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Does our electricity distribution system pose a serious risk to public health?

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Summary Elevated magnetic field exposures are associated with increased childhood leukaemia risk. A link with breast and other cancers has been postulated via modified melatonin activity. Other illnesses have been linked to electricity distribution, by association or mechanistic considerations. For selected illnesses, this paper estimates the annual number of excess cases that might occur near high-voltage powerlines in the UK. Within 150 m of powerlines, magnetic field exposures above 0.1 μT are postulated to result in 9000 excess cases of depression in adults and 60 cases of suicide. Electric field effects can mediate increased exposure to air pollution. Within 400 m of powerlines, this may result annually in 200–400 excess cases of lung cancer, 2000–3000 cases of other illnesses associated with air population and 2–6 cases of childhood leukaemia. Seventeen cases of non-melanoma skin cancer might occur by exposure directly under powerlines.

INTRODUCTION

For reasons that are largely unknown, incidences of certain cancers and of depression have over the last 75 years been rising in industrialized societies. Davis et al. (1) have remarked that in recent decades, changes in cancer other than lung are so great and so rapid that their causes demand intensive investigation. Factors of modern society such as diet, pollution, and increased exposure to light at night have all been suggested as underlying causes of increasing cancer incidence. The possible role of electric and magnetic fields from the electricity supply has also been questioned, especially with regard to childhood leukaemia. Milham and Ossiander (2) have hypothesized that the historical emergence of a peak in incidence of infant acute lymphoblastic leukaemia (ALL) might be explained by the growth of residential electrification.

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Ahlbom et al. (3) and Greenland et al. (4) have recently published pooled analyses of childhood leukaemia incidence in relation to power frequency magnetic field exposures. Together, these analyses from a number of well-conducted studies show a fairly consistent statistical association between childhood leukaemia and power frequency residential magnetic field strengths above 0.4 μT, with an approximately two-fold increase in risk. Debate amongst the authors of the component studies suggests that while part of the association may be due to case selection bias, overall a genuine association between childhood leukaemia and magnetic fields $> 0.4\,\mu$T appears to exist (5).

In searching for a possible causal mechanism to explain this association, there is evidence that magnetic fields are capable of reducing melatonin levels in both animals and humans (6–10). While reduced body melatonin levels may contribute to increased cancer risk, the role of magnetic fields in mediating the reduction of melatonin affecting cancer is unproven.

Nevertheless, on the strength of the epidemiological data, the US National Institute of Environmental Health Sciences (NEIHS) (11) and the International Agency for Research on Cancer (IARC) (12) have both concluded that electric and magnetic fields are possible carcinogens. In fact there is far more evidence to implicate electric and magnetic fields with adverse health effects than there is evidence to implicate passive smoking. Despite this, exposure guidelines to electric and magnetic fields remain anomalously high. For example, the ICNIRP (13) and NRPB (14) guidelines for maximum public exposure to magnetic fields are 100 μT and 1.6 mT, respectively, 250 and 4000 times higher than the level above which a doubling of the risk of childhood leukaemia has been observed. The situation is in sharp contrast to regulations governing human exposure to potentially carcinogenic chemicals.

While there has been strong research interest in magnetic fields and childhood leukaemia, public health risk and cost–benefit, as well as perceived research priorities amongst scientists, are factors underpinning exposure guidelines. In the UK, the NRPB Advisory Group on Non-Ionising Radiation has estimated that between 2 and 4 out of 500 cases of childhood leukaemia per year could be caused by elevated magnetic fields (15,16).

However, the focus on childhood leukaemia masks the fact that for some illness there is a degree of consistency in the research evidence suggesting that adverse health effects of power frequency electric and magnetic fields could be occurring on a far wider scale than currently appreciated. A prime example here is depression and suicide, where there is a substantial body of evidence suggesting an increased risk with magnetic field exposure and yet little or no debate in either scientific or government report literature. A second example concerns newly emerging research areas. The finding that high-voltage powerlines routinely emit corona ions into the atmosphere, thereby electrically charging particles of air pollution, could have wide implications for human exposure to air population near powerlines.

While elevated magnetic fields are associated with high-voltage powerlines, in terms of population exposure in the UK, low voltage distribution cables are a significant cause of elevated exposure (15). The situation is similar in the USA where much street distribution occurs by above ground cables of between 5 and 20 kV.

In this paper, however, attention will be restricted to electric and magnetic fields from high-voltage powerlines in the UK (those > 100 kV), because it is relatively easy to identify the size of the exposed population. The hypothesis is put forward that exposure to powerline electric and magnetic fields results in increased risk of a range of illnesses, both cancer and non-cancer, in both adults and children. An attempt is made to quantify the likely number of cases that might occur annually in the UK, on the understanding that for magnetic fields this will be a lower limit.

