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MINI REVIEW

Can disturbances in the atmospheric electric field created by powerline corona ions disrupt melatonin production in the pineal gland?

Abstract: Recent epidemiological studies have reported an increased risk of leukemia in adults and children near overhead high voltage powerlines at distances beyond the measured range of the direct electric and magnetic fields. Corona ions are emitted by powerlines, forming a plume that is carried away from the line by the wind. The plume generates highly variable disturbances in the atmospheric electric field of tens to a few hundred V/m on time scales from seconds to minutes. Such disturbances can be seen up to several hundred meters from powerlines. It is hypothesized that these random disturbances result in the disruption of nocturnal melatonin synthesis and related circadian rhythms, in turn leading to increased risk of a number of adverse health effects including leukemia. In support of the hypothesis, it is noted that melatonin is highly protective of oxidative damage to the human hemopoietic system. A review of electric field studies provides evidence that (i) diurnal variation in the natural atmospheric electric field may itself act as a weak Zeitgeber; (ii) melatonin disruption by electric fields occurs in rats; (iii) in humans, disturbances in circadian rhythms have been observed with artificial fields as low at 2.5 V/m. Specific suggestions are made to test the aspects of the hypothesis.

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Introduction

It was previously hypothesized that corona ion emission from high voltage powerlines results in increased human exposure to particulate air pollution, in turn leading to an increased risk of health effects including childhood leukemia [1]. The proposed mechanism results from the attachment of corona ions to aerosol-sized air pollution particles, increasing the electric charge on these particles, and on inhalation increasing their probability of being deposited in the lung. A feature of corona ions and the subsequent charged pollutants is that they can be carried considerable distances from powerlines by the wind. The hypothesis has gained some support in the observation of increased risk of leukemia and related illnesses associated with proximity to high voltage powerlines, beyond the range of the direct 50/60 Hz electric and magnetic fields (EMFs) [2, 3].

There are, however, additional mechanisms by which corona ions might affect human health, for example via the disturbances they create in the atmospheric electric field (EF). In this paper we develop the hypothesis that rapid, random disturbances in atmospheric EFs created by corona ions distant from the direct power frequency EMFs disrupt the production of nocturnal pineal melatonin and/or the circadian rhythm generally, which in turn may lead to increased risk of a number of illnesses, including leukemia.

The original 'melatonin hypothesis' postulated that increasing exposure to light-at-night and to power frequency magnetic fields (MFs) may act to suppress or otherwise disrupt the nocturnal production of pineal melatonin, leading to increased risk of breast cancer [4]. The hypothesis has recently been updated to include an emerging area of interest to the circadian and cancer research community in relation to circadian genes and how these might modulate cancer risk [5]. In relation to light-at-night and circadian disruption in general, the hypothesis has support in studies reporting increased breast cancer risk in night-shift workers and aircraft cabin crew [6–10], decreased breast cancer incidence in the blind and partially sighted [11–14] and decreased melatonin production in women who contract breast cancer [15]. It also has mechanistic support in which the normal nocturnal physiological concentrations of melatonin in women's blood have been shown to suppress the growth of human breast tumors in rats [16]. However, support for the hypothesis in relation to MFs and breast cancer remains equivocal. While meta-analysis of epidemiological studies suggests a small increase in risk [17], the results of a large study in Sweden [18] has led to a debate concerning the detectability of an effect of MFs on breast cancer in view of possible confounding by light-at-night [19, 20].

On the other hand, there is some evidence of melatonin disruption in controlled nonacute MF exposures and in populations exposed to the neighborhood admixture of EMFs [21, 22]. This is of interest because melatonin disruption may be a common risk factor in the otherwise disparate health effects purportedly linked to EMF exposures, ranging from specific cancers and neurodegenerative disorders to depression, suicide and miscarriage [23].

In extending the melatonin hypothesis to fluctuating atmospheric EFs, we first describe the basic features of the natural atmospheric fields and of corona ion emission from powerlines. We then discuss the evidence that time-varying EFs disrupt melatonin.

