

Electric and magnetic fields and health outcomes — an overview

by Bengt Knave, MD¹

KNAVE B. Electric and magnetic fields and health outcomes — an overview. *Scand J Work Environ Health* 1994;20 special issue:78—89. In recent years interest has increased in the biological effects and possible health outcomes of weak electric and magnetic fields. Studies have been presented on magnetic fields and cancer, reproduction, and neurobehavioral reactions. Epidemiologic studies on childhood leukemia and residential exposure from power lines seem to indicate a slight increase in risk, and excess leukemia and brain tumor risks have been reported in “electrical” occupations. In spite of a large number of experimental laboratory studies, however, no plausible and understandable mechanism has been presented by which a carcinogenic effect could be explained. International guidelines state that the scientific knowledge on magnetic fields and cancer does not warrant limiting exposure levels for the general public and work force down to the low levels of everyday exposure. Study results on reproduction, including adverse pregnancy outcomes, and neurobehavioral disorders are generally considered insufficiently clear and consistent to constitute a scientific basis for restricting exposure.

KEY TERMS — cancer, environmental exposure, neurobehavioral reactions, occupational exposure, pregnancy outcomes, restriction of exposure, review.

In recent years research interest has increased in the biological effects and possible health outcomes of low-frequency electric and magnetic fields. In Soviet studies of substation operators certain effects of electric fields on health were already reported in the 1960s, neurasthenic symptoms, cardiovascular and gastrointestinal disorders of a functional nature, and temporary changes in blood cell composition (1—3). Follow-up research in other countries, however, did not verify the Soviet findings, and interest in electromagnetic fields diminished. (For a review, see reference 4.)

At the end of the 1970s and beginning of the 1980s interest was reawakened with the publication of American studies linking childhood leukemia to magnetic fields from power lines (5) and leukemia and brain tumors to workers in “electrical” occupations with exposure to low frequency magnetic fields (6). In 1979 the first reports were published — also in the United States — about clusters of adverse pregnancy outcomes among women working at video display terminals. (For a review, see reference 7.) Suspicion was cast on the magnetic field emitted by the screens of the terminals, as, in some studies on laboratory animals, teratogenic effects were reported if animals were exposed to magnetic fields similar to those of video display terminals.

Other possible health effects related to exposure to low-intensity electric and magnetic fields have also been reported. Nonspecific skin problems and neurasthenic and neurobehavioral disorders (called “hypersensitivity to electricity”) were described for “sensitive” persons in the vicinity of video display terminals and other electric and electronic office equipment, electrical machines, and power lines (8).

During the past 15 years a vast number of experimental and epidemiologic studies on biological effects and possible health hazards has been published. The studies have been reviewed and evaluated for regulations on exposure restriction (9—12). This overview presents relevant background information and recent scientific studies, and also criteria for and discussions on restricting exposure.

Low-frequency electric and magnetic fields

Physically, electric and magnetic fields can be defined as part of the low-frequency electromagnetic radiation spectrum. The photon energy available is proportional to radiation frequency and is thus inversely proportional to its wavelength (ie, the higher the frequency or the shorter the wavelength, the higher the energy). At the high-frequency end of the spectrum, with wavelengths <200 nm, the photon energy is so high that it suffices to break chemical bonds and thereby ionize chemical compounds (ionizing radiation). Wavelengths of >200 nm are known as nonionizing radiation, which may also give rise to biological effects, but then due to other mechanisms.

¹ National Institute of Occupational Health, Department of Neuromedicine, Solna, Sweden.

Reprint requests to: Dr B Knave, National Institute of Occupational Health, Department of Neuromedicine, S-171 84 Solna, Sweden.

Radiation of wavelengths between 400 and 800 nm can, for example, be detected by special receptor cells in the retina of the eye (rods and cones), and it is experienced as visible light. Longer waves, like infrared waves, microwaves, and radio frequency waves, are biologically active in one way or another in relation to their thermal energy (ie, molecular vibration).

The low-frequency electromagnetic fields that are referred to in this context have such low frequencies and such long wavelengths that their low photon energy contents can in no way elicit any biological effects through the aforementioned mechanisms. As far as is known today, there are no special receptor cells or structures that form a missing link between the fields and possible biological effects — with the possible exception of the very recently demonstrated special magnetite crystals in different human cells (13, 14).

The low-frequency fields have two components, an electric field (proportional to the voltage) and a magnetic field (proportional to the strength of the current). Strictly speaking, there are no "electromagnetic" fields, but, instead, there is an electromagnetic force effect that is the sum of the forces of the electric and magnetic fields. The electric field strength is measured in volts per meter, and the magnetic field strength (magnetic flux density) is recorded in teslas.

The low-frequency fields can also be divided into two subgroups as regards frequency. By definition the 50 to 60 Hz frequencies are called ELF (extremely low frequencies) and the higher frequencies in the kilo-Hertz domain are called VLF (very low frequencies). Most often, though, the ELF fields occupy the center of attention because the electricity net frequency is 50 to 60 Hz. Residential exposure is more or less always in the ELF domain, occupationally however the fields sometimes vary in frequency. In front of a video display terminal, for instance, the operator is normally exposed to 50–80 Hz fields (ELF) and 15–20 kHz fields (VLF).

Exposure to electric and magnetic fields

Exposure to electric and magnetic fields occurs throughout society: in the home, at work, in schools, and by electrically powered means of transport. Wherever there are electric wires, electric motors, and electronic equipment, electric and magnetic fields are created.

At home

There are many sources of electric and magnetic fields in the home; television sets, refrigerators, electric stoves and ovens, microwave ovens, electric razors, hairdryers, clock-radios, electric wires, radiators and electric blankets form magnetic fields in their immediate environment. A feature of these fields is that exposure falls very rapidly with distance

from the source. If one uses an electric razor, for instance, there is a strong magnetic field in the immediate vicinity of the machine, but it is hardly detectable a few meters away. As only low voltage is used in the home, electric fields from household appliances are negligible. In some houses stray currents occur due to an imbalance in the electrical grounding system of the building, and this occurrence might give rise to increased magnetic fields in limited areas of the house.

If the house where one lives is under or near an overhead power line, it is exposed to both electric and magnetic fields. The outer walls of the building screen off the electric field, and therefore there is no indoor exposure to the outdoor field. A magnetic field cannot be screened out, and because of its wide dispersal (several hundred meters from the power line), the level of the magnetic field remains more or less the same irrespective of where one is in the house.

At work

Certain occupational groups are more exposed than others. The following list presents "electrical" occupations in the order roughly corresponding to the degree, from highest to lowest, of exposure to magnetic fields during a workday: welders, linesmen and substation operators (electric power industry), electronic engineers and technicians, locomotive engineers, train conductors and railway station workers, radio and television repair men, foundry and furnace workers, miners, and telephonists, telephone repairmen and installation engineers.

A welder is thus more exposed than a linesman who works with power lines. Naturally people in other occupations can also be exposed, for example, exposure to both electric and magnetic fields in the proximity to a video display terminal. To reach the levels in the list one would, however, have to be within decimeters of the screen. From occupational studies in which dosimetry has provided exposure information, 0.1 μ T has been found to represent an average magnetic field level for a workday.

Electrical vehicles

As the preceding list indicates, locomotive engineers and other railway and railroad staff are among the occupational categories exposed. Passengers on long-distance and commuter trains are also exposed to magnetic fields when in transit, if trains are run on alternating current.