ELECTRIC AND MAGNETIC FIELDS AND ELECTROMAGNETIC RADIATION

Electromagnetic radiation refers to the propagation of energy as a result of a time varying electromagnetic field in which electric and magnetic field components are linked as described by Maxwell's equations (17). Radiation in the form of radio waves, emissions from mobile phones, and visible light, all constitute electromagnetic radiation. Power frequency fields, 60 Hz in the USA, Canada and South America, and 50 Hz in Europe and elsewhere, are extremely low in electromagnetic frequency terms. Such fields are described as ELF-EMF, and there is essentially no propagation of energy at power frequencies, although there are induced currents in conducting objects nearby. At 50 Hz the wavelength of the electromagnetic field is 6000 km. At practical distances from powerlines, within what is termed the *near field*, the electric and magnetic fields are essentially separate entities and should be treated as such. Thus, the terms *electric* and *magnetic fields* will be used here to describe powerline fields.

MAGNETIC FIELDS, MELATONIN, CANCER, AND DEPRESSION

In man, as in all vertebrates, the prime source of the hormone melatonin is nocturnal production in the pineal gland followed by release into the bloodstream. Melatonin has been extensively investigated as a natural anti-cancer agent, and in its role in affecting mood. The depression of melatonin production in the pineal gland by the action of magnetic fields has been proposed as a mechanism of increased risk of breast cancer and of depression (18–21). Research into how magnetic fields might affect pineal melatonin has been carried out in both contexts.

The capability of pineal melatonin to regulate cancer has been demonstrated. Removal of the pineal gland in rats led to a significant increase in chemically initiated mammary gland tumours (22–26). The addition of melatonin at physiologically relevant levels has been shown to inhibit the growth of human breast cancer cells in vitro (26,27).

Kato and co-workers (6,7) found that 50 Hz circularly polarized magnetic fields above 1.4 μT suppressed both serum and pineal gland melatonin. This observation may be important because microtesla level rotating fields are found near three-phase electricity power lines, whereas much of the published laboratory animal experimental work has been carried out using linearly polarized magnetic fields. Linear fields reverse sinusoidally in space, going thorough zero twice every cycle. Three-phase powerline magnetic fields consist of a magnetic vector rotating in space, with constant magnitude if circularly polarized or major and minor axis lengths if elliptically polarized – these often become spherical or ellipsoidal (i.e., rotating in three axes) if more than one source is present. It is likely that such a field would have a different effect on polar molecules in the body than simply reversing fields.

Löscher and coworkers (28–33) studied the effects of magnetic field exposure on the incidence and growth of chemically induced mammary tumours in rats. Increased tumour incidence was seen, but significant effects were confined to high exposures, 50 and 100 μT, and the results were not correlated with changes in nocturnal melatonin levels. However, other studies have shown that magnetic fields suppress melatonin activity in the body (34–38). Studies in humans have also reported the depression of pineal melatonin by magnetic fields (8–10).

Overall, a causal mechanism by which power frequency magnetic fields may affect breast and other cancers remains unproven, but action via reduced pineal melatonin certainly merits continued research (15, p. 166). In particular, it should be noted that a number of well conducted occupational studies have shown associations between magnetic fields and leukaemia, brain and lung cancer (15, cpt. 6).

An association between magnetic fields and both depression and suicide has been seen in many epidemiological studies and is considered biologically plausible via reduced pineal melatonin. Abnormal melatonin levels are associated with depression with most studies reporting a link with reduced nocturnal levels (39–41). There is strong evidence that depressive illness is an important risk factor for suicide.

In addition to power frequency magnetic fields, geomagnetic fields have also been associated with depression. Kay (42) found that male hospital admissions for depression were increased 36% during periods of geomagnetic storms compared with normal periods. The author cites a number of studies where changes in magnetic fields are associated with changes in pineal function including decreased melatonin synthesis via the visual system (43–48).

Electric and magnetic fields induce currents in the body and these may also have a bearing on depression. For an electric field exposure of $10\,\mathrm{kV\,m^{-1}}$, Kaune and Forsythe (49) calculated maximum induced current densities of $8 \times 10^{-3}\,\mathrm{A\,m^{-2}}$. For magnetic fields, some studies have shown an effect on short-term memory (50,51), which can occur at exposures as low as 28 μT.

Overall, the evidence confirms the potential for an association between power frequency magnetic fields and both depression and suicide. Fifteen epidemiological studies of either depression or suicide are listed in Table 1 (52–66). A study in electric utility workers in England and Wales during 1970–72 and 1979–83 found no increase in suicide (56). McMahan et al. (59) found no increase in depressive symptoms in a group of women living near a transmission line in Orange County California, but the authors comment that the homogeneity of the study population may limit the generalizability of the finding. Johansen and Olsen (65) found a non-statistically significant increase in suicide in Danish utility workers above 1.0 μT, but this was based on only 36 cases in this category. The remaining 12 studies in Table 1 report an association between magnetic fields and either depression, depressive symptoms or with suicide. Early studies were carried out in populations in the UK (52–55). Six population studies specifically concern high-voltage powerlines exposures (52,54,57,59,63,64). Some studies also hint at an association with power frequency electric fields (52,60,61).

There is evidence that an effect occurs at a low-magnetic field threshold of ~ 0.1 μT (53). Such a low threshold would embrace exposures near a range of high- and low-voltage powerlines and low-voltage distribution cables. Occupational studies appear to show lower effects than for residential studies. This would be consistent with a mechanistic effect associated with reduced nocturnal melatonin production and having a larger effect on chronically exposed populations.