Atmospheric electric fields and corona ions

As a result of global thunderstorm activity, there exists in the atmosphere a natural DC EF, which is created by a layer of positive electric charge in the ionosphere mirrored by opposite negative charge across the surface of the Earth [24–26]. By definition an EF is created as a result of a gradient in electrical potential between two points. There exists an ambiguity of sign for the atmospheric EF, but convention has led to the fair weather field (ground negative compared to the electrosphere) to be described as positive, where more accurately it can be described as negative. Often, the term potential gradient is used which has no ambiguity of sign and is positive in fair weather conditions.

The magnitude of the EF undergoes a global diurnal variation. In terms of Universal Time (UT), the EF has a minimum around 3–6 UT and a maximum around 18–20 UT, amounting to an approximate $\pm 20\%$ excursion around the mean value. In typical fair weather conditions, this atmospheric EF measured at ground level displays a smooth diurnal variation, with typical average value around 150 V/m. Locally, changes in wind direction and precipitation can induce EF changes of a few tens of V/m over a few minutes, brought about by redistributing atmospheric aerosols some of which are naturally charged [27]. Passing thunderstorms can produce sudden changes of a few kV/m due to electric charges on the base of clouds. Some studies have reported health effects, in particular asthma attacks, associated with thunderstorms, although these have not been specifically attributed to changes in atmospheric EFs [28–31] (Table 1).

The behavior of corona ions in the atmosphere is well understood. High voltage powerlines, also known as transmission lines, can and frequently do ionise the air, splitting it up into electrons and molecular ions of oxygen and nitrogen. Within 100 nanoseconds, these bare ions attract a cluster of molecules, mainly water, resulting in so-called small ions around 1 nm in size. Close to the powerline, efficient charge separation takes place leading to a unipolar excess of an otherwise bi-polar cloud of positive and negative ions carried away by the wind. On a time scale of 10–100 s, the small ions attach to particles of air pollution and in doing so increase the charge state on those pollution particles. The result of this process is a plume of atmospheric *space charge*, comprising small ions and charged aerosols in air. The excess unipolar nature of the plume is such that dispersion and charge neutralization in the atmosphere can take over an hour to occur during which time the plume can be carried hundreds of meters, or even several kilometers from the powerline [32–34]. In the size range of current interest for particulate air pollution, from a few tens to a few hundred nanometers, only a proportion of inhaled particles are deposited in the lung, the remainder are simply exhaled again [35]. Electrical charging of aerosols by corona ion attachment facilitates increased lung deposition by electrostatic effects [36, 37]. Thereafter, such inhaled pollutants will pass from the lung into the blood stream, eventually reaching all body organs. It might, therefore, be expected that illnesses already linked to air pollution, including childhood leukemia [38–40], might be more prevalent in populations living near powerlines [1].

The largest ever study of childhood leukemia in relation to proximity to overhead high voltage powerlines was carried out in England and Wales using birth addresses from the Oxford registry of cases occurring in the period 1963–1995 [2]. This study found a 1.69-fold increased risk (95% CI = 1.13–2.53) within 200 m of National Grid 400 and 275 kV powerlines compared with >600 m away. The observation concurs with pooled analyses of previous international studies showing an approximate doubling of risk of childhood leukemia for average MF exposures above 0.3/0.4 μT [41, 42]. However, the Oxford study also found increased risk in the interval 200–600 m from powerlines: OR = 1.23 (95% CI = 1.02–1.49). While this latter finding is well beyond the range of the power frequency EMFs from powerlines ($\leq$ 200 m), it is within range of corona ion effects. No other mechanistic explanation for these findings has been proposed.

More recently, a study of adult lympho- and myeloproliferative disorders in Tasmania has reported increased risk in those living up to 300 m from powerlines compared with those who never lived near a powerline: 0–50 m: OR = 2.06 (0.87–4.91); 50–300 m: OR = 1.3 (0.88–1.91) [3]. The associations were increased for those having spent the first 15 yr of life living within 300 m of powerlines, OR = 3.23 (1.26–8.29), with a further increase in those who had spent the first 5 yr of life living within 300 m, OR = 4.74 (0.98–22.9).

