compared with those who never used them (odds ratio adjusted for all risk factors, 1.5; 95% CI, 0.96–2.2; *n* = 68). For the heaviest users who had used electric blankets continuously throughout the night every night during the cold season over the previous 10 years (only 8% of cases and 6% of controls), further analyses showed a slightly increased risk (odds ratio, 1.4; 95% CI, 0.77–2.4). [The Working Group noted that the very low response rates, particularly among controls and the lack of information on the type and age of electric blankets and on other sources of exposure to electric and magnetic fields hamper the interpretation of this study.]

In a second, similar study, Vena *et al*. (1994) again examined use of electric blankets in western New York state, this time among premenopausal women aged 40 years or more. The study included 290 premenopausal women with breast cancer diagnosed between 1986 and 1991 and 289 age-matched controls selected randomly from drivers' licence records in the same geographical area. The response rate was 66% for cases and 62% for controls. The participants were interviewed in their homes using a questionnaire that included questions about use of electric blankets; dietary, medical and reproductive histories, and lifestyle and environmental factors. Use of electric blankets during the previous 10 years was reported by 40% of cases (115 women) and 37% of controls (106 women). After adjustment for age, education, age at first pregnancy, number of pregnancies, family history of breast cancer and other risk factors, the odds ratio for use of an electric blanket at any time in the previous 10 years was 1.2 (95% CI, 0.83–1.7). There was no dose–response relationship between number of years of blanket use and risk of breast cancer. A slight increase in risk was observed among women who used electric blankets daily during the cold season compared with those who never used them (odds ratio, 1.3; 95% CI, 0.86–1.9) and among those who used them continuously throughout the night (odds ratio, 1.4; 95% CI, 0.94–2.2). For the women with the most hours of electric blanket use (continuously throughout the night every night during the cold season for the previous 10 years), the odds ratio was 1.1 (95% CI, 0.59–2.1). [The Working Group considered that this study was limited by the lack of any direct assessment of exposure to electric and magnetic fields, the potential for recall bias and misclassification and the low response rates. Information on the type and age of electric blankets and on other sources of exposure to electric and magnetic fields was also lacking.]

Following a suggestion by Stevens (1995), the two previous studies by Vena *et al*. (1991, 1994) were reanalysed using the combined data (Vena *et al*., 1995). The odds ratio was 1.1 (95% CI, 0.85–1.4) for use of an electric blanket at any time in the previous 10 years, 1.2 (95% CI, 0.90–1.5) for daily use and 1.5 (95% CI, 1.1–1.9) for continuous use throughout the night. Although the results reported for such use showed a significantly increased risk, there was no evidence of a dose–response effect. In the highest exposure group, which included women who had used electric blankets in the cold season and continuously throughout the night for 10 years, the odds ratio was less elevated, and the confidence interval included the null value (odds ratio, 1.2; 95% CI, 0.81–1.9). Analysis by duration of continuous use throughout the night showed no association with breast cancer except for women who had used the blankets continuously throughout the night for 3–5 years (odds ratio, 2.0; 95% CI, 1.1–3.8).

More recently, in a larger population-based case–control study, Gammon *et al*. (1998) examined use of electric blankets, mattress pads or heated water beds and breast cancer risk. The study included 1645 women under the age of 45 years with breast cancer newly diagnosed between 1990 and 1992 in one of three geographical regions of the United States with tumour registries (Atlanta, GA, five counties in New Jersey and the Puget Sound area in Washington State). The 1498 controls were frequency-matched to cases by five-year age group and geographical area. Also included in the study were 261 postmenopausal women aged 45–55 years and 250 matched controls. The data for postmenopausal women were based solely on Atlanta residents. Although exposure to electric and magnetic fields was not a primary focus of this study, all women were asked about their use of electric bed-heating equipment. Study results indicated that ever having used electric blankets, mattress pads or heated water beds did not increase the risk of breast cancer among premenopausal women (< 45 years old) (odds ratio, 1.0; 95% CI, 0.86–1.2) or postmenopausal women (45–54 years old) (odds ratio, 0.97; 95% CI, 0.67–1.4).

In their study described above, Coogan and Aschengrau (1998) examined the use of electric heating devices during sleep. There was no increase in breast cancer risk associated with regular use (odds ratio, 1.0; 95% CI, 0.7–1.4; 112 cases). [Although the authors did not stratify the results by menopausal status, most of the participants (more than 88%) were postmenopausal.]

A large cohort study, the Nurses' Health Study, in the USA also examined breast cancer and use of electric blankets (Laden *et al*., 2000). The parent study began in 1976, when 121 700 female registered nurses completed a postal questionnaire. Diagnoses of breast cancer were reported on follow-up questionnaires and confirmed by medical records (for most cases). A question on use of electric blankets was added in 1992. The prospective (1992–96) analysis was restricted to 78 614 women not diagnosed with cancer before 1992 who had answered this question (954 breast cancer cases). The retrospective analyses (1976–92) included 85 474 women who had answered this question (2426 breast cancer cases) and were cancer free at the start of the study. The reported relative risks for ever having used electric blankets were 1.1 (95% CI, 0.95–1.2; 426 cases) and 1.0 (95% CI, 0.92–1.1; 1041 cases), based on prospective and retrospective follow-up, respectively. After adjusting for known risk factors for the disease, there was little indication of a trend in risk associated with number of years of electric blanket use. Similar results were obtained for pre- and postmenopausal women and for women with estrogen-receptor-positive breast cancer.

Zheng *et al*. (2000) analysed data from a case–control study of breast cancer in Connecticut, USA, between 1994 and 1997. The study included two separate sources of cases (31–85 years old) and controls. One group included incident cases identified from the surgical pathology department of Yale-New Haven Hospital (432/561; 77% participation) and hospital controls who had undergone breast surgery for benign breast disease or had histologically confirmed normal tissue (404/569; 71% participation). A second group comprised cases resident in Tolland County identified through the Connecticut Tumor Registry (176; 74% participation). The controls for this group were selected by random-digit dialling (152; 64% participation) or, for those over 65 years of age, from Health Care Administration records (53; 54% participation). Information on use of electric blankets and other electrical appliances was obtained by interviewing the participants. Around 40% of cases and controls reported regular use of electric blankets and the odds ratio was 0.9 (95% CI, 0.7–1.1). The risk did not vary with age at first use, duration of use, or menopausal or estrogen-receptor status and was the same for subjects who used electric blankets regularly throughout the night. Similarly unremarkable results were obtained for use of other common domestic appliances.

(*d*) *Other cancers*

In the 1996 Finnish cohort study, described in section *(a)*, Verkasalo *et al*. (1996) examined the relationship between cancer risk and exposure to magnetic fields from high-voltage power lines. Overall, 8415 cancer cases were identified (4082 were men). No association was found between cumulative exposure and the risk for all cancers (SIR, 0.98; 95% CI, 0.96–1.0 per μT–year) or for any specific type of cancer studied. Only for skin melanoma was the risk slightly increased throughout the three highest cumulative exposure categories: SIRs were 0.87 (95% CI, 0.54–1.3; 21 cases), 1.5 (95% CI, 0.98–2.1; 28 cases), 1.5 (95% CI, 0.69–2.7; 10 cases) and 1.2 (95% CI, 0.48–2.5; 7 cases) for exposure to fields of 0.20–0.39 μT, 0.40–0.99 μT, 1.0–1.99 μT and ≥ 2.0 μT, respectively. The SIR for multiple myeloma showed a marginally significant increase in men (SIR, 1.2; 95% CI, 1.0–1.5 per μT–year) and a non-significant decrease in women (SIR, 0.87; 95% CI, 0.57–1.3 per μT–year). For colon cancer, the risk was marginally increased in women (SIR, 1.2; 95% CI, 1.0–1.3 per μT–year), but not in men. [For the comments of the Working Group on this study, see section *(a)*.]

Finally, in a population-based study of 175 men with prostate cancer aged 40–69 years and 258 controls, Zhu *et al*. (1999) reported a relative risk of 1.4 (95% CI, 0.9–2.2) for ever having used an electric blanket or heated water bed, but the risk did not appear to increase with increasing duration of use.

2.3.2 *Occupational exposure to ELF electric and magnetic fields*

(*a*) *Proportionate mortality or incidence studies*

Proportionate mortality studies should be interpreted with caution because apparent mortality excesses, particularly those of moderate size, can be the result of a deficit of mortality from other causes (Monson, 1990).

The studies described below were designed mainly for generating hypotheses, especially by use of record linkage with routinely collected data.

In early studies on the relation between electric and magnetic fields and cancer, exposure to electric and magnetic fields was inferred from the job title only, on the assumption that 'electrical workers' were exposed to higher than background electric and magnetic fields. The first list of 'electrical' occupations which supposedly entailed high exposure to electric and magnetic fields was established by Milham (1982). This list, or a modified version thereof, was used as the basis for exposure assessment in subsequent studies. The job titles most generally considered to denote 'electrical' occupations were electronic technicians and engineers, radio and telegraph operators, electricians, power and telephone linemen, television and radio repairers, power-station operators, aluminium workers, welders (see IARC, 1990) and flame cutters, and motion-picture projectionists.

Milham (1982) conducted a study in 1950–79 based on death certificates in Washington State, USA, for white men ≥ 20 years of age. The study was later updated for the period 1950–82 (Milham, 1985b). Employment in one of nine electrical occupations as listed on the death certificate, was used as a surrogate for exposure to electric and magnetic fields. Significantly elevated proportionate mortality ratios (PMRs) were observed for all leukaemia (PMR, 1.4 [95% CI, 1.1–1.6]; 146 cases), acute leukaemia (PMR, 1.6 [95% CI, 1.3–2.1]), malignant brain tumours (PMR, 1.2 [95% CI, 1.0–1.5]) and other lymphomas (PMR, 1.6 [95% CI, 1.2–2.2]), as well as malignant tumours of the pancreas (PMR, 1.2 [95% CI, 1.0–1.4]) and lung (PMR, 1.1 [95% CI, 1.1–1.2]).

In a study in Los Angeles County, USA, Wright *et al*. (1982) looked at incident cases of leukaemia that occurred from 1972–79 among white men employed in one of 11 electrical occupations. The proportionate incidence ratios (PIRs) were 1.3 [95% CI, 0.9–1.8] for all leukaemia (35 cases), 1.7 [95% CI, 1.1–2.6] for acute leukaemia and 2.1 [95% CI, 1.3–3.1] for acute myeloid leukaemia.

To evaluate leukaemia mortality in men employed in one of 10 electrical occupations, McDowall (1983) re-analysed data routinely collected in England and Wales for a report on occupational mortality in 1970–72. On the basis of all deaths in men aged 15–74 years, the PMRs of these occupations taken together were not significantly different from those expected, either for all leukaemia (PMR, 0.98; 85 cases) or for any specific subtype of leukaemia.

To evaluate leukaemia incidence in electrical occupations further, Coleman *et al*. (1983) used the routinely collected records of the South Thames Cancer Registry in England to calculate the proportionate registration ratio (PRR) for leukaemia for the period 1961–79 for men aged 15–74 employed in one of 10 electrical occupations. Eight of the 10 occupations showed an excess of all leukaemia with a significantly increased PRR of 1.2 ($p < 0.05$) for all 10 electrical occupations taken together (113 cases). There was no overall excess of chronic myeloid leukaemia, but non-significant excesses occurred in acute lymphoblastic (PRR, 1.5), chronic lymphocytic (PRR, 1.3) and acute myeloid (PRR, 1.2) leukaemia.

The death certificates of men aged ≥ 20 years were used in Wisconsin, USA, during 1963–78 to analyse leukaemia deaths in relation to 10 electrical occupations (Calle & Savitz, 1985). The PMR for all leukaemia in electrical occupations was 1.0 ([95% CI, 0.82–1.3]; 81 cases) and that for acute leukaemia was 1.1 [95% CI, 0.81–1.5].

Data from five descriptive studies that examined either the PMR (Milham, 1982; McDowall, 1983; Calle & Savitz, 1985; Milham, 1985b) or the PIR (Wright *et al.*, 1982; Coleman *et al.*, 1983) for leukaemia in workers in electrical occupations, i.e. workers with suspected high exposure to ELF electric and magnetic fields were pooled by Stern (1987). This data set which included a total of 449 cases of all leukaemia, yielded a relative risk of 1.1 [95% CI, 1.0–1.3] for all occupations combined. For the subgroups of acute leukaemia and acute myeloid leukaemia, the relative risk estimates were 1.4 [95% CI, 1.2–1.6] and 1.4 [95% CI, 1.1–1.7], respectively.

Death certificates from 1950–84 for men aged ≥ 20 years were used in a study conducted in British Columbia, Canada (Gallagher *et al.*, 1990). The PMR for all leukaemia in men working in one of nine electrical occupations was [1.1; 95% CI, 0.8–1.4] (65 cases). Using the same data, the PMR for brain cancer in workers employed in the same nine occupations was 1.3 (95% CI, 0.93–1.6; 55 cases) for men aged 20–65 years (Gallagher *et al.*, 1991).

In a study on mortality data for white men > 15 years old collected from 14 states in the USA for one or more years from 1979–85, the PMR for all leukaemia in 11 electrical occupations was 1.2 (95% CI, 1.0–1.4; 183 observed) and 1.1 (95% CI, 0.85–1.5) for acute myeloid leukaemia (Robinson *et al.*, 1991).

To evaluate PRRs of cancer among electrical workers, Fear *et al*. (1996) used routinely collected data reported to the national cancer registration scheme in England during 1981–87 on more than 1 million cancers in individuals aged 20–74 years. The analysis, however, was based on only 36% of registrations for which valid occupational information was provided. Twelve job groups out of a total of 194 were identified as electrical occupations. For these job groups combined, and for both sexes jointly, significantly raised risks were seen for all brain and meningeal cancers combined (PRR, 1.2; 95% CI, 1.0–1.3; 281 cases), malignant brain cancer alone (PRR, 1.2; 95% CI, 1.0–1.4; 204 cases), all leukaemias combined (PRR, 1.2; 95% CI, 1.1–1.4; 217 cases) and acute myeloid leukaemia alone (PRR, 1.3; 95% CI, 1.0–1.6; 80 cases). For several types of cancer, most notably malignant brain cancer and acute myeloid leukaemia, the increased PRRs were most evident in men < 65 years old.

A study in São Paulo, Brazil, based on death certificates obtained from a sample of electricity utility workers in 1975–85 was conducted by Mattos and Koifman (1996).

The PMR in the group of workers expected to have been exposed to strong electric and magnetic fields was increased for brain cancer (ICD-9 191, 192) (PMR, 3.8; 95% CI, 1.0–9.7), Hodgkin disease (PMR, 5.6; 95% CI, 1.1–16) and bladder cancer (PMR, 4.2; 95% CI, 1.4–9.7).

(*b*) *Cohort studies*

Table 29 presents selected results of studies that have looked at occupational exposure to static and ELF magnetic fields and leukaemia, brain cancer and breast cancer, the malignancies on which most attention has focused. A few studies have reported excesses of other cancers such as malignant melanoma, non-Hodgkin lymphoma and lung cancer for which the majority of other studies could not reproduce the findings. These studies are not shown in the Table but are described in the text.

(i) *Workers exposed to strong static magnetic fields*

There are certain industries (aluminium reduction (see IARC, 1984, 1987a) and production of chlorine by electrolysis in chloralkali plants) in which workers are exposed to static magnetic fields, usually created by strong rectified alternating current. The aluminium reduction process involves exposure to static magnetic fields from direct currents passing through the anodes during electrolysis (reduction). The magnetic field to which the workers are exposed has been estimated to be between 4 and 50 mT (Kowalczuk *et al*., 1991). The process also involves potential exposure to a mixture of volatiles from coal-tar pitch (see IARC, 1985, 1987b) and petroleum coke.

Barregård *et al*. (1985) studied cancer mortality and cancer incidence in a group of 157 male workers at a Swedish chloralkali plant. The employees had all worked regularly or permanently for at least one year during the period 1951–83 in the cell room where the electrolysis process took place. These workers had been exposed to strong static magnetic fields (average, 14 mT). The investigators reported no excess incidence of, or mortality from, cancer.

In a cohort study of 27 829 aluminium workers employed for ≥ 5 years between 1946 and 1977 in 14 reduction plants in the USA, Rockette and Arena (1983) reported indications of higher than expected mortality from pancreatic, genitourinary and lymphohaematopoietic cancers. Deaths from lymphohaematopoietic cancer were not confined to one subcategory of disease, or to one industrial process. [The Working Group noted that these results cannot be interpreted in relation to exposure to magnetic fields.]