Risk estimate for depression and suicide

In Table 1 the weight of evidence supports a link between magnetic fields and both depression and suicide. Perry et al. (53) suggests a 40% increase in suicide risk above 0.1 μT. This may be used to estimate the number of cases of depression and suicide that might occur near powerlines in the UK. The proportion of the population living near 275 and 400 kV powerlines is given in Table 2, which is taken from Fig. 1 of the report of the UK Childhood Cancer Study (67). The proportion of the population living near 132 kV powerlines needs also to be considered and here this is assumed to be a factor 1.5 greater. An exposure threshold of 0.1 μT is assumed to be effective up to 150 m either side of powerlines at or above 132 kV. This embraces 1.05% of the UK population of 47 million people aged over 15 (68), around 500,000 people. Some estimates suggest that 15% of the adult population experience an episode of mild depression each year. If a 40% increase in risk above 0.1 μT is assumed, this would lead to a large number of cases. Here let us make the conservative estimate that 9000 excess cases of mild depression occur annually near high-voltage powerlines (Table 3).

Suicide figures for the UK are published separately in terms of the absolute number of deaths and the rate per

Table 1 Studies of depression and suicide in relation to exposure to power frequency electric and magnetic fields

Paper	Description of study	Key findings
Reichmanis et al., 1979 (52)	Case-control study of suicide in the West Midlands, UK, with respect to proximity to 33, 132, and 275/400 kV powerlines	Statistically significant correlation between the presence of transmission-line electric and magnetic fields and occurrence of suicide. A separate correlation between electric and magnetic field strength from powerlines and suicide location. Also a correlation with underground transmission lines
Perry et al., 1981 (53)	Case-control study of magnetic fields and suicide in the West Midlands, UK. Comparison of measured magnetic field strength at addresses of suicides, with that measured at the locations of a control group and health questionnaires	Field strength at suicide addresses was significantly greater than at control addresses, $p < 0.0002$. 40% increase in suicide above 0.1 μT magnetic field exposure
Dowson et al., 1988 (54)	Case-control population study in Southampton, UK. Study population comprised the residents of a group of houses situated close to 132 kV overhead powerlines	Analysis revealed that young people living close to a 132 kV powerline were significantly more likely to suffer from headaches or migraines. 9 patients in study group reported depression – 7 of whom lived within 40 m of a cable, and 1 in control group. At 60–80 m from a powerline the incidence of headaches was highest. Within 40 m, incidence of depression was highest
Perry et al., 1989 (55)	Case-control study of depression and magnetic field exposure in the West Midlands, UK	Field strength was higher for cases than controls, $p = 0.033$
Baris and Armstrong, 1990 (56)	Suicide among electrical utility workers in England and Wales during 1970–72 and 1979–83	No increase for electrical workers
Poole et al., 1993 (57)	Prevalence of depressive symptoms and headache in populations living along transmission line right of way in USA	Proximity to the line was positively associated with depressive symptoms. OR = 2.8, 95% CI = 1.6–5.1
Savitz et al., 1994 (58)	Study of depression in electrical workers using data from the Vietnam Experience Study	The authors concluded that in the general workforce there was no sizeable increase in depression. However, a two-fold increased risk among electricians was observed. In electrical workers generally, there was a tendency for increased depression in the month before the survey (odds ratio, OR = 1.7, 95% CI = 0.7–4.3). There was a tendency for increased difficulty in concentrating, especially among short-term workers (risk ratio, RR = 2.0, 95% CI = 0.8–4.9)
McMahan et al. 1994 (59)	Study of depression in women living near a transmission line in Orange County, CA	No significant difference in depressive index scores between women living adjacent to a transmission line and those living one block away (OR = 0.94, 95% CI = 0.48–1.85; minimum detectable OR, upper limit of 95% CI = 1.85). The authors comment that the homogeneity of the study population may limit the generalisability of the findings
Baris et al., 1996a (60)	Study of suicide in 21,744 male electrical utility workers in Québec in relation to exposure to electric, magnetic, and pulsed electromagnetic fields	For cumulative exposure, rate ratios (RR) for all three fields showed mostly small non-significant increases in the medium and high exposure groups. The most increased risk was in the geometric mean medium exposure group to electric fields (RR = 2.76, 95% CI = 1.15–6.62)
Baris et al., 1996b (61)	Subcohort study of 49 suicides from Baris et al., 1996a cohort study	Broadly similar findings to Baris et al., 1996a. Non-significant increased RRs for electric, magnetic, and pulsed electromagnetic field exposures
Kelsh and Sahl, 1997 (62)	Study of mortality among 40,335 Southern California Edison electric utility workers	Consistent association between suicide and non-office occupations. Statistically significant 2- to 2.6-fold increased relative risk for line and plant workers
Verkasalo et al., 1997 (63)	Study of depression in a cohort living near a high-voltage powerline in Finland	4.7-fold increase in severe depression within 100 m of the high-voltage powerline (95% CI = 1.7–13.3)
Beale et al., 1997 (64)	Study of psychological effects of high-voltage transmission line magnetic field exposure in Auckland, New Zealand. Cases lived in houses where 50 Hz magnetic field at the gate exceeded 0.5 μT, matched with controls in houses in same street with gate level less that 0.3 μT	Performance on most memory and attention measures was unrelated to exposure but higher time-integrated exposure was associated with coding-test performance and more adverse psychiatric symptomatology