Another feature of powerline corona ion emission is its ability to affect changes in atmospheric EFs [34, 43]. In one example, the disturbance of the natural atmospheric DC EF near a 400 kV powerline was measured using a set of DC-field mill meters mounted 1 m above the ground. Six meters were placed at 108, 377, and 780 m upwind and downwind of the powerline under crosswind conditions, from which the atmospheric DC EF was logged simultaneously over a period of 1 hr [44] (Fig. 1). The three traces upwind show a relatively steady field $\sim$200 V/m, typical of fair weather conditions. In contrast, the downwind traces have higher mean values, around 800–1000 V/m, but are highly erratic reflecting a plume of excess positive space charge. While the detailed structure varies between traces, the striking features are the similar time variations in DC-field even at 780 m from the powerline.

In another example, measurements were taken over a 24-hr period 175 m from a 400 kV powerline (Fig. 2). The

Table 1. Study findings

Field value (kV/m)	Exposure (sine wave unless otherwise stated)	Reference	Investigation	Effects
Zero	Faraday cage environment Several weeks	[45] (pp. 94–100)	Human circadian rhythm with no external zeitgebers[a]	Statistically significant lengthening in circadian rhythm and occurrence of internal desynchronization
0.0025	10 Hz square wave, continuous. Several weeks	[45] (pp 100–114)	Circadian rhythms of human subjects in isolated test facilities[a]	Shortening of circadian rhythm
0.0025	10 Hz square wave, 12 hr on 12 hr off. Then 11.45 on, 11.45 off. Several weeks	[45] (pp. 156–159)	Circadian rhythms of human subjects in isolated test facilities[a]	Humans immediately entrained to the external signal. Effect lasted for a few days, indicating E-fields acting as zeitgebers
0.3	DC, continuous Several weeks	[45] (pp. 100–114)	Circadian rhythms of human subject in isolated test facilities[a]	No effect on circadian rhythms
Atmospheric disturbances of a few kV/m	Fluctuating DC[b]	[28]	Asthma cases in hospital and environmental conditions	Nonepidemic asthma strongly associated with thunderstorm activity, but also with increase in humidity, sulfur dioxide concentration, drop in temperature and rainfall
Atmospheric disturbances of a few kV/m	Fluctuating DC[b]	[29]	Number of patients admitted to hospital after a thunderstorm	604 admissions to hospital compared to an expected value of 66
Atmospheric disturbances of a few kV/m	Fluctuating DC[b]	[30]	Weekly mortality of patients in hospital assessed during thunderstorms	Weekly mortality considerably higher on days with thunderstorm activity. Findings were not directly attributed to electric fields
Atmospheric disturbances of a few kV/m	Fluctuating DC[b]	[31]	Asthma epidemics and association with pollution	Epidemic of asthma after a thunderstorm, also near high pollen count
1.7–1.9	60 Hz, 30 days at 20 hr per day	[46, 47]	Assayed 20 exposed and 20 sham male Sprague-Dawley-derived rats for pineal NAT and melatonin	Significant fourfold reduction in pineal melatonin ratio to internal standard ($P < 0.05$)
65 (applied) 39 (effective)	60 Hz, 20 hr per day, 3 wk	[48]	Assayed groups of 10 exposed and 10 sham male Sprague-Dawley rats for pineal NAT and melatonin	Onset of reduction in nighttime pineal melatonin begins after 3 wk. 50% reduction observed
10, 65, 130	60 Hz, 19 hr per day, 23 days	[49]	Assayed groups of male and female rats for pineal melatonin at various times in the day	55, 53 and 65% reduction in pineal melatonin at 10, 65 and 130 kV/m respectively when assayed at 02:00 hour ($P < 0.001$), phase shift in production
65 (applied)	60 Hz, 20 hr per day, 30 days. Experiment repeated four times	[50]	Assayed 12 exposed and 12 sham Sprague-Dawley male rats for pineal melatonin and NAT and serum melatonin	Each experimental run produced 38, 16, 20 and 4.8% reduction in serum melatonin at night in four different tests, but not pineal melatonin $P < 0.10$
65 (applied) 39 (effective)	60 Hz, 20 hr per day, 30 days	[51]	Assayed 23 male and 23 female rats for pineal melatonin	Increase in nighttime pineal melatonin 7 hr into dark period in female but not in male rats
39 (effective)	60-Hz, 20 hr a day, 28 days	[52]	Assayed 36 exposed and 36 sham rats for biogenic amines including norepinephrine, dopamine, serotonin and their metabolites	Repeated exposure produced significant alterations in diurnal rhythms of several biogenic-amines in the striatum and the hypothalamus, but not the hippocampus. Levels of serotonin in the striatum and hypothalamus were unaffected