A cohort study was carried out in British Columbia, Canada, of 4213 workers with ≥ 5 years of work experience at an aluminium reduction plant between 1954 and 1985 (Spinelli *et al*., 1991). The static magnetic fields usually generated in the plant were approximately 1 mT. The potential exposure to magnetic fields and to coal-tar pitch volatiles was determined for each job by industrial hygienists using a job–exposure matrix. The standardized mortality ratio (SMR) in the total cohort was 2.2 (90% CI, 1.2–3.7) for tumours of the brain and central nervous system (ICD-9 191, 192) and 1.8

Table 29. Cohort studies of leukaemia, brain and breast cancer in occupational groups with assumed or documented exposure to static or ELF magnetic fields

Country (reference)	Population, design (number), recruitment period; follow-up period	Assessment of exposure to ELF magnetic fields[a]	Cancer	No. of cases	Relative risk (95% CI)		Comments
Sweden (Einhorn *et al*., 1980; Wiklund *et al*., 1981)	Telephone operators SIR (14 480; 14 180 women and 300 men), 1960 census; 1961–73	Not estimated	Leukaemia	12	1.0	[0.6–1.8][b]	Unadjusted for potential occupational confounders
Sweden (Olin *et al*., 1985)	Electrical engineers SMR (1243 men), 1930–59; 1930–79	Not estimated	Leukaemia	2	0.9	(0.1–3.2)	Unadjusted for potential occupational confounders
			Brain	2	1.0	(0.1–3.7)	
Sweden (Vågerö *et al*., 1985)	Telecommunications equipment workers SIR (2914; 2047 men and 867 women), 1956–60; 1958–79	Not estimated	**Men**				Unadjusted for potential occupational confounders
			Nervous system	5	1.0	(0.3–2.3)	
			Women				
			Breast cancer	7	0.6	(0.3–1.3)	
Sweden (Törnqvist *et al*., 1986)	Power linesmen SIR (3358 men), 1960 census; 1961–79	Not estimated	Leukaemia	10	1.3	(0.7–2.1)	90% CI. Unadjusted for potential occupational confounders
			Nervous system	13	1.5	(0.9–2.4)	
	Power station operators SIR (6703 men), 1960 census; 1961–79	Not estimated	Leukaemia	16	1.0	(0.6–1.5)	90% CI. Unadjusted for potential occupational confounders
			Nervous system	17	1.0	(0.6–1.5)	
Sweden (Törnqvist *et al*., 1991)	Workers in electrical occupations SIR (133 687 men), 1960 census; 1961–79	Median during working hours: < 0.04–16.5 μT (50 measurements)	Leukaemia	334	SIR slightly raised		Unadjusted for potential confounders
			Brain tumours	250	SIR close to unity		

Table 29 (contd)

Country (reference)	Population, design (number), recruitment period; follow-up period	Assessment of exposure to ELF magnetic fields[a]	Cancer	No. of cases	Relative risk (95% CI)	Comments
USA (Garland *et al.*, 1990)	US Navy personnel SIR (> 4 million person–years white men), 1974–84; 1974–84	Not estimated	**Leukaemia**			Unadjusted for potential occupational confounders
			All cohort	102	0.9 (0.8–1.1)	
			Electrician's mate	7	2.4 (1.0–5.0)	
Finland (Juutilainen *et al.*, 1990)	Male industrial workers SIR [number not given] 1970 census; 1971–80	No measurements	**Leukaemia**			Unadjusted for potential confounders
			No exposure	117	1.0 (baseline)	
			Possible exposure	94	1.4 (1.1–1.8)	
			Probable exposure	10	1.9 (1.0–3.5)	
			Brain tumours			
			No exposure	204	1.0 (baseline)	
			Possible exposure	149	1.3 (1.0–1.6)	
			Probable exposure	13	1.3 (0.7–2.3)	
Norway (Tynes & Andersen, 1990)	Workers in electrical occupations SIR (37 952 men), 1960 census; 1961–85	No measurements	Male breast	12	2.1 (1.1–3.6)	Unadjusted for potential confounders
Norway (Tynes *et al.*, 1992)	Workers in electrical occupations SIR (37 945 men), 1960 census; 1961–85	No measurements	Leukaemia	107	1.1 (0.89–1.3)	Unadjusted for potential confounders
			AML	38	1.3 [0.88–1.7][b]	
			CLL	27	0.97 (0.64–1.4)	
			CML	19	1.5 (0.90–2.3)	
			Brain	119	1.1 (0.90–1.4)	

Table 29 (contd)

Country (reference)	Population, design (number), recruitment period; follow-up period	Assessment of exposure to ELF magnetic fields[a]	Cancer	No. of cases	Relative risk (95% CI)		Comments
USA (Matanoski *et al.*, 1991)	Telephone workers SIR (4547 male cable splicers, 9561 central office technicians), 1976–80; 1976–80	Personal monitoring of a sample of workers	Male breast				Electromechanical switches environment in central office
			Cable splicer	0	–	–	
			Central office technicians	2	6.5	(0.79–24)	
Canada, British Columbia (Spinelli *et al.*, 1991)	Aluminium reduction plant workers SIR (4213 men), 1954–85; 1954–85	No personal measurements (magnetic fields around 1 mT generated during industrial process)	Leukaemia	3	0.76	[0.15–2.2][b]	No significant association with estimated cumulative exposure to strong static magnetic fields (values not given)
			Brain	8	1.9	[0.84–3.8][b]	
Denmark (Guénel *et al.*, 1993b)	Workers in electrical occupations SIR (255 000; 172 000 men, 83 000 women), 1970 census; 1970–87	Continuously above 0.3 μT	**Men**				Unadjusted for potential confounders
			Leukaemia	39	1.6	(1.2–2.2)	
			– acute	16	1.6	(0.90–2.6)	
			– other	23	1.7	(1.1–2.5)	
			Brain and nervous system	23	0.69	(0.44–1.0)	
			Breast	2	1.4	(0.16–4.9)	
			Women				
			Leukaemia	2	0.56	(0.07–2.0)	
			Brain and nervous system	9	1.2	(0.56–2.3)	
			Breast	55	0.88	(0.68–1.2)	

Table 29 (contd)

Country (reference)	Population, design (number), recruitment period; follow-up period	Assessment of exposure to ELF magnetic fields[a]	Cancer	No. of cases	Relative risk (95% CI)		Comments
		Intermittently above 0.3 μT	**Men**				
			Leukaemia	282	0.94	(0.84–1.1)	
			– acute	119	1.0	(0.84–1.2)	
			– other	164	0.90	[0.77–1.1][b]	
			Brain and nervous system	339	0.94	(0.85–1.1)	
			Breast	23	1.2	(0.77–1.8)	
			Women				
			Leukaemia	94	0.92	(0.75–1.1)	
			– acute	47	0.93	(0.70–1.2)	
			– other	47	0.91	(0.68–1.2)	
			Brain and nervous system	198	1.1	(0.93–1.2)	
			Breast	1526	0.96	(0.91–1.0)	
Sweden (Floderus *et al*., 1994)	Male railroad workers SIR [not given], 1960 census; 1961–79	Spot measurements	**All leukaemia**				
			Engine drivers				
			1961–69	6	1.6	(0.7–3.6)	
			1970–79	8	1.0	(0.5–2.1)	
			All railway workers				
			1961–69	17	1.2	(0.7–1.9)	
			1970–79	26	0.9	(0.6–1.3)	
			CLL				
			Engine drivers				
			1961–69	4	2.7	(1.0–7.4)	
			1970–79	4	1.1	(0.4–2.9)	

Table 29 (contd)

Country (reference)	Population, design (number), recruitment period; follow-up period	Assessment of exposure to ELF magnetic fields[a]	Cancer	No. of cases	Relative risk (95% CI)		Comments
			Breast cancer				
			Engine drivers				
			1961–69	2	8.3	(2.0–34)	
			1970–79	0	0.0	(0.0–6.0)	
			Railway workers				
			1961–69	4	4.3	(1.6–12)	
			1970–79	0	0.0	(0.0–1.6)	
			Brain tumours				
			Engine drivers				
			1961–69	8	1.1	(0.6–2.2)	
			1970–79	10	0.9	(0.5–1.6)	
			Railway workers				
			1961–69	31	1.2	(0.8–1.6)	
			1970–79	39	0.9	(0.7–1.3)	
Norway (Tynes *et al*., 1994a)	Workers in 8 power companies SIR (5088 men), 1920–85; 1953–91	Spot measurements and assessment of cumulative exposure to ELF magnetic fields	**Leukaemia**	11	0.90	(0.45–1.6)	
			Duration of employment				
			< 10 years	1	0.56	NR	
			10–29 years	6	1.2	NR	
			≥ 30 years	4	0.73	NR	
			Cumulative exposure				
			< 5 µT–years	2	0.95	NR	
			5–35 µT–years	4	0.74	NR	
			> 35 µT–years	5	1.0	NR	

Table 29 (contd)

Country (reference)	Population, design (number), recruitment period; follow-up period	Assessment of exposure to ELF magnetic fields[a]	Cancer	No. of cases	Relative risk (95% CI)	Comments
			Brain tumours	13	0.88 (0.47–1.5)	
			Duration of employment			
			< 10 years	3	0.91 NR	
			10–29 years	7	1.0 NR	
			≥ 30 years	3	0.65 NR	
			Cumulative exposure			
			< 5 μT–years	6	1.8 NR	
			5–35 μT–years	5	0.71 NR	
			> 35 μT–years	2	0.44 NR	
USA (Savitz & Loomis, 1995)	Utility workers SMR (138 905 men), 1950–86; 1950–88	Job–exposure matrix based on measurements of magnetic fields	*Magnetic fields (μT–years)*			
			Leukaemia			
			0.6–< 1.2	34	1.0 (0.66–1.6)	
			1.2–< 2.0	35	1.1 (0.70–1.8)	
			2.0–< 4.3	27	0.95 (0.56–1.6)	
			≥ 4.3	14	1.1 (0.57–2.1)	
			AML			
			0.6–< 1.2	12	1.3 (0.59–2.8)	
			1.2–< 2.0	7	0.94 (0.36–2.4)	
			2.0–< 4.3	5	0.72 (0.24–2.2)	
			≥ 4.3	5	1.6 (0.51–5.1)	
			CLL			
			0.6–< 1.2	8	1.3 (0.49–3.6)	
			1.2–< 2.0	13	2.0 (0.77–5.1)	
			≥ 2.0	5	0.55 (0.17–1.8)	

Table 29 (contd)

Country (reference)	Population, design (number), recruitment period; follow-up period	Assessment of exposure to ELF magnetic fields[a]	Cancer	No. of cases	Relative risk (95% CI)		Comments
			Brain cancer				
			0.6–< 1.2	34	1.6	(0.99–2.6)	
			1.2–< 2.0	26	1.5	(0.84–2.6)	
			2.0–< 4.3	27	1.7	(0.92–3.0)	
			≥ 4.3	16	2.3	(1.2–4.6)	
Sweden (Alfredsson *et al*., 1996)	Male railway engine drivers and conductors SIR (9738), 1976–90; 1976–90	Not estimated	Leukaemia	20	1.2	(0.7–1.9)	
			Lymphocytic leukaemia				
			All ages	14	1.6	(0.9–2.6)	
			20–64 years	10	2.3	(1.3–3.2)	
Denmark (Johansen & Olsen, 1998)	Utility workers SIR (32 006; 26 135 men, 5871 women), 1908–93; 1968–93	24-h measurements and job–exposure matrix for ELF magnetic fields	**Men**				
			All leukaemias	60	0.92	(0.7–1.2)	
			acute	20	0.87	(0.5–1.4)	
			chronic lymphoblastic	27	0.92	(0.6–1.3)	
			chronic myeloid	6	0.65	(0.2–1.4)	
			Brain	57	0.79	(0.6–1.0)	
			Breast	2	0.50	(0.1–1.8)	
			Women				
			All leukaemias	3	0.50	(0.1–1.5)	
			Brain	15	1.3	(0.7–2.2)	
			Breast	96	1.1	(0.9–1.3)	
China (Petralia *et al*., 1998)	Female population in urban Shanghai SIR (population size not given), 1980–84; 1980–84	Exposure estimated from occupation at diagnosis	*Breast*				
			Exposure probability				
			Low	683	1.0	(0.9–1.0)	
			Medium	72	1.1	(0.9–1.4)	
			High	72	0.9	(0.7–1.2)	

Table 29 (contd)

Country (reference)	Population, design (number), recruitment period; follow-up period	Assessment of exposure to ELF magnetic fields[a]	Cancer	No. of cases	Relative risk (95% CI)	Comments
			Exposure level			
			Low	602	1.0 (0.9–1.1)	
			Medium	0	–	
			High	130	1.0 (0.8–1.2)	
			Any exposure	827	1.0 (0.9–1.0)	
Sweden (Floderus *et al*., 1999)	Large proportion of national working population SIR (1 596 959 men and 806 278 women), 1970 census; 1971–1984	Measurements and job–exposure matrix; upper exposure tertile (men = 0.116 µT; women = 0.138 µT) versus all subjects	**Men**			
			All leukaemias	648	1.1 (1.0–1.2)	
			AML	199	1.1 (0.9–1.4)	
			CML	116	1.1 (0.8–1.4)	
			ALL	32	1.5 (0.9–2.7)	
			CLL	301	1.1 (0.9–1.2)	
			Brain	1100	1.1 (1.0–1.2)	
			Breast	37	1.2 (0.7–1.9)	
			Women			
			All leukaemias	263	1.1 (1.0–1.4)	
			AML	107	1.1 (0.8–1.5)	
			CML	57	0.8 (0.6–1.2)	
			ALL	12	1.1 (0.5–2.4)	
			CLL	87	1.7 (1.2–2.4)	
			Brain	598	0.9 (0.8–1.1)	
			Breast	4866	1.1 (1.0–1.1)	

Table 29 (contd)

Country (reference)	Population, design (number), recruitment period; follow-up period	Assessment of exposure to ELF magnetic fields[a]	Cancer	No. of cases	Relative risk (95% CI)		Comments
Norway (Kliukiene *et al*., 1999)	Female population of country SIR (1 177 129), 1960, 1970, 1980 censuses; 1961–92	Measurements and job–exposure matrix	*Breast*				Adjusted for age, time-period and socioeconomic status
			Work hours				
			1–899	NR	1.00		
			900–999	NR	1.07		
			1000–1999	NR	1.08		
			≥ 2000	NR	1.14		
			Exposure μT–years				
			0.1–0.8	NR	1.00	(baseline)	
			0.9–1.4	NR	1.07	(1.03–1.12)	
			1.5–3.0	NR	1.12	(1.07–1.17)	
			> 3.0	NR	1.08	(1.01–1.16)	
Italy (Pira *et al*., 1999)	Geothermal power plant workers SMR (3946 men), 1950–90; 1950–90	No formal evaluation	Leukaemia	8	0.79	(0.34–1.6)	
			Brain	11	1.2	(0.57–2.1)	
Norway (Rønneberg *et al*., 1999)	Aluminium smelter workers; production worker subcohort SIR (2888 men), 1953–93	Measurements and job–exposure matrix	Brain	7	0.71	(0.29–1.5)	Strong static magnetic fields
England and Wales (Harrington *et al*., 2001)	Electricity generation and transmission workers, SMR (72 954 men and 11 043 women); 1973–82; 1973–97	Job–exposure matrix based on measurements of magnetic fields	**Leukaemia**				
			SMR: Total	111	0.84	(0.69–1.0)	
			Period from hire				
			0–9 years	6	0.51	(0.19–1.1)	
			10–19 years	34	1.1	(0.73–1.5)	
			20–29 years	37	0.91	(0.64–1.3)	
			≥ 30 years	34	0.71	(0.49–1.0)	

Table 29 (contd)

Country (reference)	Population, design (number), recruitment period; follow-up period	Assessment of exposure to ELF magnetic fields[a]	Cancer	No. of cases	Relative risk (95% CI)		Comments
			RR: cumulative exposure (µT–years)				
			0–2.4	60	1.0		
			2.5–4.9	18	1.5	(0.87–2.5)	
			5.0–9.9	20	0.99	(0.59–1.7)	
			10.0–19.9	17	0.96	(0.55–1.7)	
			≥ 20.0	9	1.4	(0.68–2.8)	
Switzerland (Minder & Pfluger, 2001)	Railway workers, SMR (18 070 men), 1972–93; 1972–93	Measurements at the workplaces with estimates of historical exposure	**Leukaemia**				
			Station masters	6	1.0	(baseline)	
			Line engineers	19	2.4	(0.97–6.1)	
			Shunting yard engineers	3	2.0	(0.50–8.1)	
			Train attendants	9	1.1	(0.39–3.1)	
			µT–years				
			0–4.9	6	1.0	(baseline)	
			5–74.9	9	0.78	(0.72–2.2)	
			≥ 75	22	1.6	(0.64–4.2)	

Table 29 (contd)

Country (reference)	Population, design (number), recruitment period; follow-up period	Assessment of exposure to ELF magnetic fields[a]	Cancer	No. of cases	Relative risk (95% CI)		Comments
			Brain tumours				
			Station masters	3	1.0	(baseline)	
			Line engineers	4	1.0	(0.23–4.6)	
			Shunting yard engineers	5	5.1	(1.2–21)	
			Train attendants	11	2.7	(0.75–9.6)	
			μT–years				
			0–4.9	1	1.0	(baseline)	
			5–74.9	11	2.8	(0.35–23)	
			≥ 75	11	2.4	(0.29–19)	

AML, acute myeloid leukaemia; CML, chronic myeloid leukaemia; ALL, acute lymphoblastic leukaemia; CLL, chronic lymphocytic leukaemia; SMR, standardized mortality ratio; SIR, standardized incidence ratio; NR, not reported
[a] The studies by Spinelli *et al.* (1991) and Rønneberg *et al.* (1999) deal with exposure to static magnetic fields.
[b] Calculated by the Working Group

(90% CI, 0.8–3.3) for leukaemia (ICD-9, 204–208). For cancer incidence ascertained from 1970 onwards, the SIR was 1.9 (90% CI, 0.97–3.5) for brain cancer (ICD-9 191), and 0.76 (90% CI, 0.21–2.0) for leukaemia. However, no individual cause of cancer death or incident cancer was related to cumulative exposure to magnetic fields, as estimated from the job–exposure matrix.

Rønneberg *et al*. (1999) studied cancer incidence in a population composed of 2647 male short-term workers and two cohorts of men employed for at least four years (2888 production workers and 373 maintenance workers) at an aluminium smelter in Norway. Data on all men first hired at an hourly wage and with at least six months of continuous employment were obtained from company files dating back to 1946. Of the 5962 men who initially satisfied the inclusion criteria, six had died before the observation period started in 1953 and 48 were lost to follow-up. The remaining 5908 men were linked to the files of the Norwegian Cancer Registry and followed up from 1953 (or date of first employment) until date of death or emigration, or the end of 1993. Exposure to magnetic fields, ranging from 2–10 mT for static magnetic fields and from 0.3–10 μT for time-varying magnetic fields (mainly 50–300 Hz), was estimated from a survey of other Norwegian smelters (Thommesen & Bjølseth, 1992). Cumulative exposure for each worker was calculated as the product of the estimated exposure intensity and duration, summed for all jobs held at the smelter. Overall, the cancer incidence was not elevated in any of the three cohorts when compared with the expected incidence calculated on the basis of the age- and calendar year-specific cancer incidence of all men in Norway applied to the person–years at risk among cohort members. There was no association observed in the entire cohort of 2888 production workers between level of exposure to static magnetic fields or ELF magnetic fields and cancers of the brain or lymphatic and haematopoietic tissue, on the basis of seven and 32 observed cases, respectively. No excess of the latter cancers was observed among the highly exposed power-plant and rectifier workers of the production cohort, where two cases were observed as against 1.9 expected. Separate estimates of risk for leukaemia were not given.

(ii) *Workers exposed to electric and magnetic fields (not strong static magnetic fields)*

Following the detection of four cases of leukaemia among telephone operators in the city of Gothenburg, Sweden during 1969–74, a retrospective record linkage study of the entire national population was undertaken (Einhorn *et al*., 1980; Wiklund *et al*., 1981). A total of 14 480 telephone operators (14 180 women and 300 men) were identified from the 1960 population census in Sweden. Data linkage with the files of the nationwide Swedish Cancer Registry for the period 1961–73 revealed a total of 12 cases of leukaemia when 11.7 cases were expected on the basis of national age- and sex-specific incidence rates of the disease. [The Working Group noted that no effort was made by the authors to estimate potential job-related exposure to ELF electric and magnetic fields.]

In a study in Sweden based on a large-scale linkage of occupational data from the 1960 census and data from the national cancer registry for the years 1961–73, Vågerö and Olin (1983) investigated 54 624 men and 18 478 women, aged 15–64 years, working in the electronics or electrical manufacturing industry. They found significantly increased risks, of 15% in men and 8% in women, for cancer at all sites combined, compared with those of the working population in general. These increases were due mainly to significant increases in the risk for cancers of the pharynx, larynx and lung, and for malignant melanoma among men, and cervical cancer among women.

In a mortality study by Olin *et al*. (1985) of 1254 male electrical engineers, all of whom had graduated from one university in Sweden during 1930–59, 11 were lost to follow-up. The remaining 1243 cohort members were followed until date of death or the end of 1979. When compared with the age- and calendar time-adjusted mortality rates of the general Swedish male population, the SMR for cancer at all sites combined was 0.5 (95% CI, 0.3–0.7) on the basis of 24 observed cases. Three deaths from malignant melanoma were observed as opposed to 0.9 expected (SMR, 3.2; 95% CI, 0.7–9.4), and two deaths from leukaemia occurred as opposed to 2.3 expected (SMR, 0.9; 95% CI, 0.1–3.2). [The Working Group noted that no effort had been made by the authors to estimate potential job-related exposure to ELF electric and magnetic fields.]