Table 1 (Continued)

Paper	Description of study	Key findings
Johansen and Olsen, 1998 (65)	Mortality in 21,236 male electrical utility workers in Denmark	Excess suicide was not seen with years of employment. A non-statistically significant increase was seen for magnetic field exposures above 1.0 μT, estimated by job title
van Wijngaarden et al., 2000 (66)	Case-control study of suicide among 138,905 male electrical utility workers in five companies in the US	Suicide mortality was increased in workers with indices of magnetic field exposure. Electrician: OR = 2.18, 95% CI = 1.25–3.80. Line workers: OR = 1.59, 95% CI = 1.18–2.14. Stronger associations, with ORs in the range of 2.12–3.62, were found for men younger than 50 years

Table 2 Approximate number of people living near high-voltage powerlines in the UK

Distance (m)	⩾275 kV powerline Number/(% UK population)[a]	⩾132 kV powerline Number/(% UK population)[b]
25	35,400 (0.06)	94,400 (0.16)
50	70,800 (0.12)	177,000 (0.30)
100	142,00 (0.24)	354,000 (0.60)
150	248,000 (0.42)	620,000 (1.05)
200	372,000 (0.63)	932,000 (1.58)
250	519,000 (0.88)	1,300,000 (2.20)
300	690,000 (1.17)	1,730,000 (2.93)
350	897,000 (1.52)	2,240,000 (3.80)
400	1,100,000 (1.86)	2,740,000 (4.65)

[a]From (67).
[b]Estimated.

million of the population (68). In 1997, for example, there were 5087 deaths attributed to suicide and a rate of 94.5 per million of population. Using 1.05% of the population within 150 m of powerlines ⩾ 132 kV, and assuming a doubling of risk, then either measure of suicide rate suggests that around 60 excess cases may occur annually near powerlines.

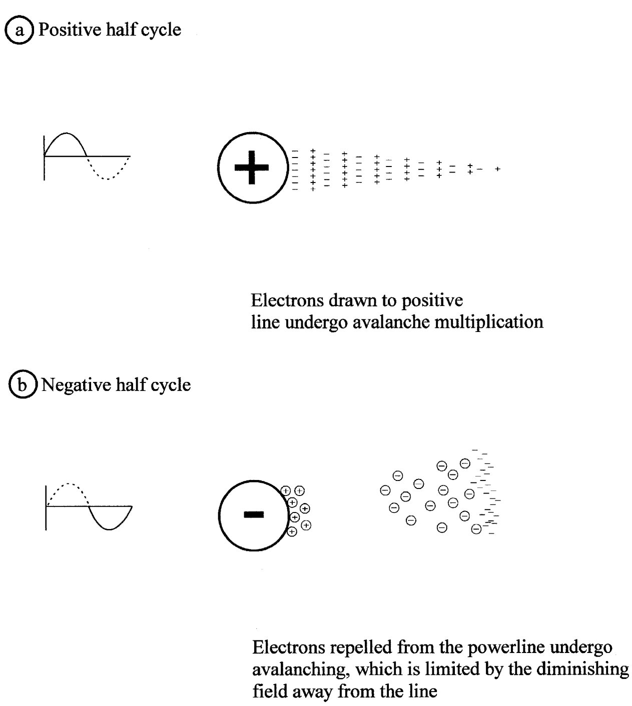

Fig. 1 Schematic outline of the formation of powerline corona ions.

CORONA ION EMISSION FROM HIGH-VOLTAGE POWERLINES

High-voltage powerlines can ionize the air producing free electrons and molecular (positive) ions of oxygen and nitrogen. The electrical mobilities of electrons and positive ions are quite different and as a result separate (unipolar) clouds of positive and negative ions are emitted into the atmosphere. Within 100 nanoseconds, these ions nucleate what is known as *nuclei mode aerosols* around one nanometre in size. Such aerosols constitute what is known as *small ions* (69). In the atmosphere these small ions disperse in two ways. They may disperse in their own right or they may attach themselves to aerosol-sized particles of air pollution thereby increasing the electrical charge on such aerosols. Thus, in the atmosphere separate clouds of positive or negative so-called *space charge* can be observed. Such space charge only becomes neutralized when dispersed well away from powerlines.

The above processes are illustrated in Figs. 1 and 2. Corona losses from powerlines can be up to 0.1 mA per metre, corresponding to 6.25×10^{14} charges per metre

Table 3 Possible excess number of cases of ill health in persons living near high-voltage powerlines in the UK