[a]All experiments by this author involved a number of subjects and repeat experiments and results were statistically significant; [b]Confounds include pressure changes, temperature changes and increase in sulfur dioxide concentrations.

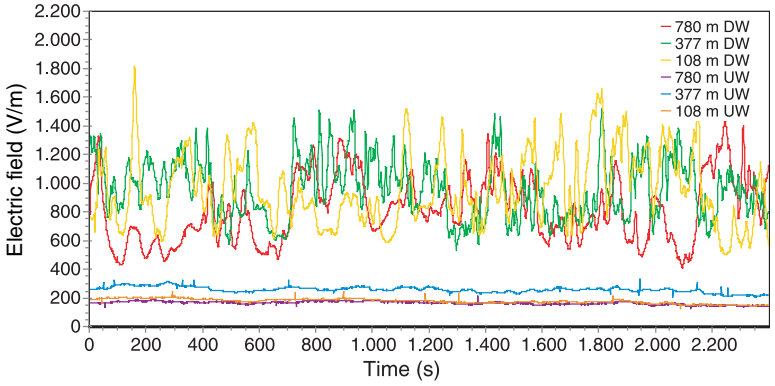


Fig. 1. Ground level time variation in atmospheric electric field at various distances upwind (UW) and downwind (DW) of a 400 kV powerline.

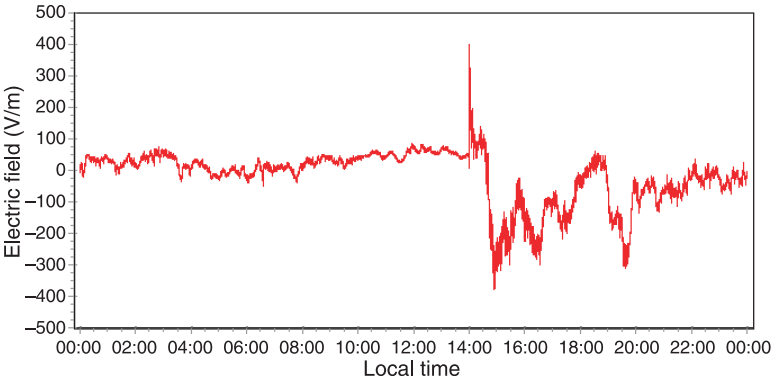


Fig. 2. Ground level 24 hr time variation in atmospheric electric field 175 m from a 400 kV powerline in variable wind conditions.

trace is initially stable over several hours while the wind direction was such that the measuring instrument was upwind of the powerline. At around 14:00 hr local time a change in wind direction results in sudden changes in EF from +410 to −340 V/m over a 1-hr period, followed by sets of further changes of lower magnitude.

In general, at distances up to several hundred meters from powerlines, fluctuations in atmospheric EFs are common. Depending on timescale and wind direction, typical rates of change can reach 100 V/m/s, with bursts of change occurring over a period of a few hours. As the human body is a good conductor compared to the air, these unperturbed field levels are magnified around the body and a 1.8 m tall man with a head radius of 10 cm would experience a field enhancement of 18 around the head. For such perturbed fields, our data indicate that some powerlines produce values up to 18 kV/m, with rates of change up to ~2 kV/m/s and ~15 kV/m over a few hour period. Such then are the chronic outdoor exposures experienced by populations living within a few hundred meters of high voltage powerlines.