Vågerö *et al*. (1985) evaluated cancer incidence in 2918 subjects (2051 men, 867 women) employed for at least six months during the period 1956–60 by a Swedish company at one of three worksites producing telecommunications equipment. All but four subjects, for whom personal data could not be verified, were linked to the files of the Swedish Cancer Registry for the period 1958–79. The observed numbers of cancers among cohort members were compared with the expected numbers, calculated on the basis of age-, sex- and calendar year-specific incidence rates for the entire Swedish population. Overall, 102 cancers were observed among men and 37 among women, yielding SIRs of 1.03 (95% CI, 0.8–1.2) and 0.98 (95% CI, 0.7–1.4), respectively. An increased risk for malignant melanoma was seen in both men (SIR, 2.5; 95% CI, 1.1–4.9; 8 cases) and women (SIR, 2.8; 95% CI, 0.8–7.2; 4 cases); the highest risk estimates were seen for departments associated with soldering work, but this observation was based on a total of only four observed cases in men and two in women (SIR, 3.9; 95% CI, 1.4–8.5) (both sexes combined). Two cases of Brill-Symmer disease (a nodular lymphoma) were seen in men as opposed to 0.1 expected. [The Working Group noted that no effort was made by the authors to estimate the potential job-related exposure to ELF electric and magnetic fields.]

From the 1960 population census in Sweden, Törnqvist *et al*. (1986) identified a total of 3358 male power linemen and 6703 male power-station operators in the electric power industry, who were all aged 20–64 years at the time of the census. Cohort members were linked to the files of the national Swedish Cancer Registry and followed up for cancer incidence until the end of 1979. The observed numbers of cancers were compared with the expected numbers, calculated on the basis of age-, county- and calendar year-specific cancer incidence rates for all men classified as blue collar workers by the census. Overall, 236 cancers were observed among power linemen and 463 cancers among power station operators, yielding SIRs of 1.1 (90% CI, 1.0–1.2) and 1.0 (90% CI, 0.9–1.0), respectively. For none of the specific cancer sites included in the analysis did the lower confidence limit exceed unity. The SIR for leukaemia among power linemen was 1.3 (90% CI, 0.7–2.1) and that among power station operators was 1.0 (90% CI, 0.6–1.5) on the basis of 10 and 16 observed cases, respectively. None of the major subgroups of leukaemia showed an excess risk in either occupational group. The SIR estimate for tumours of the nervous system was 1.5 (90% CI, 0.9–2.4) among power linemen and 1.0 (90% CI, 0.6–1.5) among power-station operators on the basis of 13 and 17 observed cases, respectively. [The Working Group noted that no effort was made by the authors to estimate potential job-related exposure to ELF electric and magnetic fields.]

This cohort was later extended (Törnqvist *et al*., 1991) to include all men in Sweden aged 20–64 who had worked in one of 11 electrically related occupations according to the job title recorded in the 1960 census, giving a total of 133 687 [or 7% of all Swedish working men]. In addition, the magnetic field exposure was estimated by five occupational hygienists, according to Swedish working conditions in the selected occupational categories. However, these estimates were based on only 50 measurements conducted over 4–8 h (except for two measurements made over nearly 18 h). A total of 334 cases of leukaemia was observed during 1961–79 which was only slightly in excess of the expected number [figure not stated] calculated on the basis of the incidence rates of cancer among all Swedish working men. Similarly, a total of 250 cases of brain tumour were identified which was approximately equal to the expected number [figure not stated]. Although significant, or marginally significant, positive associations were seen between one or more of the occupations under consideration (or industry subgroups thereof) and specific subtypes of leukaemia (acute myeloid, chronic myeloid, acute lymphoblastic, chronic lymphocytic, all subtypes combined) or brain tumour (glioma, glioblastoma, all subtypes combined), the authors concluded that no homogeneous pattern of increased risks associated with occupations for which there is presumed to be exposure to high ELF magnetic fields, was found. The authors noted that the occupation of the study subjects was known only on the census date in 1960, and that the estimates of ELF electric and magnetic fields were based on a small number of measurements.

De Guire *et al*. (1988) carried out a cohort study of 9590 workers employed between 1976 and 1983 in the Montreal plants of a telecommunications company. During the study period, 10 cases of malignant melanoma of the skin were diagnosed among men and none among women. Using reference rates for malignant melanomas in the Greater Montreal area during the same period, the SIR for men was 2.7 (95% CI, 1.3–5.0). [If the total cohort is considered, the expected number of cases is five (combined 95% CI, 1.1–3.7)] [The Working Group noted that the study was conducted in response to the observation of a cluster of melanomas among workers at one plant. No data were available on job titles or on specific types of exposure among these workers.]

In a cohort study of US Navy personnel (4 072 502 person–years), 102 cases of leukaemia were diagnosed among men on active duty in 1974–84 (Garland *et al.*, 1990). The overall incidence of leukaemia was close to that of the population of the United States. In the analysis by occupation, seven cases were reported among electrician's mates (111 944 person–years) with possible high exposure to 60-Hz electric and magnetic fields, yielding an increased risk for leukaemia in this group (SIR, 2.4; 95% CI, 1.0–5.0). No increased risk for leukaemia was observed in other occupational groups, in particular in naval workers with probable exposure to electric and magnetic fields at frequencies higher than 60 Hz. [The Working Group noted that there was no assessment of exposure to electric and magnetic fields by occupation.]

From the 1970 population census in Finland, Juutilainen *et al.* (1990) selected all Finnish men, aged 25–64 years, during the period 1971–80 who were classified as industrial workers according to their self-reported occupation. The occupations were grouped into three exposure categories according to the probability of exposure to ELF magnetic fields, i.e. no exposure, possible exposure and probable exposure. Cohort members were linked with the Finnish mortality files for determination of vital status through 1980 and to the files of the Finnish Cancer Registry for verification of incident cases of leukaemia and tumours of the central nervous system during the period 1971–80. Using all industrial workers with no exposure to ELF magnetic fields as the comparison group, the authors found relative risks for leukaemia of 1.4 (95% CI, 1.1–1.8; 221 cases) and 1.9 (95% CI, 1.0–3.5) for workers with possible and probable exposure, respectively, and, for brain tumour, the relative risks were 1.3 (95% CI, 1.0–1.6) and 1.3 (95% CI, 0.7–2.3), respectively.

From the 1960 population census in Norway, Tynes and Andersen (1990) identified a cohort of approximately 38 000 men aged ≥ 20 years who at that time had held jobs in which they might have been exposed to electric and magnetic fields. Cohort members were linked to the files of the Norwegian Cancer Registry and followed up for breast cancer incidence from 1961–85. A total of 12 cases of breast cancer was observed when 5.81 were expected on the basis of age- and calendar year-specific breast cancer incidence rates for all economically active men in Norway according to the census, yielding an SIR of 2.1 (95% CI, 1.1–3.6).

From the 1960 occupational cohort, a group was selected (37 945 men, aged 20–70 years) which was followed up to investigate other types of cancer in a second study (Tynes *et al.*, 1992). The jobs held by cohort members were categorized into one of 12 occupational groups, each of which was classified in turn according to the anticipated type of exposure to electric and magnetic fields, i.e. (i) radiofrequency, (ii) heavy magnetic, electric, (iii) intermediate magnetic, (iv) weak magnetic, electric, and (v) weak magnetic. No supporting field measurements were made. Cohort members were linked to the files of the national Norwegian Cancer Registry and followed up for cancer incidence from 1961 until the date of death or emigration, or to the end of 1985. Overall, 3806 incident cases of cancer were observed when 3583.7 were expected on the basis of age- and calendar year-specific cancer incidence rates for all economically active men in Norway according to the census, yielding an SIR of 1.06 (95% CI, 1.03–1.09). A total of 107 cases of leukaemia were reported, yielding a slightly increased SIR of 1.1 (95% CI, 0.9–1.3) with SIRs of 1.3 (95% CI, 0.88–1.2), 0.97 (95% CI, 0.64–1.4) and 1.5 (95% CI, 0.90–2.3) for acute myeloid, chronic lymphocytic and chronic myeloid subtypes of leukaemia, respectively. A total of 119 brain tumours were observed, which also resulted in a slightly increased SIR of 1.1 (95% CI, 0.90–1.4). In a separate analysis of the subgroup of cohort members still economically active at the time of the 1970 census, the SIR for leukaemia was 1.4 (95% CI, 1.1–1.8). On the basis of this subgroup, the authors found a tendency towards a dose–response relationship for leukaemia with SIRs of 1.8 (95% CI, 1.1–2.8), 1.4 (95% CI, 0.81–2.2) and 1.1 (95% CI, 0.70–1.6) for the exposure categories heavy magnetic, electric, intermediate magnetic and weak magnetic, respectively. No such tendency was apparent for brain tumours.

Matanoski *et al*. (1991) reported the results of a cohort study of telephone workers in the United States aged < 65 years. Central office technicians (9561), exposed to mean magnetic field strengths of 0.25 μT, had an SIR of 6.5 (95% CI, 0.79–24) for male breast cancer, based on two observed cases. These technicians were working in a central office with electromechanical switches, which produced a complex field environment. No men with breast cancer were observed among other telephone workers, in particular among cable splicers (4547) who had a mean exposure to magnetic fields of 0.43 μT. No results for leukaemia were reported in this study.

From the 1970 population census in Denmark, Guénel *et al*. (1993b) identified a total of 3932 combinations among men and 1885 combinations among women of a specific industry and a specific occupation. Only combinations in which ≥ 10 persons were involved were included. Each of these industry–occupation combinations was coded for potential occupational exposure (no exposure, probable exposure) to 50-Hz electric and magnetic fields using a threshold level of 0.3 μT, and the appropriate code was applied to the 2.8 million economically active Danes aged 20–64 years at the time of the census in 1970. Men and women judged to be occupationally exposed to intermittent magnetic fields (154 000 men, 79 000 women) and to continuous magnetic fields (18 000 men, 4000 women) were followed up in the Danish Cancer Registry until 1987. The numbers of first primary cancers observed in the exposed cohorts were compared with those expected, calculated on the basis of age-, sex- and calendar year-specific rates of primary cancer incidence among all persons who were economically active according to the census. The incidence of leukaemia was increased in men with probable continuous exposure to magnetic fields (SIR, 1.6; 95% CI, 1.2–2.2) on the basis of 39 observed cases. The excess risk was the same for acute leukaemia and for other leukaemias. The incidence of leukaemia was not increased in women with continuous exposure (SIR, 0.56; 95% CI, 0.07–2.0), but only two cases were observed. Both men and women with probable intermittent exposure to magnetic fields had leukaemia risks close to the average for all economically active persons. No significant result was found for breast cancer, brain tumours or malignant melanoma.

In a study from Sweden, Floderus *et al*. (1994) used the records from the 1960 Swedish population census to select all men, aged 20–64, who, in 1960, had been employed as workers by the Swedish railways. [The size of the cohort was not given; however, the study group appears identical to one of the 11 subcohorts included in a previous census-linkage study from Sweden (Törnqvist *et al*., 1991).] Using spot measurements, exposure to electric and magnetic fields was estimated to be of the order of 4.03–0.58 μT (engine drivers), 0.61–0.36 μT (conductors), 0.30–0.25 μT (station masters and train dispatchers) and 0.59–0.37 μT (railroad assistants and linemen). [It should be noted that the exposure assessment was made with a device having a less-than-flat frequency response (Floderus *et al*., 1993); the values quoted may therefore be underestimates.] Cohort members were linked to the national Swedish Cancer Registry and all cases of cancer notified to the cancer registry in 1961–79 were identified. All economically active men, aged 20–64 in 1960, acted as the reference population. No significantly increased relative risks were seen for leukaemia (all subtypes combined), for any of the subcohorts or for the combined cohort. In their consideration of the subtypes of leukaemia, the authors observed an increased risk for chronic lymphocytic leukaemia among engine drivers during the first decade of follow-up (1961–69) (SIR, 2.7; 95% CI, 1.0–7.4), but not in the second decade (1970–79) (SIR, 1.1; 95% CI, 0.4–2.9), but the relative risk estimates were based on only four cases of chronic lymphocytic leukaemia for each decade. No excess risks were seen for subtypes of brain tumour (astrocytoma I-II; astrocytoma III-IV) or for all subtypes combined (ICD-7 193 and astrocytoma only). But increased relative risks were observed for breast cancer, predominantly among engine drivers (SIR, 8.3; 95% CI, 2.0–34; 2 cases) and railway workers (SIR, 4.3; 95% CI, 1.6–12; 4 cases), and for tumours of the pituitary gland, predominantly among conductors (SIR, 3.3; 95% CI, 1.5–7.6; 6 cases) and railway workers (SIR, 2.9; 95% CI, 1.6–5.3; 11 cases). These results, however, were based on only a few observed cases and were seen only during the first decade of follow-up (1961–69). [The Working Group noted that calculation of person–years at risk was not corrected for elimination due to death, either in the study cohort or in the reference population. This implies that the relative risk estimates in the case of differential mortality in the study groups may have been distorted.]

In another study from Norway, Tynes *et al*. (1994a) studied the incidence of cancer in 5088 male workers in eight large hydroelectric power companies. From employment records available for each company, cohort members were selected on the following criteria: job title that indicated exposure to ELF electric and magnetic fields, employment for at least one year and first employment between 1920 and 1985. The average duration of employment among cohort members was 22 years. Spot measurements of magnetic fields were made at the two largest power companies and a job title–magnetic field exposure matrix was constructed. The matrix was applied to the work histories of the study subjects to provide calculated estimates of exposure to ELF electric and magnetic fields (μT–years) for each worker covering the period from first employment until date of retirement or the end of the study. Crude estimates of job-related exposure to solvents, herbicides, asbestos and cable oils were also made. Cohort members were linked to the files of the national Norwegian Cancer Registry and follow-up for cancer incidence was undertaken over the period 1953–91. Overall, 486 new cases of cancer were observed which matched the number of cases expected on the basis of person–years at risk among cohort members combined with the age- and calendar year-specific cancer incidence rates of Norwegian men (SIR, 1.0; 95% CI, 0.92–1.1). No significant deviation in risk from unity was seen for cancer at any site, including leukaemia (SIR, 0.90; 95% CI, 0.45–1.6) and brain tumours (ICD-9 193) (all tumours of the central nervous system and malignant tumours of the peripheral nervous system) (SIR, 0.88; 95% CI, 0.47–1.5) with 11 and 13 observed cases, respectively. In a sub-analysis, no trends in risks for leukaemia or brain tumours with increasing time since first employment or duration of employment were observed. Also, no association with cumulative exposure to magnetic fields was seen for leukaemia while brain tumour showed a tendency towards a negative correlation. An excess risk was seen for malignant melanoma at cumulative exposures above 35 μT–years (11 cases); however, the data showed no continuous exposure–response trend.

A mortality study was conducted in a cohort of workers at five electric utility companies in the USA (Savitz & Loomis, 1995). All men employed full-time continuously for at least six months between 1950 and 1986 were included. Vital status until 31 December 1988 was ascertained leading to the identification of 20 733 workers who had died out of a total of 138 905 workers. Exposure to magnetic fields was estimated from a job–exposure matrix, elaborated from exposure measurements made on workers randomly selected within occupational groups in each company. These measurements were taken using the AMEX meter which yields a TWA exposure. In total, 2842 usable measurements of a one-day work shift were collected. These were aggregated in five occupational groups to obtain maximum internal precision of the mean magnetic field within a group and maximum variability of mean magnetic field between groups. Occupational exposure to solvents and polychlorinated biphenyls was estimated for each occupational category through expert judgement. In the initial study, these analyses were restricted to total mortality (20 733 cases), total cancer (4833 cases), leukaemia (164 cases) and brain cancers (ICD-9 191, 192) (144 cases). A slight increased risk for brain cancer was apparent for workers employed in highly exposed occupations. The risk for leukaemia was increased for workers who had been employed for 20 years or more as electricians: SMR, 2.5 (95% CI, 1.1–5.8; 6 cases), but not in other exposed occupations. The risk for total cancer was slightly increased with indices of exposure to magnetic fields. Brain cancer, but not leukaemia, was associated with total exposure to magnetic fields, with a relative risk adjusted for potential occupational confounders of 2.3 (95% CI, 1.2–4.6) in the highest exposure category (≥ 4.3 μT–years, 90th percentile). The association with brain cancer was more apparent for recent exposure to magnetic fields, i.e. for exposure in the interval 2–10 years before death, suggesting a relatively short latency period: SMR, 1.2 (95% CI, 0.66–2.1), 1.4 (95% CI, 0.75–2.6), 1.5 (95% CI, 0.76–2.8) and 2.6 (95% CI, 1.4–4.9) for 0–< 0.2, 0.2–< 0.4;

0.4–< 0.7 and ≥ 0.7 μT–years, respectively. The relationship of brain cancer mortality to cumulative exposure to magnetic fields was not sensitive to the method used to treat historical exposure, the choice of exposure-time lags and windows, and the cut-points used to categorize the exposure variables (Loomis *et al*., 1998). Using a case–cohort approach and a refined job–exposure matrix with more precise job definitions, Savitz *et al*. (2000) found that the rate ratios for brain cancer were essentially unchanged; a weak positive association with leukaemia was apparent. Mortality from non-Hodgkin lymphoma, Hodgkin disease and multiple myeloma in this cohort were investigated by Schroeder and Savitz (1997). Weak associations between total exposure to magnetic fields and non-Hodgkin lymphoma were observed at intermediate exposure levels, with a weaker association in the highest exposure category. No association was observed with Hodgkin disease or multiple myeloma.

Mortality from lung cancer in this cohort in relation to magnetic fields has also been reported (Savitz *et al*., 1997). The rate ratio for lung cancer in the highest category of cumulative exposure to magnetic fields (4.28–15.45 μT–years, 90th percentile) was 1.1 (95% CI, 0.89–1.3). Modest associations were observed with exposure estimated in several time windows before death, or for duration of employment over 20 years in specific occupational groups exposed to strong 60-Hz magnetic fields, such as electricians or power plant operators. [The Working Group noted that adjustment for tobacco smoking was not feasible.]

In another study from Sweden, Alfredsson *et al.* (1996) investigated the incidence of cancer in 7466 railway engine drivers and 2272 conductors, who were employed by the Swedish State Railways on 1 January 1976 or who had started their employment there at any time during the period 1976–90. Information on date of hire, date of leaving and type of job was obtained from registers kept by the State Railways. No measurements of exposure to magnetic fields were made. Cohort members were followed up for cancer in the Swedish National Cancer Registry from date of first hire or 1 January 1976, whichever came first, until date of death or diagnosis, or until the end of 1990. The observed numbers of cohort members diagnosed with a first primary cancer were compared with the expected numbers calculated on the basis of person–years of follow-up among cohort members and cancer incidence rates of the general male population of Sweden. A total of 630 workers with cancers at all sites combined was observed (486 among railway engine drivers and 144 among conductors) yielding a relative risk of 0.9 (95% CI, 0.8–1.0). For railway engine drivers and conductors combined, the relative risk for acute lymphoblastic or chronic lymphocytic leukaemia was 1.6 (95% CI, 0.9–2.6). In a supplementary analysis where follow-up was restricted to workers in the age range 20–64 years, the authors found that the relative risk estimate was further increased: 2.3 (95% CI, 1.3–3.2). No clear association was seen for the other subtypes of leukaemia. For astrocytoma, the relative risk was close to one. [The Working Group noted that there must have been a substantial overlap between this study population and that studied by Floderus *et al.* (1994). It was not clear whether cancer reference rates including multiple cancers in individuals were used for the calculation of the expected numbers of cancers.]