Condition	Main references	Key findings/Risk assessment	Possible excess cases annually in the UK near high-voltage powerlines
Magnetic fields			
(i) Childhood leukaemia incidence	(3,4,5,11,12,15,16)	No accepted causal mechanism but an implied relative risk of 2.0 above 0.4 μT	One per two years
(ii) Depression	See Table 1 (54,55,57,58,59,63,64)	An increased risk of both depression and suicide is considered biologically plausible; apparent low threshold ~ 0.1 μT	Up to 9000 cases of mild depression
(iii) Suicide	See Table 1 (52,53,56,60,61,62, 65,66)	40% increase in suicide in West Midlands; small increase in general depressive illnesses; 2- to 3-fold increase in severe depression and a 2- to 3.6-fold increase in suicide among electric utility workers	60
Corona ions			
(i) Lung cancer mortality	(61,62,75,89,90,91, 107–112)	Risk assessment based on increased exposure to air pollution via corona ion effects	200–400
(ii) Other illnesses associated with air pollution	(68,76,83,92)	Risk assessment based on increased exposure to air pollution via corona ion effects	2000–3000
(iii) Childhood leukaemia incidence	Childhood leukaemia and air pollution (94–103)	Risk assessment based on increased exposure to air pollution via corona ion effects	2–6
Electric fields			
(i) Skin cancer incidence (non-melanoma)	(104,105,106,113)	Risk assessment based on increased skin exposure to radon decay products and other agents via 50 Hz oscillation of aerosols	17

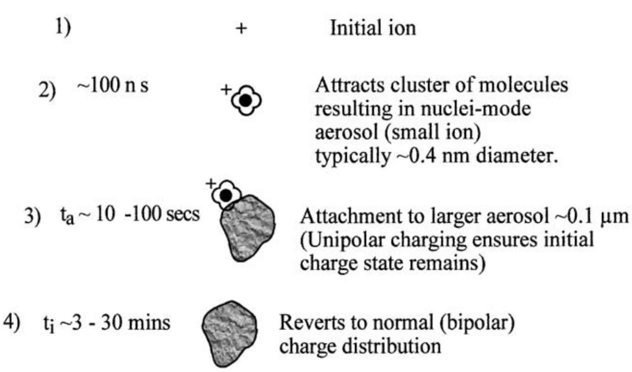

Fig. 2 Schematic illustration of the behaviour and dispersion of corona ions in the atmosphere.

per second (70). Even if the line reabsorbs the majority of these charges, substantial fluxes are potentially emitted into the atmosphere. In the 1950s, investigators observed corona ion space charge effects at ground level up to 5 and 7 km downwind from powerlines (71–73). Carter and Johnson (74) established that both corona ions and charged aerosols reached ground level. At 300 m downwind of a test powerline, 90% of the ground level space charge was in the form of charged aerosols.

In 1999, Fews et al. (75) at Bristol measured corona ion space charge from AC powerlines in Southwest England. Corona ion emission was variable, but significant effects were on average observed up to 400 m downwind from powerlines. In continuing (unpublished) work, we have now observed that most powerlines emit corona ions at some level. Ageing of the cables, and the collection of dirt from the air onto their surface, leading to the build up of sharp edges, are factors that appear to relate to elevated corona emission. We too have found that corona ions can be carried considerable distances from powerlines by the wind. On one occasion significant effects were detected between 2.7 and 7 km from a 275 kV powerline in Somerset. However, most lines examined to date have been at 132 kV and the condition of the line rather than the voltage carried appears to be a dominant factor governing corona ion emission.

When inhaled, electrically charged aerosol particles have a higher probability of being deposited in the lung compared with uncharged aerosols. Increased deposition occurs by the action of mirror charge forces, which have ranges of a few tens of microns. This is the mechanism by which corona ions can mediate increased exposure to air pollution. To quantify this mechanism we need to understand both the nature of pollutant aerosols and the extent and effect of aerosol charging by corona ions.

Respiratory and cardiovascular illnesses, allergies and lung cancer are all associated with urban pollution, especially from vehicle exhausts. In studies of the health effects of air pollution there is particular interest in the ultrafine aerosols, those 10–100 nm in diameter, as opposed to larger aerosols such as the PM10s (aerosol particles of diameter ⩽10 μm) (76).

Air pollution contains carcinogenic agents notably the polycyclic aromatic hydrocarbons (PAH). These are a group of compounds ranging in molecular weight from 128 to 300, which are emitted into the atmosphere by the burning of fossil fuels. The lung carcinogenic potential of these compounds is well established. Benzo[α]pyrene, BaP, of molecular weight 252, is thought to be particularly toxic and is the compound from which toxic equivalency factors for other PAH have been derived (77).

PAH are themselves emitted into the atmosphere in ultrafine aerosols. Measurements have shown that all PAH regardless of species are associated almost exclusively with fine or ultrafine aerosols when emitted from combustion sources. Thus, while the ultrafine aerosols contains only 1–2% of the PM10 mass (78,79), they contain 39–62% of the PAH mass (80–82). However, BaP is particularly noted for its tendency to be associated with fine or ultrafine aerosols because of its non-volatility. Allen et al. (82) showed that in urban air in Massachusetts, 90% of BaP is associated with fine or ultrafine aerosols. Epidemiological evidence supports the view that aerosols below 100 nm diameter are more toxic when compared with larger aerosols, greater than 2.5 μm diameter (83).

To an extent, aerosols are naturally charged by the background distribution of positive and negative (bipolar) ions in air, although ultrafine aerosols tend to support only single charges and below 100 nm the majority of aerosols are uncharged in their natural state. To understand the effect on lung deposition of increasing the charge state, consider first the inhalation of natural aerosols. Fig. 3 shows the total lung deposition of inhaled aerosols as a function of particle size according to the lung model developed by the International Commission on Radiological Protection (ICRP) (84). For aerosols >10 nm diameter, lung deposition on inhalation is less than 100%. A minimum in the deposition probability of around 30% occurs at 100–200 nm diameter. Venkataraman and Raymond (81) folded the size distribution of PAH in air with the ICRP model and estimated that in normal outdoor air only around 30% of inhaled PAH aerosols are deposited in the lung.