Induction of current in the body

Both electric and magnetic fields induce current in the body. For a person standing under a 50- or 60-Hz power line, the current induced in the body by the magnetic field is much less than the current induced by the electric field. In addition, the current

induced in the body by magnetic fields is considerably weaker than that occurring in the body in connection with normal heart and brain activity (ie, $10 \text{ mA} \cdot \text{m}^{-2}$ and $1 \text{ mA} \cdot \text{m}^{-2}$, respectively).

Health effects under study

Cancer

The discussion of possible health risks of low-intensity low-frequency electromagnetic fields started in the 1970s with interest mainly on the electric component of these fields. At the end of the 1970s, and in the 1980s, scientific interest shifted towards the magnetic fields, especially their relation to carcinogenesis. The reason for this shift was the appearance of several epidemiologic reports presenting data indicative of an increase in the incidence of leukemias in children (5, 15–17; for a review, see references 11, 12, 18, 19) and adults (20–24) living in the vicinity of power distribution lines and of leukemias (6, 25–37) and brain tumors (29, 34, 31, 38–42) in “electrical” occupations.

Residential studies. Of the possible cancer risks discussed today, leukemias in children living close to power distribution lines are best documented. The “early” studies between 1979 and 1991 showed increased leukemia risk ratios only when using surrogates for exposure (eg, the Wertheimer-Leeper code) (5). Field measurements of the magnetic fields did not relate to cancer risk.

Very recent case-referent studies from Sweden and Denmark with improved techniques for exposure assessment have — in an overall perspective — strengthened the evidence of a possible cancer risk for residential exposure (43–45). The Swedish study found a doubled risk for childhood leukemia above a calculated historical level of $0.2 \mu\text{T}$. The Danish study found a positive association for all major types of childhood cancer combined above an average exposure level of $0.4 \mu\text{T}$. At $0.25 \mu\text{T}$, and above, no statistically significant increases were found; the odds ratio for leukemia was 1.5 [95% confidence interval (95% CI) 0.6–4.1]. A Finnish residential cohort study (46) found no excess risk, however, of overall cancer, leukemia, lymphoma, or nervous system tumors in children exposed to residential magnetic fields close to transmission power lines. The standardized incidence ratio was 1.6 (95% CI 0.3–4.5) for leukemia above an exposure level of $0.2 \mu\text{T}$. Therefore there are apparent differences between the results of the Scandinavian studies. On the other hand, the leukemia risks found do not necessarily need to be contradictory. The Danish and Finnish studies had a lower precision than the Swedish study because of differences in study population sizes.

The Scandinavian residential studies referred to may indicate a doubled leukemia risk above $0.2 \mu\text{T}$, corresponding to a distance within 50–100 m from

an overhead power line. The number of childhood leukemia cases under power lines are few, however, and the risk is therefore low compared with that of other environmental hazards in society. It has been calculated that each year in Sweden there are two cases of childhood leukemia under or near power lines. One of these cases is attributable to the magnetic field risk, if any.

Occupational studies. During 1993 three occupational studies were published, from Sweden (47), Denmark (48), and the United States (49). In the Swedish case-referent study, in which the exposure assessment was made by individual dosimetry measurements, a magnetic field strength above $0.2 \mu\text{T}$ gave a double risk for leukemias and brain tumors, for the latter for younger men only. Of the leukemias, chronic lymphocytic leukemia was in excess, but not acute myeloid leukemia. In the Danish cohort study men with continuous, but not those with intermittent, exposure had an excess risk for leukemias, with equal contributions from acute and other leukemias. In the American study on electric utility workers (nested case-referent study), fields were measured for the exposure assessment. No risk increases in leukemias or brain tumors were found; however, the risk and interval estimates were limited by low precision. No distinction was made between the leukemia subtypes.

Occupational exposure to magnetic fields is generally higher than residential exposure, and calculations of leukemia and brain tumor risks also give higher values for exposed workers than for children living close to power lines. From calculations on the attributable risk in the Swedish study approximately 20 cases of leukemias and 20 cases of brain tumors could be attributed to the magnetic fields each year. These figures are to be compared with the total number of 40 000 annual cancer cases in Sweden, of which 800 have been calculated to have an “occupational” origin.

If the cancer effect is real, there are, however, uncertainties as to exposure characteristics (eg, magnetic field frequency and exposure intermittence) and not much is known about confounding or effect-modifying factors. As a matter of fact, it is only the Floderus study (47) that has considered confounding; exposure to benzene, solvents, ionizing radiation, pesticides, and some behavioral factors did not essentially influence the odds ratios. Furthermore, most of the occupational studies have indicated one special form of leukemia, acute myeloid leukemia. A few, on the other hand, have found higher incidences for another form, chronic lymphatic leukemia. The reasons for this discrepancy in results are not known. In several studies brain tumors have been reported, and the evidence for an association is considered stronger (11) than for leukemias because of the duration-in-employment effect noted in some studies.

Excess breast cancer among men has also been reported in association with exposure to magnetic fields (36, 50–52). Almost all of the occupational studies have been made on male study populations. Breast cancer among women has been reported in two recent studies, however. In the Danish register cohort study (48) no excess risk was found. In an American case-referent study (53) it was reported that women in traditionally male-dominated “electrical” occupations had 40% higher breast cancer mortality than other women in the labor force. Since breast cancer is such a common cause of morbidity and mortality among women, even a small excess relative risk implies many cases attributable to the fields.

Animal studies. Only a few animal studies on magnetic fields and cancer have been reported, and therefore they are little help in the risk assessment of the fields. (See references 54 and 55 for reviews.) If the fields are truly associated with cancer, laboratory studies have indicated that they do not initiate cancer; instead they promote it. For instance, a co-promotional effect was reported for mouse skin with exposure to a continuous field (56, 57). Another research team did not find any promotion with a continuous field (58), but with an intermittent field the results differed (59). It is clear that the results of additional, ongoing large studies in Canada, Sweden, the United States, and Australia must appear before it can be determined whether or not the fields promote cancer in animals.

Mechanism studies. In contrast to the sparse animal cancer studies, there is a vast number of in vitro studies in the search for possible field-induced cancer promotion mechanisms. (See, eg, references 9, 10, 55, and 60.) Several candidate models have been presented on changes in the cell surface and in the cell membrane transport of calcium ions, the disruption of cell communication, the modulation of cell growth, the activation of specific gene sequences by modulated RNA (ribonucleic acid) transcription, the depression of pineal melatonin production, the modulation of ornithine decarboxylase activity, and the possible disruption of hormonal and immune-system antitumor control mechanisms. Each of these mechanisms has features applicable to explaining reported magnetic field cancer effects; however, none has been free of problems and essential objections (61).

There are two mechanism candidates which deserve special attention, the reduction of nocturnally produced melatonin induced by exposure to magnetic fields (62) and the discovery of magnetite crystals in human tissues (13, 14).

It is known from animal studies that melatonin, indirectly via an effect on circulating sex hormone levels, has an oncostatic effect. It is also known that magnetic fields suppress pineal melatonin produc-

tion, which, for example, provides a theoretical mechanism for the increase in breast cancer reported in relation to exposure to magnetic fields. Recently, an alternate explanation for the increased cancer risk has been proposed (62). Melatonin has been found to be the most potent hydroxyl radical (-OH) scavenger discovered, and consequently the free radical damage to DNA (deoxyribonucleic acid) is markedly inhibited by melatonin. If melatonin is suppressed (eg, by magnetic fields) the DNA is left more vulnerable to oxidative attack. This theory explains how the depression of melatonin by magnetic fields could result in a higher incidence of cancer in any tissue. But do human melatonin blood levels diminish when individuals are exposed to weak magnetic fields? In an experimental study Graham et al (63) recently reported that this occurrence was possible in a subgroup of healthy young men with low melatonin base levels. It is apparent that further research along the “melatonin track” will be well worth following.

