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Effects of Noise and Electromagnetic Fields on Reproductive Outcomes

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Much public health research has been directed to studies of cancer risks due to chemical agents. Recently, increasing attention has been given to adverse reproductive outcomes as another, shorter-term biologic indicator of public health impact. Further, several low-level ubiquitous physical agents have been implicated recently as possibly affecting human health. These physical factors (noise and electromagnetic fields) represent difficult topics for research with epidemiologic study methods. This paper provides a brief review of the published data related to the risk of adverse reproductive outcomes and exposure to noise or electromagnetic fields. The discussion includes ideas for possible biologic mechanisms, considerations for exposure assessment, and suggestions for epidemiologic research.

Introduction

Increasing public concern over environmental health issues has prompted much research on the risk of cancer and birth defects resulting from exposure to chemical agents. In recent years there has been growing interest in the effects on human reproduction of exposure to physical agents encountered in the occupational or residential environment (*1-3*). These agents, which include ionizing and nonionizing radiation, heat stress, noise, and vibration, may arise from a myriad of sources at work or in the home. While the reproductive effects of some physical factors such as x-radiation are generally well characterized, less is known about the biologic activity of other, more commonly encountered agents such as extremely low frequency (ELF) electromagnetic fields and noise (*4-5*). Indeed, much of the present concern over the potential health effects of the latter two agents derives more from the ubiquity of exposure than from empirical evidence relating the exposure to subsequent adverse reproductive outcomes. Efforts to quantify the risk to human populations from exposure to such agents are hindered by inadequate exposure assessment and compromising epidemiologic study designs.

The present report is intended to provide a review of the current literature regarding exposure to noise or ELF fields and a possible increased risk of birth defects. Both agents have been implicated in animal and human studies as having potential adverse effects on reproductive outcomes. Because of these observations and the ubiquitous occurrence of these agents in the environment, both noise and ELF fields present significant potential public health concerns. Special attention is directed to the problem of assessing human exposure and to methods of improving the design of future epidemiologic research aimed at evaluating the health impacts of these and other low-level, ubiquitous agents.

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Noise

Noise can be defined simply as unwanted sound (*6*). Although a common feature in the environment of modern society, noise has only recently gained wide recognition as a significant environmental and occupational health concern. In addition to the more obvious effects on hearing, there has been increasing attention directed to the nonauditory effects of chronic exposure to noise, including the potential for disrupting normal fetal development (*7-10*).

Biologic Mechanisms

Experimental data from animal and human studies have provided a theoretical basis for understanding the teratogenic action of noise in mammalian systems. In the mammal, auditory stimulation evokes responses by the autonomic and reticular nervous systems and the brain (*11*). These neural responses, in turn, may elicit a spectrum of somatic activity, including changes in cardiovascular volume, heart rate, blood pressure, endocrine function, and gastrointestinal motility (*8*). Geber suggested that the teratogenic action of noise is primarily the result

of decreased uteroplacental blood flow resulting in fetal hypoxia and increased secretion of maternal catecholamines (epinephrine and norepinephrine) (*12–13*). The fetotoxic and teratogenic effects of uteroplacental hypoxia and increased levels of maternal catecholamines have been reported previously (*14–20*). Further research is needed to clarify the association between noise exposure and increased catecholamine levels in humans, as well as between increased catecholamine levels and the risk of adverse reproductive outcomes.

Consideration must also be given to the concern that noise may also function as a direct-acting teratogenic agent, independent of the mother's physiologic response to the insult. Several studies have sought to measure intrauterine noise levels and fetal response produced from sound stimulus applied to the mother's abdomen. Neff provides a review of this research (*10*). Increased fetal heart rate and fetal activity have been reported in several of the studies investigating human *in utero* response to external noise (*21–23*). Most studies related to sound attenuation in the uterine environment indicate that, in general, attenuation of external noise increases with increasing frequency of the sound as would be expected by the physics of sound. For example, Walker el al. reported that attenuation values for pure tones applied to the mother's abdomen ranged from 20 dB at 50 Hz to greater than 70 dB at 4000 Hz (*24*). These observations suggest that low frequency noise (such as that associated with many industrial environments) may present a potential risk to pregnant women despite the fact that these noises may not be psychologically annoying to the individual. Additional research will be needed to evaluate this possible health risk.