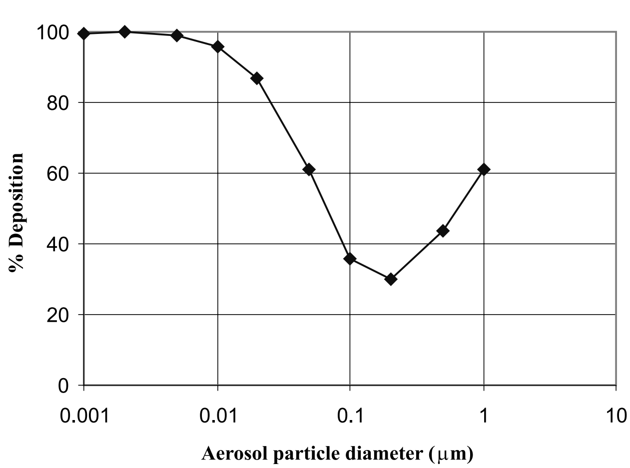

Fig. 3 The proportion of inhaled particles deposited in the lung as a function of aerosol particle diameter, according to the ICRP 66 model (84).

The ICRP model has been validated against human data. Kim and Jaques (85) measured the regional lung deposition of 40, 60, 80, and 100 nm aerosols in 11 male and 11 female volunteers. Table 4 shows their data for 100 nm aerosols. The majority deposition occurs in the alveolar region, but the total deposition is lower than suggested by the ICRP model, at 24.1% in men and 27.4% in women.

Cohen et al. (86) measured the deposition of ultrafine aerosols as a function of charge state in metal alloy casts of the human tracheobronchial tree. The metal alloy mimicked the natural conductivity of human lung. The authors found respective increased deposition factors for 20 and 125 nm aerosols of 3.4 and 2.3 when the aerosols were singly charged aerosols compared with their natural distribution of charge. The authors point out that increased deposition in the tracheobronchial region is particularly important, because a high proportion of lung cancers are bronchogenic. Those charged aerosols that pass through the tracheobronchial region would be expected to undergo enhanced deposition in the alveolar region. This would further increase the ability of ultrafine aerosols to be absorbed deep in the lung.

We now need to consider the degree of aerosol charging which may occur near a high-voltage powerline. The density of corona ion space charge has been estimated by the modification of the Earth's natural DC field of $\sim 100\,\mathrm{V\,m^{-1}}$, at body height above the ground (75). Increases or decreases in the natural DC field are observed in the presence of positive or negative space charge. However, on a time-scale of the order of one second, space charge derived from powerlines generates an erratic time variation in the observed DC field. This is a unique feature that indicates the presence of clouds of space charge drifting away from the powerline close to body height. This is in contrast to natural DC fields,

Table 4 Fractional lung deposition of inhaled 100 nm aerosols in human volunteers – from Kim and Jaques, 2000 (85)

Lung region	Fractional deposition at 100 nm (%)	
	Men	Women
Head	0.2 ± 0.5	0.6 ± 0.7
Tracheobronchial	5.7 ± 3.2	7.8 ± 1.8
Alveolar	18.2 ± 6.2	19.0 ± 2.9
Total	24.1 ± 8.9	27.4 ± 4.1

which are created by the presence of space charge high in the sky.

Analysis suggests that powerlines can create charge densities of up to 10^4 per cm^3 at body height and this may extend on average up to 400 m downwind of powerlines in the UK. This compares with aerosol densities in the rather wide range of 5000–30,000 per cm^3. The way in which corona ions (or rather, small ions) attach to aerosols is a complex problem requiring knowledge of the ion–aerosol attachment coefficient, which in turn depends on aerosol size and any existing charge state (87,88). In essence, a non-equilibrium steady-state situation is set up where a degree of unipolar charging of pollutant aerosols is maintained by the continuous production of corona ions by the powerline, balanced by the eventual dispersal of the space charge cloud away from the powerline. As already mentioned, Carter and Johnson (74) found that 300 m downwind of test lines, 90% of the measured space charge was in a form attached to aerosols. A full analysis of aerosol charging by corona ions is in progress in our laboratory, the results of which will be published elsewhere.

Risk estimate for lung cancer

There is evidence in the scientific literature indicating that apart from smoking, lung cancer risk is associated with air pollution. Katsouyanni and Pershagen (89) reviewed 12 case-control studies and nine cohort studies carried out between 1955 and 1995. More recently, Nyberg et al. (2000) reported the results of a study in Stockholm. Together these showed an excess relative risk of lung cancer in relation to urban air pollution in the range 1.3–2.5. There is some evidence that the excess risk due to air pollution occurs mainly in smokers, suggesting a synergistic interaction between smoking and air pollution (91).