For some years it has been known that the seasonal migrations and orientation ability of birds are mediated via magnetite crystals in cells responding to the earth's magnetic field. Now, as has already been mentioned, magnetite crystals have also been demonstrated in human cells (13), in some cells in a concentration high enough theoretically to respond to the weak magnetic fields in residential and occupational exposures (14). It is possible that magnetite crystals may be a missing link explaining some of the biological effects under discussion.

Effects on reproduction with special reference to adverse pregnancy outcomes

High-voltage utility and laboratory workers. Towards the end of the 1970s results of Swedish studies were presented which indicated that there was a greater risk of miscarriage and having children with congenital malformations in families in which the husband worked in the electric power industry (64). The same research group also found chromosome damage in lymphocytes of switchyard workers (65, 66), and more recently a Norwegian study reported chromosome breaks in high-voltage laboratory cable splicers (67), indicating a possible risk increase of genotoxic effects in these workers. However, in a German study no chromosome aberrations were found in lymphocytes of 380-kV utility workers (68). In another, earlier Swedish study, family size and fertility among utility substation workers differed between the exposed and unexposed men. However, these differences were apparent before utility employment, and for this reason the authors interpreted the study as negative (4).

Electric blankets. In 1986 and 1989 Wertheimer & Leeper (69, 70) reported possible adverse pregnan-

cy effects after the use of electric blankets and electrically heated water beds. Later, in a Chinese case-referent study that adjusted for drug usage, exposure to chemicals, and noise (71), an increased risk of spontaneous abortion was reported for women using electric blankets during early pregnancy. Other studies have not found increases in malformations (72, 73). It has been convincingly documented that users of electric blankets have higher magnetic field intensities than nonusers (74), and several large-scale epidemiologic studies are in progress in which the possible confounding by temperature increase will hopefully also be considered.

Residential exposures. A Finnish case-referent study found an increased incidence of early pregnancy loss among women exposed to 50-Hz magnetic fields in their homes (75). The early pregnancy losses were determined by hormone analysis in a group of women attempting to become pregnant. The 50-Hz magnetic fields were measured in the homes of 89 cases with early pregnancy loss and 102 referents. A cut-off score of 0.6 μT resulted in an odds ratio of 5.1 (95% CI 1.2–21). A study of birth defects in some municipalities through which high voltage power lines pass did not, however, find any increases in congenital malformations (76).

Late effects (childhood cancer) after parental exposure to electromagnetic fields. In a study of childhood cancer and maternal field exposure from electric blankets during pregnancy, brain tumors were found in excess (77). In two studies the incidence of brain tumors was elevated among children to men occupationally exposed to the fields (78, 79), while in a third it was not (80). As to childhood neuroblastoma, one study reported an association with presumed paternal exposure (81), while two others did

not (82, 83). The results of these late-effect studies are contradictory, and a prerequisite for a true association is field-induced genetic or chromosome damage (11, 12, 84, 85).

Video display terminals. As has already been mentioned, operators of video display terminals are exposed to both ELF and VLF electric and magnetic fields. Since the middle of the 1980s, several well-designed epidemiologic studies have been published in which pregnant women who worked with a video display terminal during pregnancy were compared with pregnant women who did not. Although the results showed some variations, these studies essentially failed to demonstrate any differences between the two groups (86–99). (For a review, see references 100 and 101.)

Two of these studies have, in addition to examining possible differences between work with and without video display terminals, also utilized data on the emission of or exposure to low-frequency magnetic fields from the terminals (96, 98). In the study by Schnorr et al (96), in which the magnetic fields were measured at a selection of the actual workplaces, there were no associations between levels of magnetic fields and miscarriages. In the study by Lindbohm et al (98), there was no association between VLF magnetic fields, as measured in a laboratory, and miscarriages, but a significant association was found between ELF magnetic fields and miscarriages. A comparison between the results of these two studies is given in table 1. Caution is recommended when the comparison is interpreted because of the considerable differences in the methods used (workplace versus laboratory measurements, instrumentation, etc). Regarding the positive results of the Lindbohm et al study, issues have been raised concerning (i) the appropriate comparison group (within video display terminal comparison or not), (ii) exposure

Table 1. Associations between miscarriage and extremely low-frequency magnetic fields in two studies. (VDT = video display terminal)

Study	No VDT use	VDT with low field	VDT with high field
Schnorr et al (96)			
Magnetic field ^a	0.036 μT	0.046 μT	0.050 μT
Odds ratio (in a comparison with a group unexposed to video display terminals) ^b	1.00	0.98 (0.58–1.64)	0.92 (0.58–1.47)
Lindbohm et al (98)			
Magnetic field ^c	Not measured	<0.13 μT	>0.3 μT
Odds ratio (comparison within a VDU group exposed to video display terminals) ^b	·	1.00	3.4 (1.4–8.6)
Odds ratio (in a comparison with a group unexposed to video display terminals)	1.00	0.4 (0.2–0.8)	1.6 ^d

^a Measured at random in a selection of workplaces, value assigned to type of VDT, measured in fetal position with operators present.

^b 95% confidence interval in parentheses.

^c Measured in a laboratory for appropriate type of VDT, at 50 cm from screen center, here recalculated into root-mean-square.

^d Not significant.

misclassification since workplace measurements were not made (nondifferential or not), and (iii) variation of exposure levels between companies (confounding or not).

To summarize, the epidemiologic studies that have been performed have not been able to demonstrate an association between work with a video display terminal during pregnancy and increased risks of miscarriage, giving birth to a malformed child, or growth retardation of the fetus. Regarding the possibility of specific subgroups of women at risk, groups to be considered are those that can be defined by exposure to VLF or ELF magnetic fields. For VLF fields, the two epidemiologic studies that have provided data have not been able to demonstrate such an excess risk for miscarriages. For ELF magnetic fields (ie, frequencies about or somewhat above the net frequency (50 or 60 Hz), one epidemiologic study has indicated an excess risk of miscarriage. The absence of a similar response in a second study, as well as some methodological considerations in both studies, do however detract somewhat from the strength of this positive finding. No experimental data seem to support the existence of such an increased risk in association with 50- or 60-Hz fields. (See the following discussion.) Nevertheless, the positive association noted in the study by Lindbohm et al (98) warrants an attempt at replication.

Animal teratogenicity of low-frequency magnetic fields. In 1982 a Spanish research team reported on the possible teratogenic effects of low-frequency magnetic fields (102) from their observations of chick embryos exposed to pulsed magnetic fields. Subsequently several other groups have tried to repeat these results, with varying success. The most concerted effort was the "Henhouse project," in

which six laboratories attempted to verify the Spanish results by using identical equipment and standardized procedures. The outcome, however, was indicative of the involvement also of other, uncontrolled factors (103, 104). Studies of rats and mice have not resulted in adverse pregnancy outcomes that could be related to 50- or 60-Hz sinusoidal or pulsed magnetic field exposure (105—111). Experiments have also been performed on rats or mice with saw-tooth-formed 15- to 20-kHz magnetic fields similar to those of video display terminals, with varied results (table 2). This variation could be due to (i) inappropriate statistical analyses (some of the effects have been noted when the statistical analysis was based on the fetus, not on the litter), (ii) incomplete study protocol (eg, lack of documentation as to control for 20-kHz noise), (iii) different species of rats or mice being used.

A combination of these differences between the studies could probably explain the different results noted. Only one of them — the species difference — is fully indicative of a real biological effect of magnetic fields on pregnant rodents, and then only for certain rodent species. This situation makes extrapolation to human risk evaluation rather difficult (84, 116).