Electric fields and physiological interactions

Studies of the effects of EFs with respect to a number of endpoints have been carried out in both humans and animals over a wide exposure range. Here, particular attention is drawn to those concerning circadian rhythm or melatonin disruption, as well as reported health effects associated with atmospheric disturbances [Table 1].

Experiments extending over several weeks duration in which human volunteers were housed in a room shielded from all external EFs, resulted in a statistically significant lengthening of the circadian rhythm and the occurrence of internal desynchronization [45]. In the same exposure facility, subjects exposed to a continuous 2.5 V/m 10 Hz square-wave field showed a shortening of their circadian rhythm. When the same fields were applied in a 12 hr on 12 hr off mode, the subjects became entrained to the signal, indicating that these E-fields were acting as zeitgebers.

Effects of melatonin disruption and alterations in diurnal rhythms have been reported in rats but mostly with power frequency fields in the tens of kV/m range [46–52]. While reduction in nocturnal pineal melatonin was observed in some studies [46–49], one study reported reduction in serum but not pineal melatonin [50], while another reported increased pineal melatonin 7 hr into the dark phase in female but not in male rats [51]. In a study investigating biogenic amines in Sprague-Dawley rats [52], repeated exposure produced significant alterations in diurnal rhythms of dihydroxyphenylacetic acid and insignificant changes of dopamine and homovanillic acid in the striatum. Serotonin rhythms were unaffected. In the hypothalamus, fields at specific times of the day caused a significant difference in the levels of norepinephrine, dopamine and 5-hydroxyindoleacetic acid while serotonin levels were also unaffected. The hippocampus was also tested, but no affects were found.

As mentioned already, there are a number of reports of adverse health effects associated with disturbances in the atmospheric E-field of a few kV/m associated with thunderstorms [28–31]. These have been discussed in the context of modifying pollen count in the atmosphere, rather than changes in the atmospheric EF.

Studies of other endpoints have been carried out using fields which together span some six orders of magnitude, up to 450 kV/m [53–67]. Interpretation of these studies is complicated by the fact that once field levels exceed ~4 kV/m, evidence suggests that they are likely to be perceived directly [68]. Responses including changes in reaction time, metabolism and body weight, increased enzyme activity and avoidance of fields have been reported.

Some studies have investigated childhood leukemia and exposure to time-weighted-average power frequency EFs, but these have been inconclusive and generally characterized by low exposures and odds ratios with wide confidence intervals [69–74]. A major difficulty in power frequency exposure assessment is that EFs are readily perturbed around conducting objects and randomly varying EFs have not been taken into account. There is also confounding with simultaneous exposure to MFs.

Biological response to magnetic fields – differences and similarities to electric fields

This paper is concerned with atmospheric EFs, principally those beyond the range of the direct power frequency EMFs. The physics of low frequency EFs and MFs is different, but to understand possible adverse health effects associated with corona-ion derived atmospheric EFs and their randomly fluctuating nature, can anything be learned from research into biological responses to power frequency MFs?

There is now a body of epidemiological evidence suggesting an association between exposure to power frequency MFs and childhood leukemia [41, 42, 75], that paternal periconceptual exposure also results in increased risk [76] and reduced survival in children with leukemia with continuing exposure [77]. Associations with adult leukemia, adult brain cancer, amyotrophic lateral sclerosis, and miscarriage have also been discussed [23].