For singly charged ultrafine aerosols, Cohen et al. (86) found increased tracheobronchial deposition factors of 3.2 and 2.4 for 20 and 125 nm aerosols. This is an average increased deposition factor of 2.85, or an absolute increase in deposition of 1.85 or 185%. Following the analysis by Venkataraman and Raymond (81), this suggests that 100% ultrafine aerosol charging may almost double the tracheobronchial deposition of inhaled PAH aerosols.

For the risk assessment let us make the conservative assumption that corona ion exposure results in a 30% increase in lung deposition. Take the affected population as living within 400 m of high-voltage powerlines, in the direction downwind of the prevailing south-westerly wind across the UK. In 1996, there were 25,700 cases of lung cancer in men and 15,200 cases in women in the UK, a rate of 69 per 100,000 of the population (68). From Table 2, the estimated number of people living within 400 m of powerlines $\geqslant$132 kV is 4.6%. If a 30% increase in lung cancer risk downwind compared with upwind is assumed, this yields 285 cases annually. The range quoted in Table 3 of 200–400 cases annually takes into account two possibilities: (i) that on average corona ion effects may not extend to 400 m from powerlines or (ii) that a contribution to risk in those living upwind of the prevailing south-westerly wind should be included.

Risk estimate for other illnesses associated with air pollution

The UK Department of Health Committee on the Medical Effects of Air Pollution (COMEAP) (68,92) estimates that 24,000 premature deaths annually in the UK are caused by exposure to PM10 aerosols, SO_2, and ozone. These figures exclude carcinogenic effects of exposure to benzene, 1,3-butadiene, and PAH. Kunzli et al. (93) estimate that 6% of total mortality in Europe is linked to air pollution, or 43,000 cases annually in the UK. The gaseous component of air pollution will not be subject to corona ion charging. However, current risk estimates take no account of the contribution from ultrafine aerosols, which is seen as increasingly important (76,83). Thus a 30% increased exposure to pollutant aerosols within 400 m downwind of powerlines is estimated to result in around 300 excess deaths annually. In addition to chemical pollutants, all airborne agents such as bacteria, viruses, and pollens are susceptible to charging by corona ions. Therefore, acute respiratory and cardiovascular illness including aggravated asthma and allergies could all occur with higher frequency near high-voltage powerlines. Taking these into account it is estimated that in total between two and three thousand excess cases of pollution-related illness could occur annually near powerlines in the UK.

Risk estimate for childhood leukaemia

A number of studies have looked at childhood leukaemia incidence in relation to urban pollution, especially from motor vehicles (94–103). Exposure has either been assessed by traffic density or by markers of pollution such as levels of NO_2 and benzene levels. A study by Raaschou-Nielson et al. (100) found an association with Hodgkin's disease but not with childhood leukaemia. A study by Reynolds et al. (101) found up to a two-fold increase in leukaemia risk but with wide 95% confidence intervals, indicative of limited resolving power. The remaining studies found evidence of increased risk. A further factor to consider is the role of parental exposure to airborne pollution. Savitz and Chen (102) reviewed 24 studies of parental occupation and childhood cancer risk in their offspring. Consistent associations for leukaemia have been found for motor vehicle- and hydrocarbon-related occupations.

In the design of case-control studies of childhood leukaemia and traffic pollution, it should be pointed out that modern cars with catalytic converters emit a large proportion of their exhausts in the form of ultrafine aerosols, which can be carried considerable distances from their source. This suggests that controls should be chosen that live well away from traffic sources.

On the assumption that childhood leukaemia is associated with air pollution, the population at risk may be taken to include children living up to 400 m downwind of high-voltage powerlines, with a 30% increase in exposure. There are about 500 cases of childhood leukaemia per year in the UK (15,16), so this yields 3.5 excess cases. The range 2–6 is given in Table 3.

OSCILLATION OF AEROSOLS

Electrically charged aerosols oscillate under the influence of power frequency electric fields. The human body is a good conductor and this perturbs the powerline electric field so that around the head its intensity is increased by a factor of approximately 18. Consequently, an *E*-field of $5\,kV\,m^{-1}$ will be increased to $90\,kV\,m^{-1}$ around the head. As a result, the amplitude of 50 Hz oscillation of small ions around the head, will be around 7 cm (104).

Radioactive decay products of naturally occurring radon gas exist in air in aerosol form with activity concentrations of order $10\,Bq\,m^{-3}$. The radioactive decay process introduces natural charging of these aerosols, regardless of the presence of corona ions. Fews et al. (104) made measurements of the deposition of radon decay product aerosols on model heads under high-voltage powerlines outdoors. Increased deposition in the range 1.4–2.9 under powerlines was found. Compared with indoors, the absolute level of deposition both under and away from powerlines was unusually high. This appears to be linked to the washout of radon decay products in rain, in which activity concentrations of ^{214}Po as high as 10^5 Bq per litre of rain have been observed (105).

Risk estimate for skin cancer

The above observations have consequences for the natural α-particle radiation dose to the basal layer of the skin. Fews et al. (104) estimated that for a person spending 10% of their time outdoors, the average dose rate away from powerlines was approximately $18.3\,mSv\,y^{-1}$. Under powerlines the value was between 22.1 and $36.4\,mSv\,y^{-1}$. The ICRP estimates an excess relative risk for non-melanoma skin cancer of around 60% per Sv (106). On this basis a risk analysis can be made for radiation induced skin cancer as a result of living directly under high-voltage powerlines. The non-melanoma skin cancer rate in males and females is taken to be 90 per 100,000 population per year. The exposed population consists of those living in a corridor 25 m either side of the central axis of the powerline. This corresponds to 0.16% or 94,400 people. An average excess annual dose rate of $11\,mSv\,y^{-1}$, 30 years exposure and excess relative risk of 60% per Sv, gives a 20% increase in risk or 17 cases annually.