"Hypersensitivity to electricity" and neurobehavioral reactions

In the 1980s the occurrence of skin symptoms and signs among operators of video display terminals was studied by different investigators in Sweden. Consistently an increase in some mild nonspecific skin symptoms was found, but, as to objectively diagnosed skin changes, there was no similar consistency in the findings (117—119). In a case-referent study on subjective skin disorders and work video

Table 2. Results of teratogenic studies with rodents and 18—20 kHz saw-tooth magnetic fields.

Study	Experimental conditions ^a	Results ^b		
		Malformation	Resorption	Other outcomes
Tribukait et al, 1987 (107)	C3H mice, 20 kHz, 15 μ T, fetus analysis	yes/no ^c	no	no
Frölen et al, 1993 (112)	CBA mice, 20 kHz, 15 μ T fetus and litter analysis	no	yes	^d
Huuskonen et al, 1993 (113)	Wistar rat, 20 kHz, 15 μ T	yes ^e	no	yes ^f
Stuchly et al, 1988 (114)	SD rat, 18 kHz, up to 66 μ T, litter (and fetus) analysis	no ^e	no	no
Wiley et al, 1992 (115)	CD-1 mice, 20 kHz, up to 200 μ T, litter analysis	no	no	no

^a Reporting on species used, magnetic field frequency, peak-to-peak field level(s), and basis for statistical analysis.

^b yes = significantly increased occurrence among exposed, as compared with unexposed, animals, no = no significant differences at any field level.

^c The study consisted of two series.

^d The study consisted of several series; fetal mortality increased in the first series only.

^e Minor skeletal deformations found.

^f Increased implantations, leading to (?) increases in the number of fetuses and uterus weight.

display terminals, certain risk factors were identified, gender (women), atopic skin reaction, work load and psychosocial factors, and the handling of paper. After low-frequency electric and magnetic fields were measured at workplaces, it was also found that the electric fields in the offices and the magnetic fields in front of the screens of the terminals were higher among the cases than among the referents (120). In another, comparative prospective study of skin disorders, it was possible to verify the connection with work load and psychosocial factors, but there was no association with the electromagnetic factors (121).

During the past four or five years attention has been paid to a minor group of persons, mainly operators of video display terminals, with more severe skin symptoms, often in combination with other symptoms (eg, from the nervous system, sense organs, upper respiratory tract, gastrointestinal tract, etc) (8). The symptoms are not exclusively related to contact with video display terminals; vicinity to outdoor and indoor electrical power and distribution lines, electrical motors and machines, household appliances, fluorescent lamps, and the like can also provoke symptoms. The persons affected have themselves defined the condition as "hypersensitivity to electricity," since a common denominator to them appears to be nearness to things that have something to do with electricity. There are several thousands of persons today in Sweden with this hypersensitivity.

The hypersensitivity is a phenomenon of late date; more than half of the examined patients have fallen ill in 1986 or later (8). A great variety of symptoms and discomforts has been put forward, mainly of the skin and the nervous system. Most of the persons state diffuse skin complaints on the face, such as flush, rosiness, ruddiness, heat, warmth, pricking sensations, ache, tightness, and the like. Symptoms from the nervous system are also stated, such as headache, dizziness, fatigue and faintness, tingling and pricking sensations in the extremities, shortness of breath, heart palpitations, profuse sweating, depression, and memory difficulties. No characteristic organic neurological disease symptoms have been presented.

Symptoms can be severe and then give rise to sick leave. The prognosis varies with the type of symptoms. Symptoms of the nervous system persist more often than skin symptoms. Most persons with this hypersensitivity can go back to work, however, after simple measures to reduce exposure at the workplace. A reduction of the time spent working with video display terminals is the most common recourse, and the most effective means of alleviating symptoms — skin symptoms especially.

The hypersensitivity is believed to be multifactorial in origin. It is not clear whether electrical or magnetic fields are involved or not. In a recent laboratory provocation study from the United States the authors presented evidence that hypersensitive per-

sons were able to detect and identify weak fields (122). Well-controlled and similarly designed Swedish provocation studies could not confirm this phenomenon, however (123–125). Chemical, ergonomic, stress, and work organization factors have been proposed to contribute to the etiology, and it seems as if a mismatch between company organization and possibilities for an individual career at work definitely play a role in the development of symptoms (126). Hypersensitive persons were also found to produce higher levels of stress hormones at work with video display terminals than referents were, a finding which, together with the clinical picture, led the authors to diagnose "technostress" in these persons (127). It is generally agreed that the phenomenon of hypersensitivity to electricity should be further studied. From laboratory studies on healthy volunteers it has been shown, for instance, that combined exposure to an electric ($9 \text{ kV} \cdot \text{m}^{-1}$) and magnetic field ($20 \text{ } \mu\text{T}$) can give rise to more physiological changes, such as slowing of heart rate and changes in late components of event-related brain potentials (128). Slowing of the heart rate has also been reported among workers and volunteers under power lines (129), and in a study on volunteers electroencephalographic changes were found after exposure to magnetic field strengths similar to those near household appliances (130).

Of interest in this connection is the altered melatonin cycle in response to weak magnetic field exposure, and it is known that altered diurnal rhythmicity in the pineal gland and melatonin production can be linked to depressive illness in humans ("seasonal affective disorders"). Recently a well-designed epidemiologic study was presented in which depressive symptoms and headaches were found to be associated with proximity of residence to high-voltage transmission lines (131). The association was not explained by demographic variables associated with depression and headaches or by attitudes about power lines or other environmental issues. Similar results on headaches and migraine were described some years ago in another study of populations residing near overhead power lines (132). Efforts are already in progress to relate changes in pineal melatonin to the described neurobehavioral reactions, including hypersensitivity to electricity.

Regulations and guidelines on limits of exposure

The discussions on regulation of exposure are based entirely on the cancer reports. As mentioned earlier, the exposure levels found in the epidemiologic studies are very low. Average field strengths of $0.2\text{--}0.4 \text{ } \mu\text{T}$ for a workday appear to be the level above which there could be an increased risk, and similar levels have been calculated for annual averages for people living under or near power lines.

Many people are similarly exposed above these levels, though for shorter periods, in their homes (electric radiators, household appliances, razors, hair-dryers, and stray currents in the plumbing system), at work (in certain industries and in offices near electric and electronic equipment), or while traveling in trains and other electric conveyances. The importance of such intermittent exposure is not known. There are animal studies indicating that it could be important; on the other hand, there are epidemiologic studies stressing an even, continuous exposure as more essential for cancer development. There are other uncertainties in the epidemiologic studies as to exposure (eg, the importance of field frequency, other modifying or confounding factors, knowledge of the total exposure day and night) and effect (inconsistencies in findings as to type of cancer) which make a risk assessment difficult. The animal experiments presented thus far, on cancer promotion, are few, and the results of ongoing studies are awaited. To this situation can be added the lack of a plausible and understandable mechanism by which the carcinogenic effect can be explained. Recently, however, exciting and promising results have been presented on possible melatonin mechanisms, and the magnetite crystals identified in the brain and in some blood cells inspire considerable interest for the future.

In studies on other possible health effects related to electric and magnetic fields (eg, reproductive and neurobehavioral disorders), the results are generally considered to be insufficiently clear and consistent to constitute a scientific basis for restricting exposure.

In international guidelines, limits for restricting field exposure are several orders of magnitude above what can be measured from overhead power lines and found in "electrical" occupations. The International Radiation Protection Association (IRPA) issued *Guidelines on Limits of Exposure to 50/60 Hz Electric and Magnetic Fields* in 1990 (133). These guidelines have been adopted in many national standards. Since important new studies were published thereafter, an addendum was issued in 1993 by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) (134). Furthermore, in 1993, risk assessments in agreement with that of IRPA were also made in the United Kingdom (135).