Toxicologic Studies

A number of animal studies have examined the embryotoxic and teratogenic potential of noise. In a study of pregnant rats exposed to intermittent audiovisual stress in the range of 74 to 94 dB, Geber observed significantly reduced litter size and a significant increase in the number of resorptions per litter among the exposed animals (*12*). The author also reported a significant reduction in mean body weight and an increased frequency of congenital anomalies (including osteogenic defects, cranial hematomas, neural tube defects, and other conditions) among the exposed fetuses.

Arvay (*25*) exposed female rats to a combination of noise, light, and electrical stress. Of the pups from the treated group, 11.4% exhibited congenital anomalies as compared with 0.7% defective among the controls.

Zakem and Alliston exposed mice to 83 to 95 dB of noise intermittently during gestation (*26*). The authors reported increased preimplantation mortality, decreased litter size, and decreased embryo size and weight among the exposed offspring. No significant effect on the number of litter resorptions was observed.

In a study of rats exposed to 100 dB of noise throughout pregnancy, Siegel and Doyle observed an increased magnitude of fluctuating dental asymmetry among the pups of the exposed females (*27*). Similar results were obtained when animals were exposed postnatally to the same noise levels. The authors proposed that these findings suggest that noise may have a direct impact on the developing organism, rather than an effect that is mediated by the mother's physiological response to the stimulus.

Kimmel et al. exposed pregnant mice to 100 dB of noise on days 3 to 6, 7 to 10, or 11 to 14 of gestation (*28*). Significantly increased resorption rates and decreased number of live fetuses per litter were observed in each of the treated groups of animals. No teratogenic effects were observed among the exposed mice. In the same study, pregnant rats were exposed to 100 dB of noise on days 6 to 15 of gestation. No significant adverse effects were observed in the fetuses of the exposed rats.

Nawrot et al. exposed mated female mice to either semicontinuous 126 dB low-frequency noise, intermittent 110 dB midfrequency noise, or semicontinuous, very high frequency (18–20 kHz) 113 dB noise on days 1–6 or 6–15 of gestation (*29*). Significantly increased embryo and fetal mortality, decreased fetal weight, and decreased pregnancy rate were reported among the exposed animals. No significant effect on the rate of congenital anomalies or litter resorptions were apparent among any of the exposed groups.

In a follow-up study, Nawrot et al. exposed mated female mice to high-frequency 110 dB noise on days 6 to 15 of gestation (*30*). Decreased pregnancy rate and mean fetal weight and increased fetal mortality were observed among the exposed animals. As in Nawrot's earlier study, no significant effect on the frequency of fetal malformations or litter resorptions was observed among the mice exposed to noise (*17*).

Cook et al. exposed mated female mice to 112 dB noise during the preimplantation or postimplantation stages of gestation (*31*). Mice exposed prior to implantation displayed significantly decreased fetal weight on day 18 of gestation. Fetuses of mice exposed postimplantation displayed significantly reduced weight and a significantly increased frequency of malformations on day 18 of gestation. Entire litter resorption was also significantly increased in the group exposed postimplantation.

Much of the animal data related to the embryotoxic or teratogenic effects of noise exposure have supported the existence of an exposure effect. The most frequently reported effects include intrauterine growth retardation, fetal mortality, increased litter resorptions, and teratogenesis. Overall, however, the data are quite inconsistent among the various experimental conditions. Research aimed at evaluating possible teratogenic effects has yielded the weakest evidence, with many authors reporting no significant effects (*28–30,32*). These inconsistent results may be attributed, in part, to differences in the acoustical stimulus (e.g., frequency, sound pressure level), exposure regimen, test species, and other variables. Further, factors such as small body size, novel startle responses, hearing threshold characteristics, and other biological attributes of laboratory test animals raise

doubt regarding the suitability of these species as models for predicting human response to noise (*10*).