Johansen and Olsen (1998) evaluated the incidence of cancer in a study population composed of 32 006 men and women with at least three months of employment at the 99 utility companies that supply Denmark with electricity. Personal data were obtained from manual files kept by the electricity companies, the Danish Supplementary Pension Fund and the public payroll administration; the date of first employment ranged from 1908–93. On the basis of a series of 24-h personal measurements and the judgements of four engineers, each of a total of 475 combinations of job title and work area for employees were assigned an average level of exposure to ELF electric and magnetic fields during a working day. These were in turn grouped into one of five categories according to exposure level: background (< 0.09 μT), low (0.1–0.29 μT), medium (0.3–0.99 μT), high (> 1.0 μT) and unknown exposure. A rough estimate was also made of exposure to asbestos. Cohort members were linked to the files of the national Danish Cancer Registry and follow-up for cancer was from 1968 until date of death, date of emigration or the end of 1993. Overall, 3008 cohort members with cancer were observed, as against 2825 expected on the basis of person–years at risk among cohort members combined with age-, sex- and calendar year-specific cancer incidence rates for the Danish population, yielding an SIR of 1.06 (95% CI, 1.03–1.10). No excess risk was seen for leukaemia [SIR, 0.88] or tumours of the brain [SIR, 0.86]; the overall reduction in the relative risk for brain tumours was due to a reduced risk of borderline significance (SIR, 0.79; 95% CI, 0.6–1.0) in men. Similarly, no excess was seen for any of the major subtypes of leukaemia, and no trends in risk could be distinguished for leukaemia or tumours of the brain in relation to time since first employment. Finally, there was no indication of a link between cumulative exposure to ELF electric and magnetic fields (duration of work combined with level of exposure) and the risk for any of these tumour types. Only two cases of breast cancer were seen in men, as against four expected, while the relative risk for breast cancer in female employees was slightly elevated (SIR, 1.1; 95% CI, 0.9–1.3), but breast cancer in women showed no correlation with cumulative exposure to ELF electric and magnetic fields. Increased risks for cancers of the lung and pleural cavity were seen mainly in workers whose jobs involved exposure to asbestos.

Petralia *et al*. (1998) carried out a study in urban Shanghai, the People's Republic of China, where all incident cases of breast cancer in women ≥ 30 years old in 1980–84 were identified. The incidence rates of breast cancer were calculated using the 1982 census data for the same population and SIRs were calculated with these rates as a reference. The extent of exposure to electric and magnetic fields was estimated through a job–exposure matrix using scores for exposure probability (high, medium, low or none) and exposure levels (high, medium, low or none). Using the occupation at the time of diagnosis for classifying women into exposure groups, electric and magnetic fields were not found to be related to breast cancer incidence; SIRs were close to 1.0 in all exposure categories for any exposure index.

In a linkage study from Sweden, Floderus *et al*. (1999) used data from the 1970 population census to evaluate overall and site-specific cancer incidence among 1 596 959 men and 806 278 women, aged 20–64 years in 1970, who had all been employed in a job the title of which had been included in a previously established job–exposure matrix for ELF electric and magnetic fields. This job–exposure matrix gave estimates of magnetic field exposure for the 100 most common jobs in Sweden according to the 1990 census, and for 10 specifically selected occupations that were less common, but more heavily exposed to ELF electric and magnetic fields (Floderus *et al*., 1993, 1996). This job–exposure matrix formed the basis for allocation of levels of exposure to magnetic fields to the jobs included in the study. Cohort members were linked to the files of the national Swedish Cancer Registry and followed up for cancer incidence from 1971 through 1984; follow-up was discontinued when members reached 70 years of age. Cumulative incidence rates, adjusted for age, but unadjusted for mortality during follow up, were calculated for all men and women employed in jobs categorized as having medium exposure (men, 0.084–0.115 μT; women, 0.067–0.129 μT) and high exposure (men, ≥ 0.116 μT; women, ≥ 0.138 μT) [and presumably compared with those of all men and women included in the study]. The risk ratios for cancer at all sites combined in the investigators' medium and high exposure categories, respectively, were 1.1 (95% CI, 1.1–1.1) and 1.1 (95% CI, 1.1–1.1) for men, and 1.1 (95% CI, 1.0–1.1) and 1.1 (95% CI, 1.0–1.1) for women. Similar results were seen for brain tumours (nervous system) and leukaemia with risk ratios of 1.1 (95% CI, 1.0–1.2) and 1.1 (95% CI, 1.0–1.2), respectively, in the highest exposure tertile for men and 0.9 (95% CI, 0.8–1.1) and 1.1 (95% CI, 1.0–1.4) for women. Also, in the highest tertile, male breast cancer was non-significantly increased (risk ratio, 1.2; 95% CI, 0.7–1.9). The risk ratios for cancer at several other sites were slightly increased in the upper exposure tertile, including malignant melanoma among men (risk ratio, 1.4; 95% CI, 1.2–1.5) and women (risk ratio, 1.2; 95% CI, 1.1–1.4); however, there was no general exposure–response pattern. [The Working Group noted that the study population must be partly overlapping with that included in a previous Swedish study by Törnqvist *et al*. (1991). The Working Group also noted that no measurements of cumulative exposure to magnetic fields were available, introducing a high risk for misclassification of the exposure of study subjects, and that no adjustment was made in the risk ratio analysis for mortality among study subjects during follow-up.]

In a linkage study from Norway, Kliukiene *et al*. (1999) used data from the 1960, 1970 and 1980 population censuses to evaluate the incidence of breast cancer in 1 177 129 women who were economically active according to at least one of the censuses. The classification of a job was based on a 3–5-digit industry code and a 3-digit occupation code; the socioeconomic status of the women was defined according to the job title. For a subcohort of women born in 1935 or later, data on age at birth of first child were also available. Exposure to ELF magnetic fields was assessed *a priori* using two different approaches. In the first approach, the number of hours per week during which potential magnetic fields were estimated to be above a background level, defined as 0.1 μT, were classified by an expert panel. In the second approach, measurements of magnetic fields from a previous study (Floderus *et al*., 1996) of Swedish men were allocated to the women's job titles as reported in the census. In both approaches, exposure was cumulated over years of employment (work hours and μT–years, respectively). Cohort members were linked to the National Cancer Registry for identification of notified cases of breast cancer, and person–years at risk were calculated from the year of entering the study to the date of death or emigration, or to the end of 1992. The SIRs for breast cancer among cohort members were calculated using the rates for the total Norwegian population as a reference. In the two highest categories for number of work hours with exposure to ELF magnetic fields above background, i.e. 1000–1999 h and ≥ 2000 h, the SIRs were 1.05 (95% CI, 1.02–1.07) and 1.08 (95% CI, 1.05–1.12), respectively. The SIRs in the two upper categories for cumulative exposure in μT–years, i.e. 1.5–3.0 and > 3.0 were 1.06 (95% CI, 1.03–1.09) and 1.03 (95% CI, 0.97–1.09), respectively. Using the lowest exposure category as a reference (0 h exposure above background, and cumulative exposure between 0.1 and 0.8 μT–years) and adjusting for socioeconomic status (based on the job title) a Poisson regression analysis showed a risk ratio for breast cancer for the two highest categories for number of work hours with exposure to magnetic fields above background, of 1.08 (95% CI, 1.04–1.12) and 1.14 (95% CI, 1.10–1.19), respectively, and for the highest categories of cumulative exposure of 1.12 (95% CI, 1.07–1.17) and 1.08 (95% CI, 1.01–1.16), respectively. In the subcohort of women born in 1935 or later, the corresponding risk ratio was somewhat lower, and of marginal significance, after adjustment for age at birth of first child.

From employment records, Pira *et al*. (1999) identified a total of 4237 subjects who had worked for at least three months in a geothermal power plant in Italy between 1950 and 1990. After exclusion of all the 225 female workers of 36 men who could not be traced, the remaining 3946 male workers were traced for date of death and cause of death, whenever appropriate, from death certificates and from population files kept by the local municipality. A total of 977 deaths was registered as opposed to 1295 expected on the basis of age- and calendar year-specific national mortality rates applied to the person–years at risk among cohort members, yielding a SMR of 0.75 (95% CI, 0.71–0.80). Eight of the deaths were due to leukaemia and 11 to tumours of the brain and nervous system yielding SMRs of 0.79 (95% CI, 0.34–1.6) and 1.2 (95% CI, 0.57–2.1), respectively. The authors reviewed the working histories of these patients at the power plant and stated that none had worked in activities for which exposure to electric and magnetic fields could be presumed to have occurred.

Mortality from leukaemia was investigated by Harrington *et al*. (2001) in a cohort of 83 977 male and female electricity generation and transmission workers at the former Central Electricity Generating Board of England and Wales for whom computer records were 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 until 1993. On the basis of the results from a previous measurement programme on occupational exposure to ELF electric and magnetic fields in parts of the

United Kingdom, exposure of workers in the electricity generation and transmission industry was estimated for 11 different work categories for power-station workers and eight categories for transmission workers. The job history for each worker was classified according to the established job categories and the cumulative occupational lifetime exposure (level multiplied by duration; μT–years) was estimated for each individual. The cumulative exposure in the most recent five-year period was also estimated. The mortality of the total cohort until 1997 was obtained by record linkage with the mortality files of the Central Register of the National Health Service. Compared with mortality rates from England and Wales, the overall SMR from leukaemia among cohort members was 0.84 (95% CI, 0.69–1.01) on the basis of 111 observed cases. Subanalyses by period from date of hire or according to subtype of leukaemia showed no consistent pattern. In the subcohort of 79 972 workers for whom work history data were available, a Poisson regression analysis showed age- and sex-adjusted relative risks of death from leukaemia of 1.5 (95% CI, 0.87–2.5), 0.99 (95% CI, 0.59–1.7), 0.96 (95% CI, 0.55–1.7) and 1.4 (95% CI, 0.68–2.8) among cohort members with a lifetime exposure of 2.5–4.9, 5.0–9.9, 10.0–19.9 and ≥ 20.0 μT–years, respectively, compared with the risk of death from leukaemia among workers with cumulative exposures ≤ 2.4 μT–years. Dose analyses on subtypes showed that only one point estimate, i.e. 'other leukaemias' in the lowest category of exposure, was significantly different from unity (relative risk, 2.0; 95% CI, 1.1–3.7). There was no significant trend of risk for any subtype of leukaemia or for all leukaemias combined with increasing cumulative exposure. A re-analysis using the most recent five years of exposure to ELF electric and magnetic fields did not change the results.

A retrospective cohort mortality study of Swiss Railway employees occupationally exposed to magnetic fields of 16 2/3-Hz and substantial harmonics was conducted by Minder and Pfluger (2001). The cohort comprised all men actively employed as line engineers, shunting-yard engineers, train attendants or stationmasters, or retired from these jobs and alive, identified through several personnel and pension records starting in 1972. The total number of men in the cohort was 18 070, representing 270 155 person–years of observation from 1972–93. Deaths of cohort members from leukaemia or brain tumour identified from death certificates were used as end-points. The assessment of exposure was carried out using a device that measured the magnetic fields in the driver's seat of the engine during complete driving cycles, for different types of train and routes taken. Historical exposure for each five-year calendar period was also assessed based on the number of engines in service and a weighted average of engine-specific exposure. The exposure to magnetic fields of train attendants and stationmasters was assessed from measurements taken at their most frequent places of work. Each cohort member was assigned the exposure associated with his last reported job, which was also generally of the longest duration, due to infrequent job changes. Estimated cumulative exposure in μT–years increased in the period 1930–90 from 9.3 to 25.9 for line engineers, from 2.6 to 13.4 for shunting-yard engineers, from 0.4 to 3.3 for train attendants and from 0.1 to 1.0 for stationmasters. When compared with stationmasters with the lowest exposure, the relative risk for leukaemia was 2.4 (95% CI, 0.97–6.1) for line engineers and 2.0 (95% CI, 0.50–8.1) for shunting-yard engineers. The relative risk for brain tumours (ICD-9 191) was 1.0 (95% CI, 0.23–4.6) for line engineers and 5.1 (95% CI, 1.2–21) for shunting-yard engineers. For cumulative exposure ≥ 75 μT–years compared with exposure 0–4.9 μT–years, the relative risk was 1.6 (95% CI, 0.64–4.2) for leukaemia and 2.4 (95% CI, 0.29–19) for brain tumours. The trend of increasing leukaemia mortality with both cumulative exposure and fraction of time above 10 μT was statistically significant.

(*c*) *Case–control studies*

In the first published studies on occupational exposure to electric and magnetic fields, no measurements of exposure were made; exposure was inferred from the job title, on the assumption that electrical workers were exposed to higher than background fields. Job–exposure matrices, which included scores for exposure probability and exposure intensity in exposed occupations as determined from expert judgement, have also been used. In most studies, no data on exposure to other potential carcinogens were available. Some of the studies presented as case–control studies are based on mortality data collected from death certificates. In these studies, the 'cases' were deaths from the cause of interest (i.e. leukaemia, brain tumour or breast cancer) and the controls were selected from other causes of death; such studies should be seen as mainly exploratory.

More recent studies have included exposure measurements and concerned mostly occupational cohorts analysed using a nested case–control study design. In some instances, the results have been presented according to the type of field measured (i.e. ELF magnetic fields, ELF electric fields). Exposure to potential occupational confounders was generally assessed in these studies.

The results of the case–control studies of ELF magnetic fields are summarized in Table 30 and for ELF electric fields in Table 31.

(i) *Leukaemia*

In a case–control study, McDowall (1983) used the deaths recorded in England and Wales for the year 1973. The cases selected were 537 men who had died aged ≥ 15 years from acute myeloid leukaemia. A total of 1074 controls were randomly selected from men who had died aged ≥ 15 years from all causes except leukaemia to match the cases within five-year age groups. The analysis showed an increased odds ratio for acute myeloid leukaemia for all five of the electrical occupations studied; however, this was statistically significant only when all five occupations were analysed combined (odds ratio, 2.1; 95% CI, 1.3–3.6). Further evaluation of the group of 'all electrical occupations and persons of any occupation engaged in an electrical telecommunications industry' gave an odds ratio of 2.3 (95% CI, 1.4–3.7).

In a population-based case–control study, Pearce *et al*. (1985) identified 546 cases of leukaemia among men aged ≥ 20 years notified to the cancer registry of New Zealand during 1979–83. The 2184 controls were men chosen at random from the

Table 30. Case–control studies of occupational groups with assumed or documented exposure to ELF magnetic fields

Country (reference)	Subjects: cases, controls (recruitment period)	Source of subjects	Source of job information; exposure assessment methods	Estimates of exposure to ELF magnetic fields	No. of cases	Odds ratio (95% CI)		Comments
Leukaemia								
England and Wales (McDowall, 1983)	537 male deaths from AML 1074 male deaths from other causes (controls) (1973)	Death certificates	Death certificates; occupation	All electrical occupations Any occupation in electrical or telecommunications industry	30 36	2.1 2.3	(1.3–3.6) (1.4–3.7)	Matched on age
New Zealand (Pearce *et al*., 1985)	546 men with leukaemia 2184 men with other cancers (controls) (1979–83)	Cancer registry	Cancer registry; occupation	All electrical occupations	18	1.7	(0.97–3.0)	Matched on age
New Zealand (Pearce *et al*., 1989) [partly overlapping with Pearce *et al*. (1985)]	534 men with leukaemia 19 370 men with other cancers (controls) (1980–84)	Cancer registry	Cancer registry; occupation	All electrical work age 20–64 age ≥ 65	21 9 12	1.6 1.4 1.9	(1.0–2.5) (0.71–2.7) (1.0–3.3)	
	Chronic leukaemia				11	2.1	(1.2–3.8)	
	Acute leukaemia				6	1.3	(0.62–2.5)	
USA (Loomis & Savitz, 1990)	3400 male deaths from leukaemia 34 000 male deaths from other causes (controls) (1985–86)	Death certificates; 16 states in the USA	Death certificates	Electrical occupations	76	1.0	(0.8–1.2)	Adjusted for race and age
	903 deaths from AML				22	1.1	(0.7–1.7)	Not adjusted
	414 deaths from CNLL				11	1.1	(0.8–1.7)	Not adjusted
	181 deaths from ALL				6	1.5	(0.7–3.4)	Not adjusted
	800 deaths from CLL				11	0.6	(0.3–1.1)	Not adjusted

Table 30 (contd)

Country (reference)	Subjects: cases, controls (recruitment period)	Source of subjects	Source of job information; exposure assessment methods	Estimates of exposure to ELF magnetic fields	No. of cases	Odds ratio	(95% CI)	Comments
France (Richardson *et al.*, 1992)	185 men and women with acute leukaemia 513 men and women with other diseases (controls) (1984–88)	In-patient files; two hospitals	Interview; job–exposure assessment	Any exposure	14	1.7	(0.9–3.5)	Matched on sex, age, ethnic group and place of residence
				Other than from arc welding				Adjusted for prior chemo-therapy or radiotherapy
				Any	7	3.9	(1.2–13)	
				Moderate/higher	3	2.9	(0.6–14)	
Italy (Ciccone *et al.*, 1993)	86 men and women with myeloid leukaemia or MDS 246 hospital and population controls (1989–90)	In-patient files	Personal interview; job–exposure matrix	**Possibly and probably exposed**				Matched on sex, age and area of residence
				Men	17	1.6	(0.6–4.1)	
				Women	4	0.8	(0.2–2.5)	
USA (Sahl *et al.*,1993; Kheifets *et al.*, 1999)	44 deaths from leukaemia 438 cohort controls (1960–88)	Cohort of electric utility workers	Company personnel records; job–exposure matrix based on measured magnetic fields	< 4 µT–years	6	1.0	(baseline)	
				4–8 µT–years	3	1.0	(0.2–4.8)	
				8–16 µT–years	7	1.6	(0.4–6.4)	
				>16 µT–years	15	1.5	(0.4–6.3)	
Sweden (Floderus *et al.*, 1993)	250 men with leukaemia 1121 male population controls (1983–87)	Cancer registry; population registry	Mailed question-naire and spot measurements; job–exposure matrix	**Mean level**				Matched on age
				≤ 0.15 µT (Q1)	48	1.0	(baseline)	
				0.16–0.19 µT (Q2)	50	0.9	(0.6–1.4)	
				0.20–0.28 µT (Q3)	61	1.2	(0.8–1.9)	
				≥ 0.29 µT (Q4)	80	1.6	(1.1–2.4)	
				≥ 0.41 µT (90%)	32	1.7	(1.0–2.7)	

Table 30 (contd)