DISCUSSION

We are all chronically exposed to electric and magnetic fields from the electricity supply. If adverse health effects do result, epidemiological studies of increased exposure might not be expected to resolve significant increases in risk because of the absence of an unexposed control population. The hypothesis presented here is that sizeable excess illness, both cancer and non-cancer, is associated with living near high-voltage powerlines in the UK. The estimate of the annual number of cases is restricted to where the evidence, either by association or by mechanistic considerations, is considered strong enough for their being a case to answer.

For magnetic fields, most elevated exposures occur away from high-voltage powerlines and are related to low-voltage distribution cables (15). Therefore, the estimated number of cases of childhood leukaemia, depression, and suicide given in Table 3 should be seen as a lower limit.

Corona ion emission from high-voltage powerlines is a well-known phenomenon, which has been investigated mainly in terms of the loss of transmitted power. Nevertheless, the level of emission and the dispersal over populated areas warrants further investigation (15; p. 165). Fews et al. (75) carried out most of their measurements near 132 kV lines, but in ongoing work a number of 275 and 400 kV have been studied. It is clear that comparatively low corona losses in power terms may correspond to substantial fluxes of corona ion emission into the atmosphere. It is equally clear that a comparatively low flux density (a few thousand per cm^3) could result in increased exposure to air pollution at a level of public health significance.

The detailed pattern of lung deposition of inhaled charged aerosols also warrants more research, especially in people living near high-voltage powerlines. It should be emphasized that the increased lung deposition occurs by self-induced mirror charge effects, which involve no external electric field and so the effect can occur well away from powerlines. Corona ions may charge up all airborne agents according to their ion capture probability. The larger-sized aerosols such as the PM10s, bacteria, and pollens can support substantial numbers of unipolar charges. Since the volume concentration of these aerosols is low compared to typical ion densities, sufficient corona ions should be present to ensure multiple charging and increased lung deposition on inhalation.

There have been no specific studies of the health effects of population exposure to corona ions. However, there is tantalizing epidemiological evidence that lung cancer risk might be associated with high-voltage powerlines. McDowall (107) considered cancer incidence in East Anglia, UK, in populations living up to 50 m from electrical installations, mainly substations, although he did not specify which were fed by overhead powerlines. Within 15 m of an installation, elevated Standardized Mortality Ratios were seen for lung cancer, all leukaemias, other lymphatic neoplasms and all respiratory disease. Only the result for lung cancer was statistically significant (odds ratio = 2.15, 95% CI = 1.18–3.61) and this was mainly driven by an effect in women. The odds ratios for lung cancer showed a consistent gradient of increasing excess mortality with proximity to the line, but at distances greater than 15 m these were not statistically significant. Six occupational studies of utility workers have, to a varying degree, reported an association with lung cancer (61,62,108–112). Some of these have concerned exposure to pulsed electric and magnetic fields and there is no information on corona ion exposure.

The United Kingdom Childhood Cancer Study (67) performed a categorical analysis of whether or not a case occurred within 400 m of either a 275 or 400 kV powerline. For childhood ALL an increased number of cases was observed within 400 m but this fell short of statistical significance (odds ratio = 1.42; 95% CI = 0.85–2.37). If corona ions do affect childhood leukaemia risk, then the fact that they may be transported several hundred metres from powerlines means that they have contaminated the controls used in most existing studies specific to high-voltage powerlines. It may be the case that particular studies can be re-analysed to take account of corona ion effects.

Possibly the most interesting finding with respect to the deposition of radon decay products on model heads outdoors is the very high deposition rates compared with indoors, regardless of the presence of a powerline. For prolonged periods spent outdoors, the radiation doses that accrue to the skin basal layer probably challenge the very philosophy of the ICRP skin dose rate limit for public exposure of $50\,mSv\,y^{-1}$. However, strict application of the ICRP risk factors does suggest that an increased incidence of non-melanoma skin cancer might be seen in populations living directly under high-voltage powerlines. Thus, a preliminary study by Preece et al. (113) found a 1.6-fold increase in non-melanoma skin cancer in people living within 20 m of high-voltage powerlines in south-west England (relative risk = 1.62, 95% CI = 1.06–2.47). Further research here would be justified.

There are a number of illnesses that have been associated with electric and magnetic fields where current evidence is insufficient to allow a risk assessment. Some studies have reported that the effectiveness of the drug tamoxifen, which is widely used in the treatment of breast cancer, is inhibited by magnetic fields above 1 μT (36–38). This could have wide implications for patients being treated for breast cancer, and who live or work near sources of elevated magnetic fields.

If as is hypothesized here several thousand excess cases of ill health occur each year near high-voltage powerlines in the UK, then clearly this would be of serious public health concern. The implications warrant urgent consideration by scientists and by health and regulatory bodies.

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