These documents emphasize the facts that the state of scientific knowledge today does not warrant limiting exposure levels for the public and the work force down to the microtesla level and that further data are required to confirm whether or not health hazards are present. The IRPA and ICNIRP guidelines are based on the effects of field-induced currents in the body, corresponding to those normally found in the body (up to about $10 \text{ mA} \cdot \text{m}^{-2}$). Occupational exposure to magnetic fields of 50 or 60 Hz is recommended to be limited to 0.5 mT for all-day exposure and to 5 mT for short exposures of up to

2 h. Exposure to electric fields should be limited to 10 and $30 \text{ kV} \cdot \text{m}^{-1}$. The 24-h limit for the public is set at $5 \text{ kV} \cdot \text{m}^{-1}$ and 0.1 mT.

However, there is concern among some standard setters, and reference has been made to the concept of "prudent avoidance" (136), which could be summarized as the *future* avoidance of unnecessary exposure in the absence of scientific certainty. A systematic strategy has been presented on how future power lines should be routed and designed in order to minimize residential and occupational exposure, and on how household appliances should be designed to reduce or eliminate the fields they generate.

References

1. Asanova TP, Rakov AM. Health conditions of workers exposed to electric fields on open switchboard installations of 400–500 kV: preliminary report. *Gig Tr Zabol* 1966;10:50–2.
2. Sazonova TE. Physiological and hygienic assessment of the working conditions at the outdoor switchyards 400 and 500 kV. In: *Proceedings of the Institute of Labor Protection under the All-Union Central Council of Trade Unions*, 1970; issue 63.
3. Filippov V. The effect of alternating electric fields on man. Presented at the 2nd international colloquium on the prevention of occupational risks due to electricity, Cologne, November 30–December 1, 1972.
4. Knave B, Gamberale G, Bergström S, Birke E, Iregren A, Kolmodin-Hedman B, et al. Long-term exposure to electric fields: a cross-sectional epidemiologic investigation of occupationally exposed workers in high-voltage substations. *Scand J Work Environ Health* 1979;5:115–25.
5. Wertheimer N, Leeper E. Electrical wiring configurations and childhood cancer. *Am J Epidemiol* 1979;109:273–84.
6. Milham S. Mortality from leukemia in workers exposed to electrical and magnetic fields. *N Engl J Med* 1982;307:249.
7. Bergqvist U. Video display terminals and health. *Scand J Work Environ Health* 1984;10 suppl 2:1–87.
8. Knave B, Bergqvist U, Wibom R. "Hypersensitivity to electricity" — a work place phenomenon related to low-frequency electric and magnetic fields. In: *Proceedings from the International Congress of the International Radiation Protection Association*, IRPA 8, Montreal, May 1992. Montreal, 1992:1121–4.
9. United Nations Environment Programme/World Health Organization/International Radiation Protection Association. Extremely low frequency (ELF) fields. Geneva: World Health Organization, 1984. Environmental health criteria 35.
10. United Nations Environment Programme/World Health Organization/International Radiation Protection Association. Magnetic fields. Geneva: World Health Organization, 1987. Environmental health criteria 69.
11. Oak Ridge Associated Universities. Health effects of low-frequency electric and magnetic fields: the committee on interagency radiation research and policy coordination. Washington, DC: US Government Printing Office, 1992. Publication number 029–000–0043–9.
12. National Radiation Protection Board (NRPB). *Electromagnetic fields and the risk of cancer: report of an advisory group on non-ionizing radiation*. Chilton,

- Didcot, Oxon: NRPB, 1992:1—138. Documents of the NRPB, vol 4, no 5.
13. Kirschvink JL, Kobayashi-Kirschvink A, Woodford BJ. Magnetite biomineralization in the human brain. *Proc Natl Acad Sci* 1992;89(16):7683—7.
14. Kirschvink JL. Can weak ELF magnetic fields produce significant effects on biogenic magnetite? In: Project abstracts from the annual review of research on biological effects of electric and magnetic fields from the generation, delivery & use of electricity, Savannah, Georgia, October 31—November 4, 1993. US Department of Energy and US Electrical Power Research Institute, 1993:79.
15. Tomenius L. 50-Hz electromagnetic environment and the incidence of childhood tumours in Stockholm county. *Bioelectromagnetics* 1986;7:191—207.
16. Savitz DA, Wachtel H, Barnes FA, John EM, Tvdrick JG. Case-control study of childhood cancer and exposure to 60-Hz magnetic fields. *Am J Epidemiol* 1988;128: 21—38.
17. London SJ, Thomas DC, Bowman JD, Sobel E, Cheng TC, Peters JM. Exposure to residential electric and magnetic fields and risk of childhood leukaemia. *Am J Epidemiol* 1991;134:923—37.
18. Bierbaum PJ, Peters JM, editors. Proceedings of the scientific workshop on the health and magnetic fields on workers. Washington, DC: US Department of Health and Human Sciences, 1991. DHHS (NIOSH) publication no 91—111.
19. Savitz DA. Overview of epidemiologic research on electric and magnetic fields and cancer. *Am Ind Hyg Assoc J* 1993;54:197—204.
20. Wertheimer N, Leeper E. Adult cancer related to electrical wires near the home. *Int J Epidemiol* 1982; 11:345—55.
21. McDowall ME. Mortality of persons resident in the vicinity of electricity transmission facilities. *Br J Cancer* 1986;53:271—9.
22. Severson RK, Stevens RG, Kaune WT, Thomas DB, Hevser L, Davis S, et al. Acute non-lymphocytic leukemia and residential exposure to power frequency magnetic fields. *Am J Epidemiol* 1988;128:10—20.
23. Coleman MP, Bell CMJ, Taylor HL, Primic-Zakelj M. Leukaemia and residence near electricity transmission equipment: a case-control study. *Br J Cancer* 1989;60:793—8.
24. Youngson JHAM, Clayden AD, Myers A, Cartwright RA. A case-control study of adult haematological malignancies in relation to overhead powerlines. *Br J Cancer* 1991;63:977—85.
25. Wright WE, Peters JM, Mack TM. Leukaemia in workers exposed to electrical and magnetic fields. *Lancet* 1982;2:1160—1.
26. Coleman M, Bell J, Skeet R. Leukemia incidence in electrical workers. *Lancet* 1983;2:982—3.
27. McDowall ME. Leukemia mortality in electrical workers in England and Wales. *Lancet* 1983;1:246.
28. Calle EE, Savitz DA. Leukemia in occupational groups with presumed exposure to electrical and magnetic fields. *N Engl J Med* 1985;313:1476—7.
29. Milham S. Mortality in workers exposed to electromagnetic fields. *Environ Health Perspect* 1985;62: 297—300.
30. Stern FB, Waxweiler RA, Beaumont JJ, Lee ST, Rinsky RA, Zumwalde RD, et al. A case-control study of leukemia at a naval nuclear shipyard. *Am J Epidemiol* 1986;123:980—92.
31. Pearce N, Reif J, Fraser J. Case control studies of cancer in New Zealand electrical workers. *Int J Epidemiol* 1989;18:55—9.
32. Juutilainen J, Läärä E, Pukkala E. Incidence of leukemia and brain tumors in Finnish workers exposed to ELF magnetic fields. *Int Arch Occup Environ Health* 1990;62:289—93.
33. Gallagher RP, McBride ML, Band PR, Spinelli JJ, Threlfall WJ, Yang P. Occupational electromagnetic field exposure, solvents exposure, and leukemia. *J Occup Med* 1990;32:64—5.
34. Loomis DP, Savitz DA. Mortality from brain cancer and leukemia among electrical workers. *Br J Ind Med* 1990;47:633—8.
35. Törnqvist S, Knave B, Ahlbom A, Persson T. Incidence of leukemia and brain tumors in some "electrical occupations." *Br J Ind Med* 1991;48:597—603.
36. Tynes T, Andersen A, Langmark F. Incidence of cancer in Norwegian workers potentially exposed to electromagnetic fields. *Am J Epidemiol* 1992;136:81—8.
37. Matanoski GM, Elliot EA, Breyse PN, Lynberg MC. Leukemia in telephone linemen. *Am J Epidemiol* 1993;137:609—19.
38. Lin RS, Dischinger PC, Conde J, Farrell KP. Occupational exposure to electromagnetic fields and the occurrence of brain tumors. *J Occup Med* 1985;27: 413—9.
39. Thomas TL, Stolley PD, Stemhagen A, Fonham ETH, Bleeker ML, Stewart PA, et al. Brain tumor mortality risk among men with electrical jobs: a case-control study. *JNCI* 1987;79:233—8.
40. Speers MA, Dobbins JG, Miller VS. Occupational exposures and brain cancer mortality: a preliminary study of east Texas residents. *Am J Ind Med* 1988; 13:629—38.
41. Preston-Martin S, Mack W, Henderson BE. Risk factors for gliomas and meningiomas in males in Los Angeles County. *Cancer Res* 1989;49:6137—43.
42. Mack W, Preston-Martin S, Peters JM. Astrocytoma risk related to job exposure to electric and magnetic fields. *Bioelectromagnetics* 1991;12:57—66.
43. Feychting M, Ahlbom A. Magnetic fields and cancer in children residing near high-voltage powerlines. *Am J Epidemiol* 1993;138:467—81.
44. Feychting M, Ahlbom A. Magnetic fields and leukemia and CNS tumors in adults residing near Swedish high voltage power lines. In: Project abstracts from the annual review of research on biological effects of electric and magnetic fields from the generation, delivery & use of electricity, Savannah, Georgia, October 31—November 4, 1993. US Department of Energy and US Electrical Power Research Institute, 1993:112—3.
45. Olsen JH, Nielsen A, Schulgen G. Residence near high-voltage facilities and risk of cancer in children. *Br Med J* 1993;307:891—5.
46. Verkasalo PK, Pukkala E, Hongisto MY, Valjus JE, Järvinen PJ, Heikkilä KV, et al. Risk of cancer in Finnish children living close to power lines. *Br Med J* 1993;307:895—9.
47. Floderus B, Persson T, Stenlund C, Wennberg A, Öst Å, Knave B. Occupational exposure to electromagnetic fields in relation to leukemia and brain tumors. *Cancer Causes Control* 1993;4:465—76.
48. Guénel P, Raskmark P, Bach Andersen J, Lynge E. Incidence of cancer in persons with occupational exposure to electromagnetic fields in Denmark. *Br J Ind Med* 1993;50:758—64.
49. Sahl JD, Kelsh MA, Greenland S. Cohort and nested case-control studies of hematopoietic cancers and brain cancer among electric utility workers. *Epidemiology* 1993;4:104—14.
50. Demers PA, Thomas DB, Rosenblatt KA, Jimenez LM, McTiernan A, Stalsberg H. Occupational exposure to electromagnetic fields and breast cancer in men. *Am J Epidemiol* 1991;134:340—7.
51. Matanoski GM, Breyse PN, Elliott E. Electromagnetic field exposure and male breast cancer. *Lancet* 1991;337:737.
52. Floderus B, Törnqvist S, Stenlund C. Tumors of the