Country (reference)	Subjects: cases, controls (recruitment period)	Source of subjects	Source of job information; exposure assessment methods	Estimates of exposure to ELF magnetic fields		No. of cases	Odds ratio (95% CI)		Comments
	112 men with CLL			≤ 0.15 µT	(Q1)	13	1.0	(baseline)	
				0.16–0.19 µT	(Q2)	17	1.1	(0.5–2.3)	
				0.20–0.28 µT	(Q3)	33	2.2	(1.1–4.3)	
				≥ 0.29 µT	(Q4)	41	3.0	(1.6–5.8)	
				≥ 0.41 µT	(90%)	22	3.7	(1.8–7.7)	
	90 men with AML			≤ 0.15 µT	(Q1)	22	1.0	(baseline)	
				0.16–0.19 µT	(Q2)	24	1.0	(0.5–1.8)	
				0.20–0.28 µT	(Q3)	18	0.8	(0.4–1.6)	
				≥ 0.29 µT	(Q4)	23	1.0	(0.6–1.9)	
				≥ 0.41 µT	(90%)	8	0.9	(0.4–2.1)	
USA (London *et al*., 1994)	2355 men with leukaemia 67 212 men with other cancers (controls) (1972–90)	Los Angeles county cancer registry	Job at diagnosis from medical record; job–exposure matrix based on measured magnetic fields in selected occupations	**Average level**					
				< 0.17 µT		2264	1.0	(baseline)	
				0.18–0.80 µT		61	1.2	(1.0–1.6)	
				≥ 0.81 µT		30	1.4	(1.0–2.0)	
	853 men with ANLL			< 0.17 µT		820	1.0	(baseline)	
				0.18–0.80 µT		23	1.3	(0.9–1.9)	
				≥ 0.81 µT		10	1.3	(0.7–2.3)	
	534 men with CLL			< 0.17 µT		512	1.0	(baseline)	
				0.18–0.80 µT		18	1.6	(1.2–2.3)	
				≥ 0.81 µT		4	0.8	(0.4–1.5)	
	487 men with CML			< 0.17 µT		469	1.0	(baseline)	
				0.18–0.80 µT		8	0.8	(0.5–1.3)	
				≥ 0.81 µT		10	2.3	(1.4–3.8)	

Table 30 (contd)

Country (reference)	Subjects: cases, controls (recruitment period)	Source of subjects	Source of job information; exposure assessment methods	Estimates of exposure to ELF magnetic fields	No. of cases	Odds ratio (95% CI)		Comments
Norway (Tynes *et al.*, 1994a)	52 men with leukaemia 259 cohort controls (1958–90)	Cohort of railway workers	Job history from employment files; job–exposure matrix	Ever worked at an electric line	33	0.7	(0.37–1.4)	Matched on age
				Cumulative exposure				
				None	19	1.0	(baseline)	
				Low (0.1–310 μT–years)	22	1.0	(0.49–2.1)	
				High (311–3600 μT–years)	11	0.49	(0.22–1.1)	
				Very high (1900–3600 μT–years)	4	0.84	(0.25–2.8)	
Canada, France (3 cohorts combined) (Thériault *et al.*, 1994)	140 incident cases of leukaemia 546 cohort controls (Canada, 1970–88; France, 1978–89)	Three cohorts of electric utility workers in Canada (Quebec and Ontario) and France	Company personnel records; job–exposure matrix based on measurements of exposure to magnetic fields	**Cumulative exposure**				
				< 3.1 μT–years	70	1.0	(baseline)	
				> 3.1 μT–years	70	1.5	(0.90–2.6)	
				> 15.7 μT–years	13	1.8	(0.77–4.0)	
	60 incident cases of ANLL 238 cohort controls			< 3.1 μT–years	27	1.0	(baseline)	
				> 3.1 μT–years	33	2.4	(1.1–5.4)	
				> 15.7 μT–years	6	2.5	(0.70–9.1)	
	24 incident cases of CML 93 cohort controls			< 3.1 μT–years	16	1.0	(baseline)	
				> 3.1 μT–years	8	0.61	(0.18–2.1)	
	14 incident cases of ALL 55 cohort controls			< 3.1 μT–years	10	1.0	(baseline)	
				> 3.1 μT–years	4	2.1	(0.12–35)	
	41 incident cases of CLL 157 cohort controls			< 3.1 μT–years	17	1.0	(baseline)	
				> 3.1 μT–years	24	1.5	(0.50–4.4)	
				> 15.7 μT–years	6	1.7	(0.44–6.7)	

Table 30 (contd)

Country (reference)	Subjects: cases, controls (recruitment period)	Source of subjects	Source of job information; exposure assessment methods	Estimates of exposure to ELF magnetic fields	No. of cases	Odds ratio (95% CI)	Comments
Quebec cohort (included in Thériault *et al*., 1994)	24 men with leukaemia 95 cohort controls (1970–88)			**Cumulative exposure**			
				< 3.1 µT–years	6	1.0 (baseline)	
				> 3.1 µT–years	18	0.29 (0.04–1.8)	
				> 15.7 µT–years	4	0.45 (0.04–3.8)	
	[8 men with ANLL] 32 cohort controls			< 3.1 µT–years	1	1.0 (baseline)	
				> 3.1 µT–years	[7]	0.75 (0.00–> 100)	
				>15.7 µT–years	2	0.14 (0.00–> 100)	
	10 men with CLL 40 cohort controls			< 3.1 µT–years	3	1.0 (baseline)	
				> 3.1 µT–years	7	0.25 (0.02–2.6)	
				>15.7 µT–years	2	0.27 (0.02–4.2)	
France cohort (included in Thériault *et al*., 1994)	71 incident cases of leukaemia 279 cohort controls (1978–89)			**Cumulative exposure**			
				< 3.1 µT–years	55	1.0 (baseline)	
				> 3.1 µT–years	16	1.4 (0.61–3.1)	
				> 15.7 µT–years	3	1.9 (0.46–7.8)	
	34 men with ANLL 134 cohort controls			< 3.1 µT–years	24	1.0 (baseline)	
				> 3.1 µT–years	10	1.8 (0.57–5.4)	
				> 15.7 µT–years	1	1.4 (0.03–16.2)	
	13 men with CLL 51 cohort controls			< 3.1 µT–years	10	1.0 (baseline)	
				> 3.1 µT–years	3	4.8 (0.45–71)	
				> 15.7 µT–years	1	2.8 (0.04–68)	

Table 30 (contd)

Country (reference)	Subjects: cases, controls (recruitment period)	Source of subjects	Source of job information; exposure assessment methods	Estimates of exposure to ELF magnetic fields	No. of cases	Odds ratio (95% CI)	Comments
Canada, Ontario cohort included in Thériault *et al.*, 1994), updated Miller *et al*. (1996)[a]	50 men with leukaemia 199 cohort controls 1970–88	Cohort of electric utility workers at Ontario Hydro	Company personnel records; job–exposure matrix for magnetic fields (Positron meter)	**Cumulative exposure** < 3.1 μT–years 3.2–7 μT–years ≥ 7.1 μT–years	 10 16 24	 1.0 (baseline) 1.7 (0.58–4.8) 1.6 (0.47–5.1)	Adjustment for potential confounders
	20 men with ANLL [80 cohort controls]			< 3.1 μT–years 3.2–7 μT–years ≥ 7.1 μT–years	3 6 11	1.0 (baseline) 1.9 (0.27–14) 2.9 (0.42–20)	
	19 men with CLL [76 cohort controls]			< 3.1 μT–years 3.2–7 μT–years ≥ 7.1 μT–years	4 6 9	1.0 (baseline) 0.49 (0.06–4.2) 0.25 (0.01–4.6)	
Brain tumours							
USA (Lin *et al*., 1985)	519 male deaths from brain tumours (370 gliomas or glioblastoma multiforme, and 149 astrocytomas) 519 male deaths from other causes (controls)	Maryland state vital records	Job on death certificate; job–exposure matrix	No exposure Possible exposure Probable exposure Definite exposure	323 128 21 27	1.0 1.4 (1.1–2.0) 2.0 (0.94–3.9) 2.2 (1.1–4.1)	
	432 male deaths from brain tumours of unspecified type 432 male deaths from other causes (controls) (1969–82)			No exposure Possible exposure Probable exposure Definite exposure	286 87 19 15	1.0 0.94 (0.68–1.3) 1.3 (0.60–2.8) 1.5 (0.68–3.4)	

Table 30 (contd)

Country (reference)	Subjects: cases, controls (recruitment period)	Source of subjects	Source of job information; exposure assessment methods	Estimates of exposure to ELF magnetic fields	No. of cases	Odds ratio (95% CI)		Comments
USA (Speers *et al*., 1988)	202 male deaths from glioma 238 male deaths from other causes (controls) (1969–78)	Death certificates (East Texas)	Job on death certificate; job–exposure matrix	No exposure Possible exposure Probable exposure Definite exposure	92 68 11 6	1.0 1.2 2.9 infinite	 (0.73–1.8) 0.80–10) $p = 0.009$	Adjusted for age
New Zealand (Pearce *et al*., 1989)	431 men with malignant brain tumours (ICD-9 191) 19 473 men with other cancers (controls) (1980–84)	Cancer registry	Cancer registry occupation	All electrical workers	12	1.0	(0.56–1.8)	
USA (Preston-Martin *et al*., 1989)	202 men with glioma 202 male neighbourhood controls (1980–84)	Los Angeles County Cancer Registry	Work history from questionnaire; electrical occupations	Any exposure duration < 5 years > 5 years	14/8 16 14	1.8 1.4 1.8	(0.7–4.8) (0.7–3.1) (0.8–4.3)	No. of discordant pairs
	70 men with meningioma 70 neighbourhood controls			Any exposure duration	2/3	0.7	(0.1–5.8)	No. of discordant pairs
USA (Loomis & Savitz, 1990)	2173 male deaths from brain cancer (ICD-9 191) 21 730 male deaths from other causes (1985–86)	Death certificates (16 US states)	Death certificate; occupation	Electrical occupations	75	1.4	(1.1–1.7)	Adjusted for race and age

Table 30 (contd)

Country (reference)	Subjects: cases, controls (recruitment period)	Source of subjects	Source of job information; exposure assessment methods	Estimates of exposure to ELF magnetic fields	No. of cases	Odds ratio (95% CI)	Comments
Australia (Ryan *et al.*, 1992)	110 glioma 60 meningioma 417 controls (1987–90)					0.75 (0.30–1.9) 0.90 (0.20–4.1)	
Sweden (Floderus *et al.*, 1993)	261 men with brain tumours (astrocytomas and oligodendrogliomas) 1121 male population controls (1983–87)	Cancer registry/ population registry	Postal question-naire and spot measurements; job–exposure matrix	**Mean level** ≤ 0.15 µT (Q1) 0.16–0.19 µT (Q2) 0.20–0.28 µT (Q3) ≥ 0.29 µT (Q4) ≥ 0.41 µT	 53 59 72 74 24	 1.0 (baseline) 1.0 (0.7–1.6) 1.5 (1.0–2.2) 1.4 (0.9–2.1) 1.2 (0.7–2.1)	Matched on age
USA (Sahl *et al.*,1993)	31 deaths from brain cancer (ICD-9 191) 286 cohort controls	Cohort of electric utility workers	Company personnel records; job–exposure matrix based on measured magnetic fields	Treating cumulative mean exposure as a continuous variable. Odds ratio per 25 µT–years of exposure	4	0.81 (0.48–1.4)	
Canada, France (3 cohorts combined) (Thériault *et al.*, 1994)	108 men with brain cancer (ICD-9 191) 415 cohort controls	Three cohorts of electric utility workers in Canada (Québec and Ontario) and France	Company personnel records; job–exposure matrix based on measurements of exposure to magnetic fields (Positron meter)	**Cumulative exposure** < 3.1 µT–years > 3.1 µT–years > 15.7 µT–years	 60 48 12	 1.0 (baseline) 1.5 (0.85–2.8) 2.0 (0.76–5.0)	

Table 30 (contd)

Country (reference)	Subjects: cases, controls (recruitment period)	Source of subjects	Source of job information; exposure assessment methods	Estimates of exposure to ELF magnetic fields	No. of cases	Odds ratio (95% CI)		Comments
Quebec cohort (Thériault *et al*., 1994)	24 men with brain cancer 94 cohort controls (1970–88)			**Cumulative exposure**				
				< 3.1 µT–years	6	1.0	(baseline)	
				> 3.1 µT–years	18	1.6	(0.38–6.8)	
				> 15.7 µT–years	6	1.7	(0.29–9.7)	
Ontario cohort (Thériault *et al*., 1994)	24 men with brain cancer 90 cohort controls (1970–88)			**Cumulative exposure**				
				< 3.1 µT–years	7	1.0	(baseline)	
				> 3.1 µT–years	17	1.9	(0.53–6.5)	
				> 15.7 µT–years	4	5.5	(0.59–51)	
France cohort (Thériault *et al*., 1994)	60 men with brain cancer 231 cohort controls (1978–89)			**Cumulative exposure**				
				< 3.1 µT–years	47	1.0	(baseline)	
				>3.1 µT–years	13	1.4	(0.65–3.1)	
				>15.7 µT–years	2	NR	–	
Norway (Tynes *et al*., 1994a)	39 men with brain tumours 194 cohort controls (1958–90)	Cohort of railway workers	Job history from employment files; job–exposure matrix	Ever worked at an electric line	28	0.82	(0.38–1.8)	Matched on age
				Cumulative exposure				
				None	11	1.0	(baseline)	Unadjusted
				Low (0.1–310 µT–years)	14	0.81	(0.33–2.0)	
				High (311–3600 µT–years)	14	0.94	(0.39–2.3)	
				Very high (1900–3600 µT–years)	3	0.97	(0.24–4.0)	
USA (Grayson, 1996)	230 men with brain cancer (ICD-9 191) 920 cohort controls (1970–89)	Cohort of male members of the US Air Force	Work history from personnel records; job–exposure matrix (scores for exposure probability)	Ever exposed	129	1.3	(0.95–1.7)	
				1–59[b]	39	1.3	(0.81–2.1)	
				60–134	33	0.93	(0.56–1.5)	
				135–270	44	1.6	(1.0–2.6)	
				271–885	13	1.4	(0.88–2.3)	

Table 30 (contd)

Country (reference)	Subjects: cases, controls (recruitment period)	Source of subjects	Source of job information; exposure assessment methods	Estimates of exposure to ELF magnetic fields	No. of cases	Odds ratio (95% CI)		Comments
England & Wales (Harrington *et al.*, 1997)	112 men and women with brain cancer (primary) 654 cohort controls (1972–84)	Cohort of electricity generation and transmission workers	Job history from employment files; job–exposure matrix	≤ 3.0 µT–years 3.1–5.9 µT–years ≥ 6.0 µT–years Unclassifiable	30 37 27 18	1.0 1.3 0.91 1.8	(baseline) (0.75–2.2) (0.51–1.6) (0.93–3.6)	
Sweden (Rodvall *et al.*, 1998)	84 men with glioma 155 population controls (1987–90)	In-patient files and cancer registry/ population registry	Postal question-naire; job–exposure matrix	< 0.20 µT > 0.40 µT		1.0 1.9	(baseline) (0.8–5.0)	Adjusted for socio-economic status and exposure to solvents and plastic materials
	20 men with meningioma 155 population controls			< 0.20 µT > 0.40 µT		1.0 1.6	(baseline) (0.3-10)	
USA (Cocco *et al.*, 1998a)	28 416 deaths from central nervous system cancer (men and women) 113 664 deaths from other causes (controls) (1984–92)	Death certificates (24 US states)	Job on death certificate; job–exposure matrix (exposure yes/no)	White men Black men White women Black women	5271 234 1382 78	1.0 1.0 1.0 1.2	(1.0–1.0) (0.8–1.2) (0.9–1.1) (0.9–1.6)	Adjusted for socioeconomic status and other variables
USA (Cocco *et al.*, 1999)	12 980 female deaths from central nervous system cancer + meningioma 51 920 deaths from other causes (controls) (1984–92)	Death certificates (24 US states)	Job on death certificate; job–exposure matrix: probability and intensity of exposure					

Table 30 (contd)

Country (reference)	Subjects: cases, controls (recruitment period)	Source of subjects	Source of job information; exposure assessment methods	Estimates of exposure to ELF magnetic fields	No. of cases	Odds ratio (95% CI)		Comments
	12 819 deaths from central nervous system cancer			Any exposure level	2901	1.2	(1.1–1.2)	
				Probability				
				Low	2312	1.2	(1.1–1.2)	
				Medium	255	1.2	(1.0–1.4)	
				High	334	1.2	(1.0–1.3)	
				Intensity				
				Low	2200	1.2	(1.1–1.2)	
				Medium	616	1.1	(1.0–1.3)	
				High	85	1.3	(1.0–1.6)	
	161 deaths from meningioma			Any exposure level	34	0.9	(0.6–1.4)	
Breast cancer								
Women								
USA (Loomis *et al*., 1994b) [included in Cantor *et al*., 1995]	28 434 deaths from breast cancer (women, excluding homemakers) 113 011 other causes of death (controls) (1985–89)	Death certificates (24 US states)	Job on death certificate; occupation	Electrical occupations	68	1.4	(1.0–1.8)	Adjusted for age, race, social class
USA (Cantor *et al*., 1995)	33 509 deaths from breast cancer (women, excluding homemakers) 117 794 other causes of death (controls) (1984–89)		Job on death certificate; job–exposure matrix: probability and level of exposure	*White women*				
				Probability				
				Low	8581	0.92	(0.89–0.95)	
				Medium	779	1.1	(1.05–1.3)	
				High	1869	1.1	(1.02–1.2)	
				Level				
				Low	9360	0.94	(0.9–0.96)	
				Medium	1746	1.1	(1.03–1.2)	
				High	123	0.97	(0.8–1.2)	

Table 30 (contd)

Country (reference)	Subjects: cases, controls (recruitment period)	Source of subjects	Source of job information; exposure assessment methods	Estimates of exposure to ELF magnetic fields	No. of cases	Odds ratio (95% CI)	Comments
				Black women			
				Probability			
				Low	1516	0.81 (0.7–0.9)	
				Medium	168	1.3 (1.1–1.6)	
				High	293	1.3 (1.1–1.6)	
				Level			
				Low	1684	0.85 (0.8–0.92)	
				Medium	273	1.3 (1.1–1.5)	
				High	20	1.2 (0.7–2.1)	
USA (Coogan *et al*., 1996)	6888 women with breast cancer 9529 population controls (1988–91)	4 US states	Usual occupation from telephone interview; job–exposure matrix	**Potential for exposure**			Adjusted for risk factors for breast cancer
				Low	577	1.0 (0.91–1.2)	
				Medium	104	1.1 (0.83–1.4)	
				High	57	1.4 (0.99–2.1)	
	1424 women with premenopausal breast cancer 2675 population controls			Low	91	0.91 (0.69–1.2)	
				Medium	18	0.82 (0.45–1.5)	
				High	20	2.0 (1.0–3.8)	
	5163 women with postmenopausal breast cancer 6421 population controls			Low	462	1.0 (0.89–1.2)	
				Medium	78	1.1 (0.80–1.5)	
				High	35	1.3 (0.82–2.2)	
USA (Coogan & Aschengrau, 1998)	259 women with breast cancer 738 general population controls (1983–86)	5 Upper Cape Cod towns in MA	Work history from questionnaire; job–exposure matrix	Occupational exposure to medium magnetic fields	16	0.9 (0.5–1.7)	Adjusted for risk factors for breast cancer
				Occupational exposure to high magnetic fields	7	1.2 (0.4–3.6)	