Human Studies

Exposure Assessment. Noise presents a particular problem for epidemiologic exposure assessment because of the psychological response factor, that is, the perception of noise versus sound. The effect of the same noise level on any two individuals can be markedly different depending upon how each person interprets and responds to the signal, the degree to which the subject may be acclimated to the noise, and various other factors. Because of this variability, noise exposure assessment should include some measure of an individual's subjective response, such as reported annoyance or stress. This information could be used in conjunction with dosimetric data to construct composite exposure profiles for each study subject.

A second consideration relates to the use of outdoor sound level measurements to estimate individual exposure. This ecologic method of exposure assessment would increase the potential for misclassification bias by failing to account for variation in the amount of time people spend at home, the degree of sound attenuation afforded by different homes (e.g., type of building materials, insulation, air conditioning), and other exposure-related factors (*11,33*). Measurement of indoor sound levels would eliminate much of this error but may not be economically feasible in a large-scale study. At the minimum, dosimetric evaluation of a small random sample of homes located within the study areas would be recommended in order to give some indication of the degree of variablity of indoor noise levels among different homes and to determine whether outdoor noise measurements would provide meaningful estimates of actual exposure.

A final consideration concerns the use of peak noise levels versus weighted averages to derive relevant exposure data. It has been suggested that weighted sound level measurements (such as DNL, a weighted day-night average) appear to correlate well with noise-induced stress, and may provide a better measure of the risk of adverse health effects than use of peak noise levels (*11,34*). However, peak noise may provide a superior measure for assessment of health impacts related to infrequent but intense exposures. The applicability of these various measurement parameters must be examined in greater detail for use in future epidemiologic investigations.

Epidemiologic Evidence. To investigate the potential risk of adverse reproductive outcomes associated with noise exposure in humans, several community-based epidemiologic surveys have been conducted. The majority of this research has been directed to studies of birth defects or low birth weight associated with residential proximity to large metropolitan airports.

In a prevalence assessment of the potential teratogenic effects of airport noise in Los Angeles County, Jones and Tauscher compared race-specific rates of birth defects (identified through birth certificates) among infants born to mothers residing in high-noise (90 dB) census tracts to the rates for the rest of the county (*35*). The study population included all recorded births in Los Angeles County from 1970 through 1972 (a total of 225,146 births). There was a significantly higher overall rate of malformations (excluding polydactylism) in blacks residing in the high-noise census tracts than among blacks from other areas of the county. Among whites, no significant difference in overall malformation rates was observed between the two groups. However, white infants from high-noise areas displayed a small but significant excess of anencephaly and spina bifida combined relative to infants from the control areas.

In a similar study in Atlanta, Edmonds et al. compared the frequency of birth defects among families residing near Hartsfield International Airport with the rest of Metropolitan Atlanta area (*34*). For the years 1970 through 1972, 1745 cases were ascertained through the Metropolitan Atlanta Congenital Defects Program (MACDP) (a total of 82,471 births for the period). Race-specific rates for 17 categories of congenital malformations and overall rates were compared for infants from high- and low-noise census tracts, as well as for three subgroups of the high-noise areas. High-noise areas were defined as those with noise levels above 65 DNL. No significant differences in any of the 17 birth defect categories were observed between either the high- and low-noise census tracts or among the three high-noise area subgroups, controlling for hospital of birth and socioeconomic status. However, when the neural-tube defect category was broken down further by specific defect, the authors observed a significant excess of spina bifida with hydrocephalus in the noisiest census tracts relative to the control areas. Further analysis of 453 neural-tube defect cases employing a matched case-control study design (matching for hospital of birth, month and year of birth, and race) produced marginally significant findings.