- pituitary gland and some other types of cancer in Swedish railway workers, 1961—79. *Cancer Causes Control*. In press.
53. Loomis DP, Savitz DA. Case-control study of breast cancer mortality among female electrical workers. In: Project abstracts from the annual review of research on biological effects of electric and magnetic fields from the generation, delivery & use of electricity, Savannah, Georgia, October 31—November 4, 1993. US Department of Energy and US Electrical Power Research Institute, 1993:115.
54. Anderson LE. Biological effects of extremely low-frequency electromagnetic fields: in vivo studies. *Am Ind Assoc J* 1993;54:186—96.
55. Repacholi MH. Laboratory studies on cancer and 50/60 Hz field exposure. In: *Electric and magnetic fields and health: proceedings from 1992 CIGRÉ Session*, Paris, 30 August—5 September, 1992; panel 2, paper 3. Paris: International Conference on Large High Voltage Electric Systems, 1992.
56. McLean JRN, Stuchly MA, Mitchel REJ, Wilkinson D, Yang H, Goddard M, et al. Cancer promotion in the mouse skin model by a 60 Hz magnetic field: II. tumor development and immune response. *Bioelectromagnetics* 1991;12:237—87.
57. Stuchly MA, McLean JRN, Burnett R, Goddard M, Lecuyer DW, Mitchel REJ. Modification of tumor promotion in the mouse skin by exposure to an alternating magnetic field. *Cancer Lett* 1992;65:1—7.
58. Rannug A, Ekström T, Hansson Mild K, Holmberg B, Gimenez-Conti I, Slaga TJ. A study on skin tumour formation in mice with 50 Hz magnetic field exposure. *Carcinogenesis* 1993;14:573—8.
59. Holmberg B, Rannug A, Ekström T, Hansson Mild K, Gimenez-Conti I, Slaga TJ. Intermittent 50 Hz magnetic field and skin tumour promotion in senescent mice. In: Project abstracts from the annual review of research on biological effects of electric and magnetic fields from the generation, delivery & use of electricity, Savannah, Georgia, October 31—November 4, 1993. US Department of Energy and US Electrical Power Research Institute, 1993:102.
60. Cleary SF. A review of in vitro studies: low-frequency electromagnetic fields. *Am Ind Hyg Assoc J* 1993;54:178—85.
61. Saunders RD, Sienkiewicz ZJ, Kowalczyk CI. Biological effects of electromagnetic fields and radiation. *J Radiol Prot* 1991;11:27—42.
62. Reiter RJ, Poeggeler B, Tan D-X, Chen L-D. Melatonin suppression by magnetic fields and the relation to cancer: a theoretical hypothesis to explain the interactions. In: Project abstracts from the annual review of research on biological effects of electric and magnetic fields from the generation, delivery & use of electricity, Savannah, Georgia, October 31—November 4, 1993. US Department of Energy and US Electrical Power Research Institute, 1993:99—100.
63. Graham C, Cook MR, Cohen HD, Riffle DW, Hoffman SJ, McClernon FJ, et al. EMF suppression of nocturnal melatonin in human volunteers. In: Project abstracts from the annual review of research on biological effects of electric and magnetic fields from the generation, delivery & use of electricity, Savannah, Georgia, October 31—November 4, 1993. US Department of Energy and US Electrical Power Research Institute, 1993:98—9.
64. Nordström S, Birke E, Gustafsson L. Reproductive hazards among workers at high-voltage substations. *Bioelectromagnetics* 1983;4:91—101.
65. Nordenson I, Hansson Mild K, Nordström S, Sweins A, Birke E. Clastogenic effects in human lymphocytes of power frequency electric fields: in vivo and in vitro studies. *Radiat Environ Biophys* 1984;23:191—201.
66. Nordenson I, Hansson Mild K, Östman U, Ljungberg H. Chromosomal effects in lymphocytes of 400-kV substation workers. *Radiat Environ Biophys* 1988;27:39—47.
67. Skyberg K, Hansteen I-L, Vistnes AI. Chromosome aberrations in lymphocytes of high-voltage laboratory cable splicers exposed to electromagnetic fields. *Scand J Work Environ Health* 1993;19:29—34.
68. Bauchinger M, Hauf R, Schmid E, Dresch J. Analysis of structural chromosome changes and SCE after occupational long-term exposure to electric and magnetic fields from 380 kV-systems. *Radiat Environ Biophys* 1981;19:235—8.
69. Wertheimer N, Leeper E. Possible effects of electric blankets and heated waterbeds on fetal development. *Bioelectromagnetics* 1986;7:13—22.
70. Wertheimer N, Leeper E. Fetal loss associated with two seasonal sources of electromagnetic field exposure. *Am J Epidemiol* 1989;129:220—4.
71. Yong QE, Chiang H, Chen K, Yoo GD, Fu YD. Case-control study of spontaneous abortions and electric blanket usage during pregnancy. In: Abstract book from the first world congress for electricity and magnetism in biology and medicine, Bioelectromagnetics Society, Orlando, 1992. US Department of Energy and US Electrical Power Research Institute, 1992:75.
72. Dlugosz L, Vena J, Byers T, Sever L, Bracken MB, Marshall E. Congenital defects and electric bed heating in New York State: a register based case-control study. *Am J Epidemiol* 1992;135:1000—11.
73. Milunsky A, Ulicickas M, Rothman KJ, Willett W, Jick SS, Jick H, et al. Maternal heat exposure and neural tube defects. *J Am Med Assoc* 1992;268:882—5.
74. Lee GM, Yost MG, Neutra RR, Hristova L, Leonard A. Exposure assessment of electric bed heaters. In: Project abstracts from the annual review of research on biological effects of electric and magnetic fields from the generation, delivery & use of electricity, Savannah, Georgia, October 31—November 4, 1993. US Department of Energy and US Electrical Power Research Institute, 1993:109—10.
75. Juutilainen J, Matilainen P, Saarikoski S, Läärä E, Suonio S. Early pregnancy loss and exposure to 50-Hz magnetic fields. *Bioelectromagnetics* 1993;14:229—36.
76. Robert E. Birth defects and high voltage power lines: an exploratory study based on registry data. *Reprod Toxicol* 1993;7:283—7.
77. Savitz DA, John EM, Kleckner RC. Magnetic field exposure from electric appliances and childhood cancer. *Am J Epidemiol* 1990;131:763—73.
78. Johnson CC, Spitz MR. Childhood nervous system tumours: an assessment of risk associated with paternal occupations involving use, repair or manufacture of electric and electronic equipment. *Int J Epidemiol* 1989;18:756—62.
79. Wilkins JR, Koutras RA. Paternal occupation and brain cancer in offspring: a mortality based case-control study. *Am J Ind Med* 1988;14:299—318.
80. Nasca PC, Baptiste MS, MacCubbin PA, Metzger BB, Carlton K, Greenwald P, et al. An epidemiological case-control study of central nervous system tumors in children and parental occupational exposure. *Am J Epidemiol* 1988;128:1256—65.
81. Spitz MR, Johnson CC. Neuroblastoma and paternal occupation. *Am J Epidemiol* 1985;121:924—9.
82. Bunin GR, Ward E, Kramer S, Rhee CA, Meadows AT. Neuroblastoma and parental occupation. *Am J Epidemiol* 1990;131:776—80.
83. Wilkins JR, Hundley VD. Paternal occupational exposure to electromagnetic fields and neuroblastoma in offspring. *Am J Epidemiol* 1990;131:995—1006.
84. Chernoff N, Rogers JM, Kavet R. A review of the