Table 30 (contd)

Country (reference)	Subjects: cases, controls (recruitment period)	Source of subjects	Source of job information; exposure assessment methods	Estimates of exposure to ELF magnetic fields	No. of cases	Odds ratio (95% CI)	Comments
Sweden (Forssén *et al*., 2000)	1767 women with breast cancer 1766 population controls (1960–65)	Cohort of residents near power lines	Occupation from census; job–exposure matrix	**Occupational exposures**			Matched on age, individual power line and municipality
				< 0.12 µT	156	1.0 (baseline)	
				0.12–0.19 µT	178	1.0 (0.7–1.4)	
				≥ 0.20 µT	62	1.0 (0.7–1.6)	
				Occupational and residential exposures			
				< 0.12 µT	31	1.0 (baseline)	
				= 0.12 µT	8	0.9 (0.3–2.7)	
Men							
USA (Demers *et al*., 1991)	227 men with incident breast cancer 300 population controls (1983–87)	10 US population-based cancer registries	2 occupations of longest duration from questionnaire; occupation	**Any electrical occupation**	33	1.8 (1.0–3.7)	
				Ever exposed	10	1.8 (0.7–4.9)	
				< 10 years	6	1.8 (0.5–6.2)	
				10–19 years	8	1.5 (0.5–4.3)	
				20–29 years	9	2.1 (0.7–6.2)	
				≥ 30 years			
USA (Rosenbaum *et al*., 1994)	71 men with incident breast cancer 256 volunteers from cancer screening clinic (1979–88)	Western New York state	Hospital registration cards, city directories; electrical occupations	Electrical occupations	6	0.6 (0.2–1.6)	Adjusted for age, county and heat exposure
Sweden (Stenlund & Floderus, 1997)	63 men with breast cancer 1121 population controls (1985–91)	Cancer registry	Postal questionnaire and spot measurements; job–exposure matrix	**Mean level**			Adjusted for age, education and exposure to solvents
				≤ 0.15 µT (Q1)	11	1.0 (baseline)	
				0.16–0.19 µT (Q2)	17	1.2 (0.6–2.7)	
				0.20–0.28 µT (Q3)	17	1.3 (0.6–2.8)	
				≥ 0.29 µT (Q4)	11	0.7 (0.3–1.9)	
				≥ 0.41 µT	4	0.7 (0.2 –2.3)	

Table 30 (contd)

Country (reference)	Subjects: cases, controls (recruitment period)	Source of subjects	Source of job information; exposure assessment methods	Estimates of exposure to ELF magnetic fields	No. of cases	Odds ratio (95% CI)		Comments
USA (Cocco *et al*., 1998b)	178 male deaths from breast cancer 1041 male deaths from other causes (controls) (1985–86)	Death certificates	Occupation of longest duration from questionnaire to next-of-kin; job–exposure matrix	**Probability of exposure**				
				Low	30	1.0	(0.6–1.6)	
				Medium	7	1.2	(0.5–3.1)	
				High	19	1.1	(0.6–1.9)	
				Level of exposure				
				Low	31	1.0	(0.6–1.7)	
				Medium	16	1.1	(0.6–2.0)	
				High	9	1.0	(0.5–2.1)	

ALL, acute lymphoblastic leukaemia; AML, acute myeloid leukaemia; ANLL, acute non-lymphoblastic leukaemia; CLL, chronic lymphocytic leukaemia; CML, chronic myeloid leukaemia; CNLL, chronic non-lymphocytic leukaemia; MDS, myelodysplastic syndrome; NR, not reported; Q, quartile

[a] This study included five cases of leukaemia not included in the initial analysis by Thériault *et al*. (1994); this explains the different results for Ontario workers reported in the two papers.

[b] Product of potential exposure score and duration in months

Table 31. Case–control studies of occupational groups with assumed or documented exposure to ELF electric fields[a]

Country (reference)	Subjects (recruitment period)	Source of subjects	Source of job information; exposure assessment methods	Estimates of exposure to ELF electric fields	No. of cases	Odds ratio (95% CI)	Comments
Leukaemia							
Canada (Miller *et al*., 1996) [included in Thériault *et al*., 1994][b]	50 men with leukaemia 199 cohort controls (1970–88)	Cohort of electric utility workers at Ontario Hydro	Company personnel records; job–exposure matrix based on magnetic fields and measurements of exposure to electric fields (Positron meter)	Electric fields (V/m–years)			Adjusted for socioeconomic status and potential occupational confounders
				0–171	11	1.0 (baseline)	
				172–344	13	2.1 (0.59–7.2)	
				≥ 345	26	4.5 (1.0–20)	
	20 incident cases of ANLL 80 cohort controls			0–171	4	1.0 (baseline)	
				172–344	6	10 (0.58–172)	
				≥ 345	10	7.9 (0.43–143)	
	19 incident cases of CLL 76 cohort controls			0–171	3	1.0 (baseline)	
				172–344	6	1.3 (0.07–21)	
				≥ 345	10	7.2 (0.31–169)	
France (Guénel *et al*., 1996) [included in Thériault *et al*., 1994]	72 men with leukaemia 285 cohort controls (1978–89)	Cohort of electric utility workers at Electricité de France	Company personnel records; job–exposure matrix based on measurements of exposure to electric fields (Positron meter)	Electric fields (V/m–years)			Adjusted for socioeconomic status
				< 253	38	1.0 (baseline)	
				253–329	20	0.96 (0.45–2.0)	
				330–401	10	0.71 (0.27–1.9)	
				≥ 402	4	0.37 (0.11–13)	
	34 men with ANLL 134 cohort controls			percentiles			Adjusted for socioeconomic status and exposure to magnetic fields
				< 50	18	1.0 (baseline)	
				≥ 50–< 75	10	0.95 (0.45–2.0)	
				≥ 75–< 90	4	0.71 (0.26–1.9)	
				≥ 90	2	0.36 (0.10–1.3)	

Table 31 (contd)

Country (reference)	Subjects (recruitment period)	Source of subjects	Source of job information; exposure assessment methods	Estimates of exposure to ELF electric fields	No. of cases	Odds ratio (95% CI)		Comments
USA (Kheifets *et al*., 1997b) [same study as London *et al*., 1994]	2355 men with leukaemia 67 212 other cancer cases (1972–90)	Los Angeles county cancer registry	Job at diagnosis from medical record; job–exposure matrix based on measured electric fields in selected occupations	Electric fields (V/m)				
				< 10	2296	1.0	(baseline)	
				10–20	28	1.2	(0.80–1.9)	
				> 20	31	1.2	(0.78–1.7)	
	853 men with ANLL			< 10	831	1.0	(baseline)	
				10–20	11	1.3	(0.68–2.5)	
				> 20	11	1.2	(0.59–2.2)	
	534 men with CLL			< 10	517	1.0	(baseline)	
				10–20	9	1.9	(1.1–3.2)	
				> 20	8	1.3	(0.72–2.2)	
	487 men with CML			< 10	478	1.0	(baseline)	
				10–20	2	0.39	(0.09–1.6)	
				> 20	7	1.3	(0.60–2.8)	
Norway (Tynes *et al*., 1994b)	52 men with leukaemia 259 cohort controls (1958–90)	Cohort of railway workers	Job history from employment files; job–exposure matrix	Electric fields (kV/m–years)				
				None	19	1.0	(baseline)	
				Low (0.1–5)	9	0.44	(0.18–1.1)	
				High (> 5–30)	24	0.98	(0.48–2.0)	
				Very high (21–30)	3	0.68	(0.18–2.6)	

Table 31 (contd)

Country (reference)	Subjects (recruitment period)	Source of subjects	Source of job information; exposure assessment methods	Estimates of exposure to ELF electric fields	No. of cases	Odds ratio (95% CI)		Comments
Brain tumours								
Norway (Tynes *et al*., 1994b)	39 men with brain tumours 194 cohort controls (1959–90)	Cohort of railway workers	Job history from employment files; job–exposure matrix	Electric fields (kV/m–years)				
				None	11	1.0	(baseline)	
				Low (0.1–5)	12	0.69	(0.28–1.7)	
				High (> 5–30)	16	1.2	(0.49–2.8)	
				Very high (21–30)	4	1.2	(0.33–4.6)	
Canada (Miller *et al*., 1996) [included in Thériault *et al*., 1994]	24 incident cases of malignant brain tumours 96 cohort controls [exact number not given] (1970–88)	Cohort of electric utility workers at Ontario Hydro	Company personnel records; job–exposure matrix based on electric field exposure measurements (Positron meter)	Electric fields (V/m–years)				Adjusted for socioeconomic status and potential occupational confounders
				0–171	12	1.0	(baseline)	
				172–344	4	0.57	(0.10–3.2)	
				≥ 345	8	0.99	(0.16–6.2)	

Table 31 (contd)

Country (reference)	Subjects (recruitment period)	Source of subjects	Source of job information; exposure assessment methods	Estimates of exposure to ELF electric fields	No. of cases	Odds ratio (95% CI)	Comments
France (Guénel *et al*., 1996) [included in Thériault *et al*., 1994]	69 incident cases of brain tumour (ICD-9 191, 225) 271 cohort controls (1978–89)	Cohort of electric utility workers at Electricité de France	Company personnel records; job–exposure matrix based on electric field exposure measurements (Positron meter)	Electric fields (V/m–years)			Adjusted for socioeconomic status
				< 238	29	1.0 (baseline)	
				238–318	22	2.5 (0.99–6.2)	
				319–386	8	1.4 (0.46–4.5)	
				≥ 387	10	3.1 (1.1–8.7)	
	59 incident cases of malignant brain tumour (ICD-9 191) 231 cohort controls			Percentiles			Adjusted for socioeconomic status and exposure to magnetic fields
				< 50		1.0 (baseline)	
				≥ 50–< 75		2.5 (0.93–6.8)	
				≥ 75–< 90		1.6 (0.46–5.4)	
				≥ 90		1.8 (0.54–5.7)	

ANLL, acute non-lymphoblastic leukaemia; CLL, chronic lymphocytic leukaemia; CML, chronic myeloid leukaemia

[a] Electric field measurements in occupational studies are made using meters that are worn on the body. The results are therefore difficult to interpret because in this situation the field is distorted and the measurement is sensitive to body position.

[b] This study included five cases of leukaemia not included in the initial analysis by Thériault *et al*. (1994); this explains the different results for Ontario workers reported in the two papers.

cancer registry, with four controls per case matched on age and year of registration. For the combined group of selected occupations involving potential exposure to electrical and magnetic fields, a marginally significant excess risk for leukaemia was seen (odds ratio, 1.7; 95% CI, 0.97–3.0) on the basis of 18 observed cases. In an extension of this study to cover the registration period 1980–84, Pearce *et al*. (1989) used 19 904 of 24 762 notified cases of cancer among men ≥ 20 years old for whom information on occupation was available (80% of all relevant registry notifications) to evaluate any link between site-specific cancer and 'electrical work'. For each site of cancer under investigation, other sites formed the control group. 'Electrical work' was associated with an increased risk for leukaemia (odds ratio, 1.6; 95% CI, 1.0–2.5) on the basis of 21 observed cases. The odds ratios were generally greater for chronic leukaemia (odds ratio, 2.1; 95% CI, 1.2–3.8) than for acute leukaemia (odds ratio, 1.3; 95% CI, 0.62–2.5) and the risk was generally greater for subjects aged 65 years or more than for those aged 20–64 years.

In a case–control study based on death certificates recorded in 1985 and 1986 in 16 states in the USA (Loomis & Savitz, 1990), 3400 cases of leukaemia among men ≥ 20 years were compared with approximately 34 000 controls matched on year of death and who had died from causes other than brain cancer or leukaemia. Decedents were allocated to the exposed group if the occupation or industry given on their death certificate indicated that they had held a job included in a predefined list of electrical occupations (Milham, 1982). All other jobs were considered as unexposed. There was no association between electrical occupation and leukaemia (odds ratio, 1.0; 95% CI, 0.8–1.2). A slightly increased risk was observed for acute lymphoblastic leukaemia (odds ratio, 1.5; 95% CI, 0.7–3.4).

Richardson *et al*. (1992) conducted a case–control study of men and women ≥ 30 years old, resident in France. The cases had been diagnosed with acute leukaemia in two hospitals in France between 1984 and 1988; the 561 controls were patients in other departments at the same hospitals, matched to cases for sex, age (± 5 years), ethnic group and place and type of dwelling. Information on past medical history including radiotherapy and chemotherapy, drug use, some sources of environmental exposure and exposure related to leisure activities and a full occupational history described by job titles and industrial activities was obtained by personal interview for 204 cases (72% of those eligible) and 561 controls. Case and control subjects for whom the interviewer had recorded poor cooperation (approximately 5%) and case subjects without controls and vice versa were subsequently excluded, leaving 185 (154 acute myeloid leukaemia and 31 acute lymphoblastic leukaemia) cases (50.2% men) and 513 (48.2% men) controls for analysis. Exposure to ELF electric and magnetic fields, benzene, ionizing radiation, exhaust fumes and pesticides were assessed by an industrial hygienist on the basis of the reported occupational history of each study subject. Whenever possible, the exposure to an agent was coded as either low (< 5% of working time), medium (5–50%) or high (> 50%). There were three electronic engineers among cases and none among controls. After adjusting for prior chemotherapy or radiotherapy and taking into account the matching variables in an unconditional logistic regression model, any occupational exposure to electric and magnetic fields (all types of exposure) was shown to be associated with an elevated relative risk for acute leukaemia (odds ratio, 1.7; 95% CI, 0.9–3.5; 14 cases), while occupational exposure to ionizing radiation was not (odds ratio, 0.7; 95% CI, 0.2–2.0). Dividing the group of workers exposed to electric and magnetic fields into arc welders and others gave odds ratios of 1.2 (95% CI, 0.5–3.0) for welders and 3.9 (95% CI, 1.2–13) for others, based on eight and seven cases, respectively. [The Working Group noted that the risk estimation made after the separation of sources of exposure to electric and magnetic fields into arc-welding and non-arc-welding should be regarded as a post-hoc analysis. The Working Group also noted that all seven cases of acute leukaemia in workers exposed to electric and magnetic fields from arc-welding were acute myeloid leukaemia and that there was no information on the subtype distribution among the eight cases who were exposed to electric and magnetic fields from sources other than arc-welding.]

A case–control study within a cohort of telephone linemen at the American Telephone and Telegraph company was conducted by Matanoski *et al*. (1993). The cases were deaths from leukaemia, except chronic lymphocytic leukaemia, that occurred from 1975–80 among white men who had worked for the company for at least two years. Deaths were identified from company records for all workers who were still employed by the company when they died and for a subset of retired workers. From 177 eligible cases and their matched controls, a complete job history was obtained in 35 sets, each set was composed of a case plus at least one of its matched controls. The assessment of exposure to magnetic fields was made using the EMDEX-C personal monitor to make measurements on 15–61 individuals in each occupational category (204 measurements at 10-second intervals). No assessment of exposure to other potentially leukaemogenic agents was performed. The odds ratio for exposure above median of the mean values was 2.5 (95% CI, 0.7–8.6) compared with exposure below median of the mean values. There was also an indication of a dose–response relationship when subjects were divided into quartiles of peak exposure. [The Working Group noted that little weight should be given to a study in which only 35 of 177 eligible cases were included. It is not listed in Table 30.]

In a hospital-based case–control study conducted in one hospital in northern Italy, 46 men and 40 women aged between 15 and 74 years who had been newly diagnosed during 1989–90 with myeloid leukaemia (acute and chronic) or myelodysplastic syndrome were identified (Ciccone *et al*., 1993). Two control groups were chosen, one selected from all patients newly diagnosed with other diseases at the same hospital and one selected from the city population in the area of the hospital. Both groups were frequency-matched to the cases on sex, age and area of residence. The response rates were 91% for cases, 99% for the hospital controls and 82% for the population controls, leaving 86 cases (50 patients with acute myeloid leukaemia, 17 with chronic myeloid leukaemia and 19 with myelodysplastic syndrome) and 246 controls for analysis. The occupational history of the study subjects was used by one industrial hygienist to assess the probability of exposure to ELF electric and magnetic fields and to eight other agents or classes of agent known or suspected to increase the risk for myeloid leukaemia, myelodysplastic syndrome or other haematolymphopoietic malignancies. Using logistic regression analysis, male study subjects possibly or probably exposed to electric and magnetic fields had a non-significantly increased odds ratio of 1.6 (95% CI, 0.6–4.1) for myeloid leukaemia or myelodysplastic syndrome combined, compared with subjects not exposed to electric and magnetic fields or any of the other risk factors under study. The equivalent risk estimate for women was 0.8 (95% CI, 0.2–2.5). The estimates were based on 17 men and four women who had been exposed to electric and magnetic fields.

In a cohort study of cancer mortality in 36 221 electricity utility workers who had been employed at the Southern California Edison Company for at least one year between 1960 and 1988, the main analyses used a nested case–control study design, based on 3125 identified causes of death at the end of the follow-up period in 1988 (Sahl *et al*., 1993). Magnetic fields were measured over 776 person–days in 35 occupational categories using the EMDEX-2 meter. Case–control analyses were presented for 44 cases of leukaemia, but no association with scores for exposure to magnetic fields was observed (mean, median, 99th percentile, fraction above different thresholds). In a re-analysis of these data based on different exposure categories, a modest non-significantly increased risk for leukaemia was apparent (Kheifets *et al*., 1999).

Within a well-defined population of men who, according to the 1980 census, were employed and living in mid-Sweden, Floderus *et al*. (1993) conducted a study of all men aged 20–64 years notified to the Swedish Cancer Registry with a recent diagnosis of leukaemia (n = 426) during 1983–87. For the control group, two subjects per case (n = 1700) were chosen from the source population and matched to the case on age. Only acute lymphoblastic leukaemia, acute myeloid leukaemia, chronic myeloid leukaemia and chronic lymphocytic leukaemia were included. A postal questionnaire was used in which a full employment history was requested, including a description of all major work tasks undertaken by the study subject during the 10-year period before the diagnosis (and the equivalent dates for the controls). The questionnaire was completed by 77% of leukaemia patients or their relatives and 72% of the control subjects who received the questionnaire, so that 250 leukaemia cases and 1121 controls were available for analysis. On the basis of the work task held for the longest time by 1015 cases and control participants, a full-day measurement of exposure to ELF electric and magnetic fields at a frequency of 50 Hz was conducted using EMDEX-100 and EMDEX-C meters. Exposure categories were defined on the basis of the quartiles of exposure levels measured among the control subjects. The evaluation of exposure to potential confounders (benzene, other solvents, ionizing radiation and smoking) was based on self-reported information from study subjects and workplace information. On the basis of the job held for the longest time during the l0-year period before diagnosis, the age-adjusted odds ratios for all types of leukaemia combined were 0.9 (95% CI, 0.6–1.4), 1.2 (95% CI, 0.8–1.9) and 1.6 (95% CI, 1.1–2.4) among study subjects with daily mean level of exposure to magnetic fields in the second (0.16–0.19 μT), third (0.20–0.28 μT) and upper (≥ 0.29 μT) exposure quartiles, respectively, when compared with the risk of subjects with exposure in the lower quartile (≤ 0.15 μT). In an extended analysis on leukaemia subtypes, the excess risk seemed to be due exclusively to an increased risk for chronic lymphocytic leukaemia, with an odds ratio for exposure in the upper quartile of 3.0 (95% CI, 1.6–5.8). With exposure above the 90th percentile (≥ 0.41 μT), the odds ratio for chronic lymphocytic leukaemia was 3.7 (95% CI, 1.8–7.7). The results were not changed when potential confounders were taken into consideration; however, no independent risk estimates were given for these potential confounders. [The Working Group noted that the different proportions of postal questionnaires completed by next-of-kin (cases, 67%; controls, 0%) may have affected the odds ratios.]