In terms of the potential etiology, a purely MF effect is the radical pair mechanism (RPM) [78–80]. Low intensity MFs can increase the rate of transition of pairs of radicals from the singlet to the triplet spin state. Pairs of radicals created in the singlet state are then partly inhibited from recombination and become available for other chemical reactions such as damaging DNA. The RPM is driven by a quantum mechanical interaction of the electron spin of one of the radicals with one of its component atomic nuclei. Support for the RPM in biological systems comes from the observation that MFs can enhance the effects of known carcinogenic, mutagenic or otherwise harmful physical or chemical agents [81]. Interestingly, some experiments report oxidative damage to DNA without the presence of other agents [82, 83]. The observation that MFs induce monocytes from human cord blood to release reactive oxygen intermediates [84] is particularly important for consideration of childhood leukemia risk because these cells would be recruited to sites of inflammation and proliferation where such intermediates could generate genetic aberrations.

To date, experimental support for the RPM is confined to fields in the principal range 50 μT to 4 mT and as such does not address the situation below 1 μT where most adverse health effects are reported. The question also remains as to how an RPM response to power frequency sub-microtesla fields might operate against the background of the Earth's static geomagnetic (GM) field which, depending on latitude, is the range 20–70 μT. However, adverse health effects and melatonin disruption have been associated with small fluctuations in the GM field, principally those up to 0.3 μT in magnitude associated with GM storms [85–92]. Similarly, power frequency MFs contain fluctuations in the form of random switching and transients. It could be that these are the essential driver leading to adverse biological responses.

There is also evidence that for nonacute and chronic exposures, MFs disrupt the nocturnal production of pineal melatonin [21, 22]. There is the intriguing possibility that such disruption is itself mediated by an RPM. Advances in understanding magneto-reception and navigation in animals suggest that in birds compass information in the geomagnetic field is derived from light, utilizing the RPM through wavelength-dependent cryptochrome sensors in the eye [93, 94]. Such cryptochromes are concentrated in specific cells, particularly ganglion cells. A class of ganglion cells with the specific purpose of conveying ambient light levels to the pineal gland to control nocturnal pineal melatonin, have recently been identified [95, 96]. Could it be that MFs disrupt pineal melatonin in humans by interfering with this pathway of light communication via magneto-sensitive cryptochromes utilizing an RPM? Of interest, human light sensitivity depends on the direction of view with respect to the Earth's geomagnetic field [97–99].

Electric field coupling to biological systems must proceed via a different mechanism. It is generally assumed that as the human body is a good conductor, power frequency EFs do not penetrate the body. However, theoretical analysis, taking account that the body contains tissues and organs of differing conductivity suggest that while there is no meaningful penetration for electrical energy, electrical signal information may readily penetrate [100]. It is of course the case that electrical impulses feature in communication in cellular operations and between the brain, muscles and nerves. Static EFs have been shown to enhance the efficacy of chemotherapy [67], where it has been suggested that the fields facilitate ion movement between cells. We could therefore speculate that fluctuating atmospheric EFs are well able to communicate with and disrupt the pineal gland by electrical signaling within the body.

While the *primary* RPM transducer of compass information in birds is magnetic, evidence suggests a neuronal pathway for subsequent communication to the brain [101]. The latter is presumably electrical in nature, with the result that both the MF and EF interactions utilize electrical processes.

Melatonin disruption and childhood leukemia

The possible role of melatonin disruption in affecting childhood leukemia risk in the context of MF exposures has recently been reviewed [21]. Interestingly, melatonin disruption seems most evident in neighborhood exposures, where EFs as well as MFs are present along with switching or random changes in fields.

The potential importance of melatonin suppression to leukemia risk arises from the observation that the indoleamine is highly protective of oxidative damage to the human hemopoietic system. In a volunteer experiment, 300 mg of melatonin was administered to four healthy individuals [102]. Immediately, and 1 and 2 hr later, blood samples were taken and irradiated with 1.5 Gy ^{137}Cs gamma radiation. Compared with blood samples taken immediately, those taken at 2 hr had significantly decreased (50–70%) chromosome aberrations and micronuclei. It was concluded that the observations may have important implications for the protection of human lymphocytes from genetic damage induced by free radical-producing mutagens and carcinogens. Also investigated was the mechanism of melatonin protection in terms of both direct scavenging in the cell nucleus of radiation-induced free radicals, including the hydroxyl radical and action at the cell membrane and in the cytosol to trigger activation of existing DNA repair enzymes and/or activation of a set of genes that lead to de novo protein synthesis associated with DNA repair [103, 104]. Melatonin as well as several of its metabolites are potent free radical scavengers [105–107]. In a further experiment [108], mice were irradiated with 8.15 Gy gamma radiation untreated and pretreated with 125 and 250 mg melatonin. In the untreated mice, 45% was alive after 30 days, but 85% was still alive in those pretreated with 250 mg melatonin.