- literature on potential reproductive and development toxicity of electric and magnetic fields. *Toxicology* 1992;74: 91—126.
85. McCann J, Dietrich F, Rafferty C, Martin AO. A critical review of the genotoxic potential of electric and magnetic fields. *Mutat Res* 1993;297:61—95.
86. Kurppa K, Holmberg PC, Rantala K, Nurminen T, Saxén L. Birth defects and exposure to video display terminals during pregnancy: a Finnish case-referent study. *Scand J Work Environ Health* 1985;11:353—6.
87. Ericson A, Källén B. An epidemiological study of work with video screens and pregnancy outcomes: II. a case-control study. *Am J Ind Med* 1986;9:459—75.
88. Butler WJ, Brix KA. Video display terminal work and pregnancy outcome in Michigan clerical workers. In: Pearce BG, editor. *Allegations of reproductive hazards from VDUs*. Nottingham: Humane Technology, 1986:31—52.
89. McDonald AD, McDonald JC, Armstrong B, Cherry N, Nolin AD, Robert D. Work with visual display units in pregnancy. *Br J Ind Med* 1988;45:509—15.
90. Goldhaber MK, Polen MR, Hiatt RA. The risk of miscarriage and birth defects among women who use visual display terminals during pregnancy. *Am J Ind Med* 1988;13:695—706.
91. Bryant HE, Love EJ. Video display terminal use and spontaneous abortion risk. *Int J Epidemiol* 1989;19: 132—8.
92. Brandt L, Nielsen CV. Congenital malformations among children of women working with video display terminals. *Scand J Work Environ Health* 1990; 16:329—33.
93. Nielsen CV, Brandt L. Spontaneous abortion among women using video display terminals. *Scand J Work Environ Health* 1990;16:323—8.
94. Windham GC, Fenster L, Swan SH, Neutra RR. Use of video display terminals during pregnancy and the risk of spontaneous abortion, low birthweight, or intrauterine growth retardation. *Am J Ind Med* 1990;18: 675—88.
95. Tikkanen J, Heinonen OP, Kurppa K, Rantala K. Cardiovascular malformations and maternal exposure to video display terminals during pregnancy. *Eur J Epidemiol* 1990;6:61—66.
96. Schnorr TM, Grajewski BA, Hornung RW, Thun MJ, Egeland GM, Murray WE, et al. Video display terminals and the risk of spontaneous abortion. *N Engl J Med* 1991;324:727—33.
97. Bramwell RA. Prospective study of the impact of VDU work on women's reproductive health. In: Luczak H, Cakir A, Cakir G, editors. *Work with display units 92: proceedings from the international scientific conference on work with display units*, September 1992, Berlin. Berlin, 1992:A—23.
98. Lindbohm M-L, Hietanen M, Kyyrönen P, Sallmén M, von Nandelstadh P, Taskinen H, et al. Magnetic fields of video display terminals and spontaneous abortion. *Am J Epidemiol* 1992;136:1041—51.
99. Roman E, Beral V, Pelerin M, Hermon C. Spontaneous abortion and work with visual display units. *Br J Ind Med* 1992;49:507—12.
100. Bergqvist U. Pregnancy outcome and VDU work — a review. In: Luczak H, Cakir A, Cakir G, editors. *Work with display units 92: selected proceedings of the third international scientific conference on work with display units*, Berlin, September 1992. Elsevier Science Publishers BV, 1993:70—6.
101. Bergqvist U, Knave B. Is the outcome of a woman's pregnancy influenced by her work at a VDU? In: Smith MJ, Salvendy G, editors. *Human-computer interaction: applications and case studies: proceedings of the fifth international conference on human-computer interaction*, Orlando, August 1993. Amsterdam: Elsevier, 1993:740—4.
102. Delgado JMR, Leal L, Monteagudo JL, Garcia MG. Embryological changes induced by weak, extremely low frequency electromagnetic fields. *J Anat* 1982;134:533—51.
103. Berman E, Chacom L, House D, Koch BA, Leal J, Løvstrup S, et al. Development of chicken embryos in a pulsed magnetic field. *Bioelectromagnetics* 1990;11:169—87.
104. Handcock MS, Kolassa J E. Statistical review of the henhouse experiments: the effects of a pulsed magnetic field on chick embryos. *Bioelectromagnetics* 1992;13:429—33.
105. Zecca L, Ferrario P, Dal Conte G. Toxicological and teratological studies in rats after exposure to pulsed magnetic fields. *Bioelectrochem Bioenerg* 1985;14: 63—9.
106. Rivas L, Rius C, Tello I, Oroza MA. Effects of chronic exposure to weak electromagnetic fields in mice. *IRCS Med Sci* 1985;13:661—2.
107. Tribukait B, Cekan E, Paulsson LE. Effects of pulsed magnetic fields on embryonic development in mice. In: Knave B, Widebäck P-G, editors. *Work with display units 86: selected papers from the international scientific conference on work with display units*, May 1986 Stockholm. Amsterdam: Elsevier, 1987:129—34.
108. Rommereim DN, Rommereim RL, Buschbom RL, Anderson L. Developmental toxicity study in rats exposed to 60 Hz horizontal magnetic fields. In: *Project abstracts from the bioelectromagnetics society 12th annual meeting*, San Antonio, June 1990. US Department of Energy and US Electrical Power Research Institute 1990:20—1.
109. McGivern RF, Sokol RZ, Adey WR. Prenatal exposure to a low-frequency electromagnetic field demasculinizes adult scent marking behavior and increases accessory sex organ weights in rats. *Teratology* 1990;41:1—8.
110. Salzinger K, Freimark S, McCullough M, Phillips D, Birenbaum L. Altered operant behavior of adult rats after perinatal exposure to a 60-Hz electromagnetic field. *Bioelectromagnetics* 1990;11:105—16.
111. Kowalczyk CI, Sienkiewicz ZJ, Robbins L, Butland BK, Haylock RGE, Thomas JM, et al. Teratological effects of exposure to 20 mT, 50 Hz magnetic fields in CD1 mice. Chilton, Didcot, Oxon: National Radiological Protection Board, 1992:R253.
112. Frölén H, Svedenstål B-M, Paulsson L-E. Effects of pulsed magnetic fields on the developing mouse embryo. *Bioelectromagnetics* 1993;14:197—204.
113. Huuskonen H, Juutilainen J, Komulainen H. Effects of low-frequency magnetic fields on fetal development in rats. *Bioelectromagnetics* 1993;14:205—13.
114. Stuchly MA, Ruddick J, Villeneuve D, Robinson K, Reed B, Lecuyer DW, et al. Teratological assessment of exposure to time-varying magnetic fields. *Teratology* 1988;38:461—6.
115. Wiley MJ, Corey P, Kavet R, Charry J, Harvey S, Walsh M, et al. The effects of continuous exposure to 20-kHz sawtooth magnetic fields on the litters of CD-1 mice. *Teratology* 1992;46:391—8.
116. Juutilainen J. Effects of low-frequency magnetic fields on embryonic development and pregnancy. *Scand J Work Environ Health* 1991;17:149—58.
117. Knave BG, Wibom RI, Voss M, Hedström LD, Bergqvist UOV. Work with video display terminals among office employees: I. subjective symptoms and discomfort. *Scand J Work Environ Health* 1985;11: 457—66.
118. Lidén C, Wahlberg JE. Work with video display terminals among office employees: V. dermatological factors. *Scand J Work Environ Health* 1985;11:489—93.
119. Berg M, Lidén S, Axelsson O. Facial skin complaints