London *et al*. (1994) conducted a case–control study based on cancer registry data. The cases were 2355 men aged 20–64 years diagnosed with leukaemia, and reported to the population-based cancer registry for Los Angeles county between 1972 and 1990. The controls were 67 212 men diagnosed with other cancers, excluding malignancies of the central nervous system. Only the occupation recorded in the medical record at the time of diagnosis was available to estimate occupational exposure to electric and magnetic fields. The assessment of exposure was based on measurements of magnetic fields obtained for 278 electrical workers in nine electrical occupations and 105 workers in 18 non-electrical occupations selected at random from the general population. The workers selected from each occupational group wore an EMDEX monitor for one work shift. A task-weighted estimate of exposure to magnetic fields in a given occupation was made. A single exposure index was calculated for all non-electrical occupations for which the mean exposure to magnetic fields was generally lower than that in electrical jobs. Occupational exposure to ionizing radiation, benzene, chlorinated hydrocarbon solvents, other solvents and pesticides was evaluated by an expert panel. Using the magnetic field exposure estimates, the odds ratios were 1.0, 1.2 (95% CI, 1.0–1.6) and 1.4 (95% CI, 1.0–2.0), respectively, for exposure to < 0.17 μT, 0.18–0.80 μT and ≥ 0.81 μT, and the trend was statistically significant. An analysis by leukaemia subtype showed a high odds ratio for chronic myeloid leukaemia (odds ratio, 2.3; 95% CI, 1.4–3.8) for average exposure ≥ 0.81 μT, compared with exposure < 0.17 μT, but there was also some evidence of increased risk for acute non-lymphoblastic leukaemia and chronic lymphocytic leukaemia. According to the authors, these results were not appreciably affected by adjustment for other occupational exposures. Data on electric fields were also collected in this study (Table 31). The measurements of electric fields by occupational group revealed no clear evidence of an association between this exposure and leukaemia, and no exposure–response relationship for any leukaemia subtype was seen (Kheifets *et al*., 1997b). [The Working Group noted that the assessment of occupational exposure was based on a single occupation recorded at the time of cancer diagnosis; only a few non-electrical occupations were measured, but they were used as an exposure proxy for all other non-electrical occupations; controls were other cancer cases: if workers in electrical occupations have a lower incidence of other cancers than non-electrical workers, the odds ratio for leukaemia could be spuriously elevated relative to non-electrical workers. It was also noted that the cut-points used for the categorization of exposure correspond to the 97% and 99% percentile in the control population. No clear explanation was given for this apparently unusual choice.]

Tynes *et al*. (1994b) conducted a case–control study of leukaemia nested in a cohort of 13 030 male railway line workers, exposed to 16 2/3-Hz electric and magnetic fields, outdoor station workers and railway electricity workers (railway electricity line workers, installation electricians, radio communication workers and railway power substation workers) selected from the records of all employees working on either electric or non-electric railways in Norway in 1957 and from historical and current databases provided by the railway workers' trade union. The case groups comprised all 52 members (one case was excluded because no work history was available) diagnosed according to the files of the national Norwegian Cancer Registry with leukaemia during the follow-up period 1958–90. Each case was matched on year of birth with four or five controls selected from the cohort (a total of 259 controls). Work histories were combined with a job–exposure matrix for ELF-electric and magnetic fields to provide a simple exposure categorization: i.e. ever exposed versus never exposed to electric railway lines, and a more complex one: i.e. cumulative exposure (μT–year) during a person's entire period of employment (up to the date of diagnosis of cancer or a similar date for the matched controls) with the railways in Norway. Limited information on potential confounders such as exposure to creosote, solvents and herbicides was also collected; information on smoking (ever smokers) was obtained by telephone interviews with the subjects or their work colleagues. Ever exposure to magnetic fields from electric railway lines was associated with an odds ratio of 0.72 (95% CI, 0.37–1.4) for all types of leukaemia combined. An analysis of leukaemia subtypes also showed no association. Using study subjects never exposed to magnetic fields from electric railway lines as the exposure reference category, cumulative exposures of 0.1–310 μT–years (low exposure), 311–3600 μT–years (high) and 1900–3600 μT–years (very high) were associated with odds ratios of 1.0 (95% CI, 0.49–2.1), 0.49 (95% CI, 0.22–1.1) and 0.84 (95% CI, 0.25–2.8), respectively, for leukaemia. Adjustment for smoking habits and potential confounders in a multivariate regression analysis for matched pairs did not change the results. Sub-analyses with inclusion of lag time intervals (5 and 15 years) and exposure windows (5–25 years and 2–12 years) did not reveal any associations. Analysis for electric fields did not show any association with leukaemia (see Table 31).

A large case–control study of exposure to magnetic fields nested within three cohorts of electric utility workers in Quebec and Ontario, Canada, and in France was conducted by Thériault *et al*. (1994). There were small differences in study design and the results were not consistent across the three utilities; each cohort is therefore described separately.

In Quebec, the cohort included all men with at least one year of employment at Hydro-Québec, between January 1970 and December 1988. The observation period ended either at death or December 31, 1988. The cases were 774 men from the cohort newly diagnosed with cancer during this period (24 leukaemia). The controls were 1223 cohort members matched to the cases by year of birth with a case–control ratio of 1:4 for cancer of the haematopoietic system, brain cancer and skin melanoma, and 1:1 for all other cancer sites. Measurements of magnetic field exposure were made with a personal Positron meter, worn for a full working week by 466 workers at Hydro Québec, who had been selected to achieve a representative sample of all workers in 32 occupational groups. The time-weighted average exposure to magnetic fields was calculated from the measurements to construct a job–exposure matrix. Past exposure to magnetic fields was estimated using adjustment factors based on changes in power systems, work techniques and exposure sources. Exposure to other potential occupational carcinogens was evaluated through expert judgement. The odds ratio for cumulative exposure to magnetic fields above median (3.1 μT–years) was 0.29 (95% CI, 0.04–1.8) for all leukaemia and 0.75 (95% CI, 0.00–>100) for acute non-lymphoblastic leukaemia, based on small numbers. No clear association with other leukaemia types was observed.

In Ontario, the cohort comprised men with one full year of employment at Ontario Hydro between 1973 and 1988, as well as men on the pension roll in 1970–73. The observation period ended at death or December 31, 1988. A total of 1472 incident cancer cases (45 leukaemia) were identified from the Ontario Cancer Registry during the study period. The controls were 2080 men selected in the same way as those from Hydro Québec. Measurements of exposure to magnetic fields were made for 771 workers with 260 job titles. The occupations were then combined in 17 broad categories, based on mean exposure, occupational profiles and consideration of past changes in these factors. These 17 occupational categories were used as the rows of the job–exposure matrix on magnetic fields. Exposure to other occupational agents ((2,4-dichlorophenoxy)acetic acid, (2,4,5-trichlorophenoxy)acetic acid and benzene) was assessed from consultation with experts (Miller *et al.*, 1996). The odds ratio for cumulative exposure to magnetic fields above 3.1 μT–years was 3.1 (95% CI, 1.1–9.7) for all leukaemia and 6.2 (95% CI, 0.95–78) for acute non-lymphoblastic leukaemia. Non-significant increases in odds ratios were also observed for chronic lymphocytic leukaemia.

In France, the cohort included men with at least one year of employment at Électricité de France–Gaz de France during 1978–89. The cases were 1905 men identified from company medical records who were newly diagnosed with cancer (71 leukaemia) during the same period. This group of cases included all workers diagnosed with cancer while they were active in the company. Since the identification of cases was not possible for cancer diagnosed after retirement, the observation period ended at termination of employment or December 1989. The controls were 2803 subjects matched to the cancer cases by year of birth in the same way as in the cohort of Hydro Québec workers. The method of assessment of exposure to magnetic fields was similar to that used in Quebec.

Measurements were made using a Positron meter worn by 829 workers for a full working week, selected from 37 occupational groups defined *a priori*. Past exposure to magnetic fields was assessed using adjustment factors. Estimates of exposure to other potential occupational carcinogens were also evaluated using expert judgement in a separate job–exposure matrix. The odds ratios for cumulative exposure to magnetic fields above 3.1 μT–years were 1.4 (95% CI, 0.61–3.1) for all leukaemia and 1.8 (95% CI, 0.57–5.4) for acute non-lymphoblastic leukaemia.

For the three cohorts combined, the odds ratios for all leukaemia were 1.5 (95% CI, 0.90–2.6) for cumulative exposure to magnetic fields above median (3.1 μT–years) and 1.8 (95% CI, 0.77–4.0) for exposure above the 90th percentile (15.7 μT–years). The odds ratios for acute non-lymphoblastic leukaemia were 2.4 (95% CI, 1.1–5.4) and 2.5 (95% CI, 0.70–9.1), respectively. However, there was no clear trend of increased risk with increasing exposure. Elevated odds ratios were also observed for chronic lymphocytic leukaemia for cumulative exposure during the 20 years prior to diagnosis (Thériault *et al.*, 1994).

Data from the Ontario Hydro cohort were re-analysed (Miller *et al.*, 1996). This re-analysis included five additional cases of leukaemia not considered in the initial analysis by Thériault *et al.* (1994) (a total of 50 cases). A refined assessment of exposure to potential occupational confounders was also used. The odds ratio for all leukaemia decreased from 2.0 to 1.7 (95% CI, 0.58–4.8) for cumulative exposure between 3.2 and 7 μT–years and from 2.8 to 1.6 (95% CI, 0.47–5.1) for cumulative exposure ≥ 7.1 μT–years, after adjustment for potential occupational confounders. For acute non-lymphoblastic leukaemia, the corresponding odds ratios were reduced from 3.0 to 1.9 (95% CI, 0.27–14) and from 5.0 to 2.9 (95% CI, 0.42–20), respectively. This report also described the risk for leukaemia in relation to exposure to electric fields which were also measured by the Positron meter (Table 31). For leukaemia, the odds ratios for cumulative exposure to electric fields between 172 and 344 V/m–years and for exposure ≥ 345 V/m–years, as compared with exposure below 172 V/m–years (median), were 2.1 (95% CI, 0.59–7.2) and 4.5 (95% CI, 1.0–20), respectively, after adjustment for potential occupational confounders. For acute non-lymphoblastic leukaemia, and the main component, acute myeloid leukaemia, the odds ratios associated with electric fields were elevated but did not reach statistical significance. Analysis of the combined effects of electric and magnetic fields showed that exposure to electric fields carried a greater risk for leukaemia than exposure to magnetic fields. It was shown that risk for leukaemia was more particularly associated with duration of exposure above the exposure threshold (Villeneuve *et al.*, 2000).

The effects of electric fields were also investigated among electric utility workers from France. These workers were part of the Canada–France study (Thériault *et al.*, 1994). Electric fields were recorded by a Positron meter at the same time as magnetic fields and were used to assess the exposure to electric fields by occupation in a job–exposure matrix (Guénel *et al.*, 1996). No association between cumulative exposure to electric fields and leukaemia was observed in this study (Table 31).

Feychting *et al.* (1997) looked at combined residential and occupational exposure (see section 2.3.1).

In an Italian study, Pulsoni *et al*. (1998) compared selected characteristics of 335 patients with acute promyelocytic leukaemia aged > 15 years with those of 2894 patients aged > 15 years diagnosed with other acute myeloid leukaemia. Patients were identified from the files of a clinical database, initiated in 1992, until 1997. A significant association was found between working as an electrician and development of acute promyelocytic leukaemia with an age-adjusted odds ratio of 4.4 (95% CI, 2.0–9.7). [The Working Group noted that the occupational group considered (i.e. electricians) comprised less than 1% of the comparison group of other acute myeloid leukaemia patients making interpretation difficult.]

(ii) *Brain tumours* (see Table 30)

Brain tumours without further histological classification represent a heterogeneous group of lesions. Studies based on death certificates only may include deaths from secondary tumours that have metastasized from an unknown primary cancer, or tumours that are histologically benign (Percy *et al.*, 1981). Where possible the results reported here are specifically for malignant tumours or for known histological types.

Death certificates for white men in Maryland who died between 1969 and 1982 were used to conduct a case–control study on brain tumours (Lin *et al*., 1985). A total of 951 men aged ≥ 20 years who had died from a tumour of the brain (519 gliomas, glioblastoma multiforme, or astrocytomas) were matched by age and date of death with controls who had died from non-malignant diseases. The occupation recorded on the death certificate was used to classify the subjects according to a predefined category of exposure to electric and magnetic fields (definite, probable, possible or no exposure). Jobs were classified according to a list of ‘electrical occupations’ revised from that of Milham (1982). Using the no-exposure group as referent, the odds ratios for primary brain tumours increased with increasing probability of exposure to electric and magnetic fields.

Speers *et al*. (1988) conducted a study based on mortality data in East Texas, USA during the period 1969–78. The cases were 202 white male decedents between 35 and 79 years of age who had been diagnosed with glioma. The controls were 238 men selected from among white residents of the East Texas study area who had died from a cause other than brain tumour. Information abstracted from the death certificate included the usual occupation for which exposure to electric and magnetic fields was classified using the system proposed by Lin *et al*. (1985). The analysis by level of exposure to electric and magnetic fields yielded an increase in risk with increasing probability of exposure with a significant linear trend.

In a cancer registry-based study in New Zealand, Pearce *et al*. (1989) used 19 904 cases of cancer notified from 1980–84 among men ≥ 20 years old, for whom information on occupation was available (80% of all relevant registry notifications) to evaluate any link between site-specific cancer and ‘electrical work’. For each site of cancer studied, patients with cancer at other sites formed the control group. Among 481 patients with brain cancer (ICD-9 191), 12 had been employed in electrical work, giving an odds ratio for brain tumours of 1.0 (95% CI, 0.56–1.8) on the basis of the 12 observed cases.

Preston-Martin *et al*. (1989) conducted a case-control study on brain tumours in Los Angeles county, USA. The cases were men 25–69 years of age for whom a first diagnosis of glioma or meningioma had been made during 1980–84. Two hundred and seventy-two of 478 eligible cases (202 gliomas and 70 meningiomas) and 272 controls were available for analysis. A complete work history was obtained for each subject, together with information on previous brain diseases, head traumas, alcohol and tobacco habits and diet. Work in an occupation with suspected exposure to electric and magnetic fields, according to Milham's definition (Milham, 1982), was associated with an increased odds ratio for glioma (1.8; 95% CI, 0.7–4.8), and the risk increased with increase in the number of years spent working in these occupations. The association was strongest for astrocytoma (odds ratio, 4.3; 95% CI, 1.2–16) for > 5 years). The authors noted that confounding from occupational exposure to other harmful agents (e.g. solvents) may be an alternative explanation for this finding. [The Working Group noted that selection bias may have occurred because only living patients could be interviewed.]

The study by Loomis and Savitz (1990) based on death certificates in 16 states in the USA, described in the section on leukaemia, also presented results for brain cancer. The cases were 2173 deaths in men from brain cancer (ICD-9 191). The controls were selected from among men who had died from other causes with a 10:1 ratio. Men who were reported to have been electrical workers on their death certificates had an odds ratio of 1.4 (95% CI, 1.1–1.7) when compared with non-electrical occupations.

Ryan *et al.* (1992) also looked at exposure to ELF electric and magnetic fields in the electrical and electronics industries and found no increase in glioma and meningioma.

Floderus *et al*. (1993) (described in the section on leukaemia) conducted a case–control study of all individuals with a recent diagnosis of brain tumour (n = 424) during 1983–87. Only patients with histologically confirmed astrocytoma (type I-IV) or oligodendroglioma were included. A questionnaire was completed by 76% of patients or their relatives and 72% of control subjects, leaving 261 cases of brain tumour and 1121 controls for analysis. Exposure was defined as in the section on leukaemia (p. 215). On the basis of the 10-year period before diagnosis, the age-adjusted odds ratios for all types of brain tumour combined were 1.0 (95% CI, 0.7–1.6), 1.5 (95% CI, 1.0–2.2) and 1.4 (95% CI, 0.9–2.1) among study subjects with a daily mean exposure to electric and magnetic fields in the second (0.16–0.19 μT), third (0.20–0.28 μT) and upper (≥ 0.29 μT) exposure quartiles, respectively, when compared with the lower quartile (≤ 0.15 μT). When exposure was above the 90th percentile (≥ 0.41 μT), the odds ratio was 1.2 (95% CI, 0.7–2.1). The results were unchanged when the potential confounders were taken into consideration. [The Working Group noted that the different proportions of postal questionnaires completed by next-of-kin; for cases (85%) and for controls (0%) may have affected the odds ratios.]

In a study on cancer mortality among employees at the Southern California Edison Company described in the section on leukaemia (Sahl *et al*., 1993), brain cancer (ICD-9 191) (31 cases) was also investigated and the results are summarized in Table 30. No association between brain cancer mortality and scores of exposure to magnetic fields was apparent.

The Canada–France study on electric utility workers, described in the section on leukaemia (Thériault *et al*., 1994), also presented results for brain cancer (ICD-9 191); they are shown in Table 30. For the three cohorts combined, the odds ratios for all brain cancers were 1.5 (95% CI, 0.85–2.8) for cumulative exposure to magnetic fields above median (3.1 μT–years) and 2.0 (95% CI, 0.76–5.0) for exposure above the 90th percentile (15.7 μT–years). In the analysis by histological subtype, the risk for astrocytoma was particularly elevated in the highest exposure category (odds ratio, 12; 95% CI, 1.1–144), but this result was based on only five exposed cases, and according to the authors was dependent on the statistical method used.

The association between malignant brain cancer and electric fields among workers at Ontario Hydro was investigated by Miller *et al*. (1996) (Table 31). No association between exposure to electric fields and brain cancer was apparent.

The relationship between exposure to electric fields and risk of brain tumour (ICD-9 191, 225) (59 malignant and 10 benign cancers) was also investigated in workers at Électricité de France (Table 31) (Guénel *et al*., 1996), who were part of the Canada–France study described above. Using the arithmetic mean of electric field measurements obtained with the Positron meter, the odds ratio in the highest exposure category was 3.1 (95% CI, 1.1–8.7), but the risk did not increase monotonically with exposure. There was no clear indication of an increased risk when exposure was assessed using the geometric mean of electric fields.