A cross-sectional analysis of low birth weight and maternal exposure to airport noise in Japan revealed an increased prevalence of low birth weight infants born to mothers living near a large airport compared with infants born to mothers in quieter cities (*26*). Further analysis suggested some evidence of a dose-response relationship between the frequency of low birth weight infants and the level of noise exposure. The frequency of low birth weight infants increased from 4.8% in areas measuring less than 74 dB to 8.2% in areas measuring 90 dB and above.

Knipschild et al. compared the birth weight of 498 infants whose mothers resided in a noisy area near the Amsterdam airport with that of 404 infants from less noisy areas (*37*). The authors reported a significant association between noise exposure ($>$ 65 dB) and low birth weight, controlling for parent's income and sex of the infant. This association was present only among female infants. Evidence of a dose-response effect within the noisiest areas was also reported.

In another prevalence study, Schell examined the association between maternal exposure to aircraft noise (ranging from 75–100 dB) and birth weight or gestation

length for 115 infants (*38*). The data were collected through personal interviews with the mothers (identified through elementary school records). This study revealed a significant negative partial correlation between noise exposure and gestation length in female infants, controlling for maternal age, smoking, parity, socioeconomic status, and parental height and weight. Noise exposure also displayed a slight negative correlation with male birth weight and gestation length and with female birth weight; however, these correlations were not statistically significant.

In a retrospective analysis of infertility and reported exposure to noise and other chemical and physical agents, Rachootin and Olsen compared the reproductive experience of 927 case and 3728 control couples from data gathered by mailed, self-administered questionnaires and through medical records (*39*). Self-reported exposure to noise was associated with a significant 2-fold increased risk of hormonal disturbances and idiopathic infertility, controlling for maternal age, education, residence, and parity.

Because of the ecologic nature of these investigations, it is difficult to infer an etiological association between exposure to noise and the observed adverse reproductive outcomes. Although several of the studies reported some evidence of an association, these findings must be interpreted with much caution. For example, the observed increase in overall rates of birth defects among blacks in the Los Angeles study is probably more realistically explained by variability in case reporting among the study areas than by exposure to a putative teratogen (*34–35*). In contrast, the increased rates of specific defects (anencephaly and spina bifida) among whites in the same study may be present a somewhat more biologically plausible association, although reporting bias may still account for these differences as well. Reporting bias is not a likely explanation for the observed association between noise exposure and low birth weight because the reliability of recorded birth weight would not be expected to vary greatly among different hospitals.

The impact of several potential confounding factors was inadequately addressed in most of the analyses. Included among these factors are maternal age, parity, tobacco use, and socioeconomic status. Curiously, some of this information (e.g., age, parity) probably would have been readily available on the vital records and other sources of data used in these studies, yet it was often ignored.

The most deficient aspect of the present research pertains to the method of exposure assessment. Because exposure was generally defined in terms of residence at the census tract level, the potential for systematic misclassification (in this case, inclusion of many unexposed persons in the exposed group) is quite large in all of the studies. The expected result of such misclassification would be to bias the results toward the null value, that is, to conceal a true association (*40*).

ELF Fields

Electromagnetic fields surround all living things, i.e., gravity is a static electromagnetic force. In fact, our modern society is washed by a sea of electromagnetic fields, which would include radio and television signals (high frequency waves) and low frequency fields used for generating electrical power. Household and commercial electrical power is distributed as alternating current at 60 Hz (cycles per second); this frequency is defined as extremely low frequency (ELF). ELF electromagnetic fields do not produce ionization of atomic particles, hence they are considered nonionizing. However, as ELF fields are not biologically inert, there is considerable controversy as to their potential for deleterious effects.

Biological Mechanisms

Although it has not been shown definitively that extremely low frequency (ELF) electromagnetic fields adversely affect normal embryonic and fetal development, there is some biologic plausibility for such a potential. Recent evidence suggests that electric fields produced intrinsically during the primitive streak stage may play an important role in embryonic development (*41–43*). It has been suggested that perturbation of these currents caused by extrinsic ELF fields may disrupt normal development processes (*44*).