- and work at visual display units: an epidemiological study of office employees. *J Am Acad Dermatol* 1990;22:621—5.
120. Sandström M, Hansson Mild K, Lönnberg G, Stenberg B, Wall S. Inomhusmiljö och hälsa bland Kontorsarbetare: västerbotten: elektriska och magnetiska fält: en fall-referent-studie bland bildskärmsarbetare [The office illness project in northern Sweden: electric and magnetic fields: a case referent study among VDT workers]. Umeå (Sweden): National Institute of Occupational Health, 1991. Undersökningsrapport 1991:12.
121. Bergqvist U, Wahlberg JE. Skin symptoms and disease during work with visual display terminals. *Contact Dermatitis*. In press.
122. Rea WR, Pan Y, Fényves EJ, Sujisawa I, Suyama H, Samadi N, et al. Electromagnetic field sensitivity. *J Bioelectricity* 1991;10:241—56.
123. Sandström M, Stenberg B, Hansson Mild K. Provocation tests with ELF and VLF electromagnetic fields on patients with skin problems associated with VDT work. In: Berlinguet L, Berthelette D, editors. Book of abstracts from the 2nd work with display conference, Montreal, September 1989. Montreal, 1989:117.
124. Franzén O, Paulsson L-E, Wennberg A. Human exposure to electric and magnetic fields: an experimental detection study. In: Luczak H, Cakir A, Cakir C, editors. Work with display units 92: proceedings from the international scientific conference on work with display units; September 1992, Berlin. Berlin, 1992: A-20.
125. Hamnerius Y, Agrup G, Galt S, Nilsson R, Sandblom J, Lindgren R. Provocation study of hypersensitivity reactions associated with exposure to electromagnetic fields from VDUs. In: Luczak H, Cakir A, editors. Work with display units 92: proceedings from the international scientific conference on work with display units; September 1992, Berlin. Berlin, 1992: A-17.
126. Arnetz B, Berg M, Lidén S. Psychophysiological aspects of "electric hypersensitivity". In: Luczak H, Cakir A, Cakir G, editors. Work with display units 92: proceedings from the international scientific conference on work with display units; September 1992, Berlin. Berlin, 1992: A-19.
127. Berg M, Arnetz B, Lidén S, Eneroth P. Techno-stress: a psychophysiological study of employees with VDU-associated skin complaints. *J Occup Med* 1992;34: 698—701.
128. Cook MR, Graham C, Cohen HD, Gerkovich MM. A replication study of human exposure to 60-Hz fields: effects on neurobehavioral measures. *Bioelectromagnetics* 1992;13:261—85.
129. Korpinen L, Partanen J, Uusitalo A. Influence of 50 Hz electric and magnetic fields on the human heart. *Bioelectromagnetics* 1993;14:329—40.
130. Bell GB, Marino AA, Chesson AL, Struve FA. Human sensitivity to weak magnetic fields. *Lancet* 1991; 338:1521—2.
131. Poole C, Kavet R, Funch DP, Donelan K, Charry JM, Dreyer NA. Depressive symptoms and headaches in relation to proximity to an alternating-current transmission line right-of-way. *Am J Epidemiol* 1993;137:318—30.
132. Haysom C, Dowson D, Campbell MJ. The relevance of headaches and migraine in populations resident near overhead power lines — an epidemiological study. *Comp Med Res* 1990;4:12—5.
133. International Non-Ionizing Radiation Committee (INIRC) of the International Radiation Protection Association (IRPA). Interim guidelines on limits of exposure to 50/60 Hz electric and magnetic fields. *Health Phys* 1990;58:113—22.
134. International Commission on Non-Ionizing Radiation Protection (ICNIRP). Interim guidelines on limits of exposure to 50/60 Hz electric and magnetic fields. *Health Phys*. In press.
135. National Radiation Protection Board (NRPB). Board statement on restrictions on human exposure to static and time varying electromagnetic fields and radiation. Chilton, Didcot, Oxon: NRPB, 1993:1—69. Documents of the NRPB, vol 4, no 5.
136. Nair I, Morgan MG, Florig HK. Biological effects of power frequency electric and magnetic fields. Washington DC: US Government Printing Office, 1989. OTA BP-E-53.