There is another issue which relates more directly to leukemia and melatonin suppression. A variety of bone marrow cells have been shown to produce melatonin [109–111]. While its specific function in these cells remain unknown, if their levels are depressed by EF exposure, as has been shown to be the case for MFs and pineal melatonin in a variety of studies, it could have clear implications for leukemia. A reduction in melatonin in the leucocytic precursor cells would be expected to enhance free radical-mediated DNA damage, thereby increasing the likelihood of these cells developing tumors. Melatonin was recently reported to reduce human leukemic cell proliferation in vitro [112].

There is compelling evidence that the initiating event(s) in acute lymphoblastic leukemia, the most common form in childhood, take place in utero [113]. It is therefore of interest to note that in animals melatonin has been shown to be highly protective of oxidative damage to the fetus [114–117]. The human fetus does not produce pineal melatonin, rather melatonin in derived from the mother, where there is efficient maternal-fetal transfer near term [118]. In pregnant women, nocturnal serum melatonin levels increase markedly after 24 wk gestation until term, and levels are related to the feto-placental unit [119]. These observations may reflect a role for melatonin in protecting the human fetus against oxidative damage.

Discussion

In response to the reported increased risk of childhood and adult leukemia with proximity to high voltage overhead powerlines beyond the range of the power frequency EMFs [2, 3], and following an existing hypothesis [1], we here suggest that randomly fluctuating atmospheric EFs created by powerline corona ions disrupt circadian rhythms and the production of nocturnal pineal melatonin, which in turn may lead to increased risk of a number of illnesses, including leukemia.

In the studies reviewed above (Table 1), the observation of circadian rhythm extension and occurrence of internal desynchronization in subjects shielded from the natural atmospheric EF, which itself shows a diurnal variation, suggests that this may act as a weak zeitgeber. The observation of shortening of the circadian rhythm and apparent entrainment with 10 Hz fields of magnitude only 2.5 V/m is remarkable. Such values are well below the fluctuations in corona-ion-derived atmospheric fields discussed here. On the other hand, 10 Hz may have significance in being close to natural rhythms of the body and the use of a square wave may facilitate signal transduction in the body. Nevertheless, that apparently low intensity EFs can penetrate the body and convey signaling information in an environment already awash with electrical signals, sets them apart from the primary interaction mechanism of MFs, though not necessarily their consequential interactions.

If corona-ion-induced disturbances in atmospheric EFs disrupt nocturnal pineal melatonin, then the postulated adverse health outcomes should display differences to those suggested by corona-ion charging of pollutant aerosol particles postulated to lead to increased lung deposition of these particles and increased risk of air pollution related illnesses. Suitably designed epidemiological studies could test aspects of both of these hypotheses.

The current hypothesis suggests a number of areas for investigation: (i) illnesses reportedly associated with thunderstorms should be investigated in more detail, (ii) further studies of circadian rhythm and melatonin disruption in humans should be encouraged using non-periodic randomly varying EFs, (iii) studies of melatonin disruption in animals should be carried out at lower EF intensities than currently reported, especially with non-periodic randomly varying fields (the aim should be to use imperceptible fields), and (iv) laboratory experiments should be carried out to test the penetration of EF signals in tissue equivalent human phantoms. Overall, studies of the biological responses to externally applied EFs as opposed to MFs should aid our understanding of the primary mechanisms of EMF interactions with the body.

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