Several studies demonstrated that cell membranes may be major receptor sites for ELF fields in living systems (*45–47*). These observations have led to speculation that ELF fields may act as a cancer promoter by disrupting normal biochemical pathways of communication between cell membranes and intracellular components (*45,48*). By extension, these findings may lead to questions regarding the potential effect of ELF fields on the selective permeability of the placental membrane. Such a condition could, in theory, lead to adverse effects on the fetus either by disrupting the flow of essential nutrients from the mother or by facilitating the transport of teratogenic chemical agents across the placenta. Further, ELF fields are suspected to affect the pineal gland, thereby influencing hormone regulation and diurnal patterns (*49–51*). Disruption of the maternal endocrine system could have potential adverse effects on fetal growth and development. Finally, there is some evidence to suggest that, under highly specific conditions, ELF fields may affect DNA synthesis and tumor cell growth and may induce chromosome aberrations (*52–54*).

Toxicologic Studies

ELF fields are produced as a result of the generation, transmission, and use of electric power. Sources of human exposure to electromagnetic fields are myriad and include overhead power transmission lines, home appliances, lighting fixtures, and other devices. Recent observations that ELF fields can induce changes in biological systems have led to increased public awareness and concern over the possible human health effects associated with exposure to these fields (*4,45,49,55*).

Experiments with animal test systems exposed to elec-

tromagnetic fields have produced inconsistent findings. Marino et al. reported significantly decreased body weight and increased mortality among the offspring of three generations of mice exposed to 15 kV/m, 60-Hz vertical electric fields (*56*). Decreased body weight was observed in two successive generations of mice exposed to horizontal fields. In a later study, Marino et al. observed increased mortality in each generation exposed to 3.5 kV/m vertical or horizontal fields and significantly increased body weight among the F_3 generation offspring (*56*).

Hansson exposed albino rabbits to 14 kV/m, 50-Hz electric fields outdoors from gestation through several weeks of postnatal life (*57*). In the initial experiment, exposed animals exhibited evidence of depressed growth and abnormal behavior. These effects were postulated to be associated with ultrastructural abnormalities of Purkinje nerve cells. Later laboratory replicates of these same experiments failed to show the same effects.

In a study of chick embryos exposed to pulsed electromagnetic currents at varying frequencies and magnetic field intensities, Delgado et al. reported a significant increase in malformations and retarded growth among the exposed chicks (*44*). These observations were attributed to exposure to a specific window of electromagnetic fields (i.e., highly specific combination of pulse shape, intensity, and exposure timing).

In another experiment with chick embryos designed to study the effects of pulsed electromagnetic fields on limb regeneration, Sisken et al. reported an increased frequency of morphological abnormalities among the exposed embryos relative to a control group (*58*). Induction of regeneration was not observed in any of the exposed chicks or in the controls. In a second experiment, Sisken et al. exposed intact embryos to pulsed electromagnetic fields at 37°C or 39°C (*59*). Among the chicks exposed at 37°C, no significant effects were reported. However, among the chicks exposed at the higher temperature, a significant increase in abnormalities was noted, suggesting a possible interactive effect between increased temperature and pulsed electric fields.

To ascertain possible effects on food and water consumption and growth, Seto et al. exposed rats to 80 kV/m, 60-Hz vertical electric fields from conception to 120 days of age (*60*). The authors reported significantly retarded growth from 4 to 8 weeks of age among the exposed animals. However, this effect was temporary, and no other significant differences between the treated and control animals were observed.

In an experiment with rats exposed prenatally to 80 kV/m, 60-Hz fields, Burack et al. reported delayed ear flap separation and eye opening and a slight reduction in body weight among the exposed rats (*61*). Copulatory behavior was impaired in males exposed *in utero*.