In parallel to the leukaemia study described above, Tynes *et al*. (1994b) conducted a case–control study of brain tumours (unspecified) nested in a cohort of 13 030 male railway workers. The case group comprised all 39 cohort members diagnosed according to the files of the national Norwegian Cancer Registry with brain tumour, during the follow-up period 1958–90. Each case was matched on year of birth with four or five controls selected from the cohort (a total of 194). Ever exposure to electric railway lines was associated with an odds ratio of 0.82 (95% CI, 0.38–1.8) for brain tumours. Using study subjects who had never been exposed to electric railway lines as the exposure reference category, cumulative exposure to magnetic fields of 0.1–310 μT–years (low exposure), 311–3600 μT–years (high) and 1900–3600 μT–years (very high) were associated with odds ratios for brain tumours of 0.81 (95% CI, 0.33–2.0), 0.94 (95% CI, 0.39–2.3) and 0.97 (95% CI, 0.24–4.0), respectively. Sub-analyses with inclusion of lag time intervals (5 and 15 years) and exposure windows (5–25 years and 2–12 years) did not reveal any associations. No association between brain tumours and exposure to electric fields was apparent (see Table 31).

In a case–control study nested within a cohort of male members of the US Air Force with at least one year of service in the period 1970–89, 230 cases of brain tumour (ICD-9 191) were matched on year of birth and race with 920 controls (Grayson, 1996). Complete job histories were linked to a job–exposure matrix that assessed the probability of exposure to ELF electric and magnetic fields (definite, probable, possible or no exposure) by job title and time of employment. The odds ratio for workers ever exposed to ELF electric and magnetic fields was 1.3 (95% CI, 0.95–1.7). However, no clear trend relating risk for brain tumour to cumulative exposure was apparent.

In a substudy from Sweden, Feychting *et al*. (1997) estimated the separate and combined effects of occupational and residential exposure to ELF magnetic fields on the risk for tumours of the central nervous system (see section 2.3.1 on residential exposure).

Mortality from brain cancer was investigated by Harrington *et al*. (1997) in a case–control study nested in a cohort of 84 018 men and women employed for at least six months between 1972 and 1984 as electricity generation and transmission workers at the Central Electricity Generating Board of England and Wales. Computerized work histories were available for a part of the cohort from 1972 and for all cohort members from 1979. Follow-up of cohort members until the end of 1991 in the national mortality files revealed a total of 176 deaths from brain cancer of which 112 were confirmed through the national cancer registry as primary brain cancers (case group). Approximately six controls per case were chosen from the cohort and matched to the corresponding case on sex and date of birth, giving a total of 654 controls who were all alive at the date of diagnosis of the corresponding case. Exposure assessment was based on an earlier set of measurements of exposure to ELF electric and magnetic fields (50 Hz) in the electricity supply industry made for 675 person–work shifts (Merchant *et al*., 1994); the cumulative exposure was categorized into tertiles on the basis of the distribution among all study subjects. Using the study subjects in the lower tertile of cumulative exposure to electric and magnetic fields as the exposure reference category (≤ 3.0 μT–years), study subjects in the middle and upper tertiles had odds ratios for primary brain cancer of 1.3 (95% CI, 0.75–2.2) and 0.91 (95% CI, 0.51–1.6), respectively. Subjects who could not be classified according to their cumulative exposure had an odds ratio of 1.8 (95% CI, 0.93–3.6). There was no significant association between the risk for brain cancer and any of the potential confounders included in the study.

In an update of this cohort study, Sorahan *et al*. (2001) analysed brain tumour mortality until 1997 for the subset of 79 972 study subjects for whom computerized work histories were available for the period 1971–93. A Poisson regression analysis showed age- and sex-adjusted relative risks for death from brain tumour of 0.88 (95% CI, 0.53–1.5), 0.65 (95% CI, 0.41–1.0), 0.68 (95% CI, 0.42–1.1) and 0.68 (95% CI, 0.33–1.4) among cohort members with a lifetime exposure to magnetic fields of 2.5–4.9, 5.0–9.9, 10.0–19.9 and ≥ 20.00 μT–years, respectively, compared with the risk for death from brain tumour among workers with cumulative exposure ≤ 2.4 μT–years.

A re-analysis using the most recent five years of exposure to ELF magnetic fields did not change the results substantially.

In a small study from Sweden, Rodvall *et al*. (1998) identified 105 histologically confirmed cases of intracranial glioma (ICD-9 191) and 26 of meningioma (ICD-9 192.1), newly diagnosed in men aged 25–74 years during 1987–90. The cases were identified from the files of a large university hospital and the regional cancer registry. A total of 155 controls was selected from population listings and matched to the cases on date of birth and parish. Only controls who were alive at the time of diagnosis of the corresponding case were included. A postal questionnaire requesting data on the occupational history of the study subjects was completed for 84 (80%) of the glioma cases (71 by the patient and 13 by a close relative), 20 (77%) of the meningioma cases (19 by the patient and one by a close relative) and, after the inclusion of a number of replacement controls, by 155 [response rate unknown] of the control subjects themselves. The analyses used multiple logistic regression models with adjustment for socioeconomic status and self-reported occupational exposure to solvents and plastic materials. Ever having worked in an electrical occupation was associated with odds ratios of 1.0 (95% CI, 0.4–2.4) for glioma and 1.8 (95% CI, 0.3–3.6) for meningioma. Employment in a job classified by an electrical engineer as probably highly exposed to magnetic fields showed odds ratios of 1.6 (95% CI, 0.6–4.0) for glioma and 2.1 (95% CI, 0.4–10) for meningioma. Risks were also analysed according to the exposure to electric and magnetic fields classified using a previously constructed job–exposure matrix for ELF electric and magnetic fields (Floderus *et al*., 1993, 1996), applied to the job history of the study subjects. Ever having been in an occupation with exposure to magnetic fields > 0.4 μT was associated with odds ratios of 1.9 (95% CI, 0.8–5.0) and 1.6 (95% CI, 0.3–10) for glioma and meningioma, respectively.

Mortality data including all death certificates from 24 US states for the period 1984–92 were used to explore the association of industry and occupation with risk for brain cancer (Cocco *et al*., 1998a). The cases were 28 416 subjects ≥ 25 years old who had died from cancer of the brain (ICD-9 191) and other parts of the central nervous system (ICD-9 192), and the controls were 113 664 subjects who had died from non-malignant diseases other than those affecting the central nervous system, frequency-matched to cases by state, race, sex and age. The subjects were classified as having been exposed or unexposed to electric and magnetic fields and other potential risk factors for brain cancer (herbicides, other pesticides, solvents, lead, contact with animals, contact with the public) using an a-priori job–exposure matrix. Brain cancer showed a consistent association with high socioeconomic status. Exposure to electric and magnetic fields was not associated with risk in any sex–race strata, although an odds ratio of 1.2 (95% CI, 0.9–1.6) was observed among African-American women.

In a re-analysis of 12 980 women based on death certificates, and a refined job–exposure matrix using exposure scores for probability and intensity of exposure, the odds ratio for tumours of the central nervous system was 1.2 (95% CI, 1.1–1.2) for women with any exposure to electric and magnetic fields. Slightly increased odds ratios of 1.2–1.3 were observed for high exposure probability or high exposure intensity (Cocco *et al*., 1999).

(iii) *Pooled analysis* (leukaemia and brain tumours)

A pooled analysis of the data from three studies of electric utility workers (Sahl *et al.*, 1993, California, USA; Thériault *et al.*, 1994, France, Ontario, Quebec; Savitz & Loomis, 1995, USA) including four companies and five utilities where quantitative measurements of magnetic fields had been carried out, was conducted to examine the relation between cumulative exposure to magnetic fields and risk of leukaemia and brain tumours (Kheifets *et al.*, 1999). Overall, excluding the data for Ontario, the results indicated a small increase in risk for both brain cancer (relative risk, 1.8; 95% CI, 1.1–2.9) and leukaemia (relative risk, 1.4; 95% CI, 0.85–2.1) for exposure > 16 μT–years as compared to exposure < 4 μT–years. For a 10 μT–year increase in exposure, the relative risks were 1.12 (95% CI, 0.98–1.3) and 1.09 (95% CI, 0.98–1.2) for brain cancer and leukaemia, respectively. There was some consistency of the results across the utility companies.

(iv) *Female breast cancer*

Breast cancer was analysed using the mortality database of 24 US states for the period 1985–89 in a case–control study (Loomis *et al*., 1994b). After exclusion of ‘homemakers’, the cases were 28 434 women > 19 years old whose underlying cause of death had been breast cancer and the controls were 113 011 women who had died from other causes, excluding brain cancer and leukaemia. The usual occupation as recorded on their death certificates was used to classify women according to the likelihood of having been exposed to electric and magnetic fields, using an extended list of ‘electrical occupations’. The odds ratio for the association between electrical occupation and cancer, adjusted on race and social class, was 1.4 (95% CI, 1.0–1.8).

The same US mortality database was analysed by Cantor *et al*. (1995) using an alternative method for exposure assessment. The study included 33 509 women who had died from breast cancer and 117 794 controls selected from women who had died from causes other than cancer. Exposure scores were determined for each occupation using different indices for levels of exposure to ELF electric and magnetic fields and exposure probability. The results were presented separately for black and white women. There was no consistent excess risk with increasing level or probability of exposure to ELF electric and magnetic fields.

Coogan *et al*. (1996) conducted a case–control study of 6888 (81%) respondent cases out of 8532 eligible women ≤ 74 years of age with breast cancer diagnosed between April 1988 and December 1991 in Maine, Massachusetts, New Hampshire and Wisconsin. The controls were 9529 (84%) respondents out of 11 329 eligible women, frequency-matched on age and state of residence, and identified from driver’s license and the lists of the Health Care Financing Administration. Because all subjects were interviewed by telephone, a listed telephone number was required for eligibility by both cases and controls. The women were asked about their usual occupation, which was classified into one of four categories of potential exposure to 60-Hz magnetic fields (high, medium, low and background exposure), as defined by an industrial hygienist. Compared to women with background exposure, an odds ratio of 1.4 (95% CI, 1.0–2.1) was found for women whose usual occupation was in the high exposure category. The odds ratios for the medium and low exposure categories did not differ appreciably from unity. No significant difference was seen between pre- and post-menopausal women (odds ratio, 2.0 (95% CI, 1.0–3.8) and odds ratio, 1.3 (95% CI, 0.82–2.2), respectively) in the highest exposure groups.

Coogan and Aschengrau (1998) carried out a case–control study on 259 of the 334 women residing in the Upper Cape Cod area who were diagnosed with breast cancer in 1983–86. They selected 738 controls by random-digit dialling, from lists of Medicare beneficiaries or from the death certificates of women who had lived in the same area. Complete work histories were obtained for each subject, and jobs were classified according to their potential for higher than background exposure to magnetic fields (high, medium or no exposure). Residential exposure to magnetic fields from power lines and substations was also considered, as well as exposure to magnetic fields from electrical appliances in the home. Suspected or established risk factors for breast cancer were included in the analyses as potential confounders. There was no association between breast cancer risk and occupational exposure to magnetic fields, nor with any other source of magnetic fields. The adjusted odds ratios for jobs with potential exposure to high electric and magnetic fields and jobs with potential exposure to medium electric and magnetic fields were 1.2 (95% CI, 0.4–3.6) and 0.9 (95% CI, 0.5–1.7), respectively. No association was observed with duration of employment in these occupational groups.

In a study from Sweden, Forssén *et al*. (2000) estimated the separate and combined effects of occupational and residential exposure to ELF magnetic fields on the risk for female breast cancer (see section 2.3.1). Occupational exposure data were available for 744 cases and 764 controls and both contemporary residential and occupational exposure data were available for 197 cases and 200 controls. No increased risk in breast cancer was associated with occupational exposure to ELF magnetic fields.

(v) *Male breast cancer*

Demers *et al*. (1991) investigated occupational exposure to ELF electric and magnetic fields in 227 incident cases of breast cancer in males, 22–90 years old, identified in 1983–87 in 10 population-based cancer registries in the USA (320 cases were eligible). Three hundred controls matched on age and study area (out of 499 eligible controls) were selected by random-digit dialling for controls aged under 65 years and from Medicare lists for older controls. Personal interviews using a standardized questionnaire were used to obtain a partial work history (information on the two longest-held occupations). The estimates of exposure to electric and magnetic fields were based on job titles. Data on several suspected risk factors for male breast cancer were also collected. The odds ratio associated with jobs entailing exposure to electric and magnetic fields was 1.8 (95% CI, 1.0–3.7). No significant trend with increasing duration of employment in an exposed occupation was observed. No confounding by the non-occupational risk factors investigated in the study was observed. [The Working Group noted that the participation rate was low, especially among controls.]

In a case–control study based on mortality data from 24 states in the USA in the period 1985–88, Loomis (1992) analysed 250 males aged < 19 years who had died from breast cancer and approximately 2500 controls, selected from men who had died from other causes and matched by year of death. Four of the cases had an electrical occupation listed on their death certificate (odds ratio, 0.9). [The Working Group noted the limited number of exposed cases.]

Rosenbaum *et al*. (1994) studied 71 incident cases of male breast cancer diagnosed in western New York between 1979 and 1988, and 256 controls selected from men who had been screened for cancer in the Prevention–Detection Clinic (voluntary cancer screening). The cases and controls were resident in the same areas and were matched by race, year of diagnosis or screening and age. Occupational exposure to electric and magnetic fields was evaluated using a job–exposure matrix, based on the assumption that workers in ‘electrical occupations’ were exposed to higher than background electric and magnetic fields. Exposure to electric and magnetic fields was associated with an odds ratio of 0.6 (95% CI, 0.2–1.6). [The Working Group noted that selection bias may have occurred for controls and information bias for occupation.]

To study the relationship between exposure to ELF magnetic fields and male breast cancer, Stenlund and Floderus (1997) re-used the study design and the control group established five years earlier by Floderus *et al*. (1993) in the previously described study from mid-Sweden of leukaemias and brain tumours. The new study included 92 men who had been diagnosed with breast cancer during 1985–91 in any part of Sweden. Fifteen patients with cancer of the breast were ineligible for study because permission to contact the patient or a relative was not obtained, or because no relatives were identified. The postal questionnaire was completed by the patient or a close relative for 63 of the cases (69%). The response rate for the controls was 72% giving 1121 controls for analysis. Using the same job–exposure matrix as in the original study and following the same strategy of analysis, the authors found odds ratios for breast cancer of 1.2 (95% CI, 0.6–2.7), 1.3 (95% CI, 0.6–2.8) and 0.7 (95% CI, 0.3–1.9) associated with exposure levels to electric and magnetic fields in the second, third and upper quartile, respectively. [The Working Group noted, as did the authors, that the breast cancer cases were not selected from the same study base as that defined for control subjects, implying a possibility for bias in the selection of study subjects.]

In a case–control mortality-based study on male breast cancer, Cocco *et al*. (1998b) used the data of the US national mortality follow-back survey. The cases were 178 men who had died from breast cancer in a sample of 1% of all adult deaths that occurred in the USA in 1986 (excluding Oregon) and all men who had died from breast cancer in

1985 among black and white adults 25–74 years old. The controls were 1041 male decedents selected from men who had died from all other causes of death, after the exclusion of smoking- and alcohol-related causes, and matched on race, age and region of death. Questionnaires were sent to the next-of-kin of the decedents to obtain information on sociodemographic variables; the longest-held occupation and industry, and non-occupational data on consumption of selected dietary items; alcohol consumption, tobacco smoking, and medical history. Occupational exposure to electric and magnetic fields, solvents, herbicides, other pesticides, high temperatures and polycyclic aromatic hydrocarbons was estimated from a job–exposure matrix that included scores for exposure intensity and probability of exposure. Although an increased odds ratio was observed in men with high socioeconomic status, and in certain occupations or industries not classified as having high exposure to electric and magnetic fields, no association was observed with the probability or the intensity of exposure to electric and magnetic fields, organic solvents, polycyclic aromatic hydrocarbons, herbicides and other pesticides.

(vi) *Other cancer sites*

Several other sites of cancer have been investigated in relation to ELF electric and magnetic fields, particularly in case–control studies nested within occupational cohorts of electric utility workers, since data on all sites of cancer were collected in these studies. However, there was generally no indication of an increased risk for any site of cancer other than those already described for leukaemia and brain tumours. The results obtained for the sites of cancer that were considered of interest *a priori* in studies of electric utility workers, namely lymphomas (Sahl *et al*., 1993; Thériault *et al*., 1994) and malignant melanoma (Thériault *et al*., 1994) showed no association with exposure to magnetic fields.

In a population-based case–control study in the four northern counties of Sweden, Hallquist *et al*. (1993) identified a total of 188 surviving patients with thyroid cancer who were aged 20–70 years at the time of diagnosis during 1980–89. The cases were drawn from the national Swedish Cancer Registry and represented 81% of all cases of thyroid cancer notified in persons of the same age group during the period of interest in the four counties (44 patients had other diseases and were excluded). The original histopathological diagnoses were re-evaluated by a pathologist, resulting in the exclusion of seven patients who were reclassified as having diseases other than thyroid cancer. One subject died shortly before the interview, leaving 180 histologically verified cases for study. For each case, two living controls close in age and of the same sex, and resident in one of the four northern counties, were drawn from the national population registry. Information on the occupational history of the study subjects and on known and suspected risk factors for thyroid cancer was obtained through a postal questionnaire that was completed by 171 case subjects (response rate, 95%) (123 women and 48 men), and 325 control subjects (240 women and 85 men) (response rate, 90%). Five male cases had worked as linemen while no controls had reported that occupation. The authors stated that this occupation might entail exposure to ELF electric and magnetic fields; however, no exposure estimates were given. Three of these linemen were exposed to impregnating agents, i.e. chlorophenols and creosote, which were found in the analysis to be significantly associated with thyroid cancer (odds ratio, 2.8; 95% CI, 1.0–8.6). Employment as an electrical worker was associated with an odds ratio of 1.9 (95% CI, 0.6–6.1) on the basis of eight exposed cases.

In order to study the relationship between exposure to ELF magnetic fields and testicular cancer, Stenlund and Floderus (1997) re-used the study design and the control group established five years earlier by Floderus *et al*. (1993) in the previously described study from mid-Sweden of leukaemias and brain tumours. The extended study included 214 men diagnosed with testicular cancer during 1983–87 and living in the original catchment area. The postal questionnaire was completed by the patient [proportion not given] or a relative [proportion not given] for 144 of the 185 eligible subjects with testicular cancer (78%). The response rate among the controls was 72% leaving 1121 controls. Using the same job–exposure matrix as in the original study and following the same strategy of analysis, the authors found odds ratios for testicular cancer of 1.3 (95% CI, 0.7–2.4), 1.4 (95% CI, 0.8–2.7) and 1.3 (95% CI, 0.7–2.5) associated with exposure to magnetic fields in the second, third and upper quartile (0.16–0.19 μT, 0.20–0.28 μT and ≥ 0.29 μT), respectively. Among the 13% of study subjects who were exposed to the highest estimated levels (≥ 0.41 μT), the odds ratio for testicular cancer was 2.1 (95% CI, 1.0–4.3). In a subsequent analysis on subtypes of testicular cancer, the authors observed an increased risk for non-seminomas particularly in subjects less than 40 years of age (odds ratio, 7.1 (95% CI, 1.4–36), odds ratio, 7.1 (95% CI, 1.3–38), odds ratio, 8.1 (95% CI, 1.7–39) and odds ratio, 16 (95% CI, 2.7–95) in the four exposure quartiles, respectively).