Sikov et al. conducted a series of experiments to evaluate the effects of 100 kV/m electric fields on various stages of prenatal and postnatal development in rats (*62*). Three 30-day treatment regimens ranging from 6 days prior to mating to 25 days of postnatal life were employed in this research. Aside from some transient behavioral effects, no significant differences in birth weight or frequency of malformations were observed between the exposed rats and the controls.

A multigenerational experiment with Hanford miniature swine exposed daily to 30 kV/m, 60-Hz fields for 20 hr/day indicated a possible adverse reproductive effect (*63*). After 4 months of exposure, the female swine were bred. The exposure continued during gestation. No teratogenic effects were observed with the first F_1 generation. After 18 months of exposure the F_0 generation was bred again. This experiment revealed a significant 2-fold increase of fetal malformations. Next, the F_1 females were bred following 18 months of exposure. The authors observed impaired mating behavior and decreased fertility among these animals and a significantly increased frequency of abnormalities among their offspring. However, a second breeding of the F_1 females 10 months later revealed no effect.

In an experiment with rats designed to replicate the swine study, no significant effects were observed in the first breeding of the F_0 females (*64–65*). In a second breeding of these animals, an increased frequency of fetal malformations was observed. In a breeding of the exposed F_1 females, decreased fertility and an increased frequency of abnormal fetuses were observed. However, later experiments failed to replicate these findings. The Electric Power Research Institute currently is conducting an experiment to replicate and examine in more detail this evidence (*66*).

In a retrospective analysis of decreased fertility among dairy cows in Sweden, Algers and Hennichs compared artifical insemination data for cows grazing for 15 days per year or more under 400 kV power lines with similar data from control herds (*67–68*). The authors reported no significant differences in fertility between the exposed and unexposed herds (*67–68*). These findings failed to confirm earlier preliminary observations of an association between the placement over a grazing pasture of high voltage power lines and subsequent fertility disturbances among two herds of dairy cows (*67–68*).

The data from the experiments are difficult to interpret and compare for several reasons. Some of the studies were conducted using only pure electric fields while others were done using both electric and magnetic field exposures. A variety of wave forms and field intensities were employed in these assays, and treatment regimens varied substantially among the different studies. Finally, several confounding artifacts (e.g., spark discharge, background exposures, etc.) associated with the various experimental conditions have prompted criticism of much of this research. The potential of small effects being undetected due to small sample sizes in these experiments also has to be considered (*70*). These nuances have hindered attempts by other workers to replicate positive findings.

Human Studies

Exposure Assessment. Two strategies are needed for exposure assessment of ELF fields; one strategy relates

to occupational exposures, the other to residential exposures. In both cases, the exposure configuration, intensity, and duration should be characterized. These exposure elements may then be used to characterize particular sources of ELF fields (e.g., items inside the house versus powerlines outside the house). However, this level of specification is not necessary to define relative exposure levels. Several devices exist for measuring ELF fields, and there is much prior experience with both residential and occupational exposure assessment to draw upon for guidance (*71–72*).

For the purpose of occupational ELF field exposure assessment, occupational groups and industries must be distinguished on the basis of relative potential for exposure to these fields. Within a particular study population, variability in ELF field exposure due to background sources, as well as confounding risks such as smoking and other chemical exposures, need to be addressed (e.g., through stratification, multivariable logistic methods, etc.).

Many factors influence the pattern of residential ELF field exposures. These factors include internal and external wiring configurations, home grouding patterns, and placement and operation of household appliances. However, there is a reasonable level of consistency for magnetic field measurements within a specific structure based upon a pattern of power-on and power-off measurements (*73–74*). A method for coding residential ELF magnetic field exposures based on outdoor wiring configurations near the home has been developed (*77*). The reliability of this exposure classification scheme has been verified by independent researchers (*73–74*).

Although numerous devices contribute to electric field exposures inside the home, a recent survey of residential ELF fields indicated that, even with moderate use, electric blankets accounted for at least half of the total annual exposure (*72*). This observation can be attributed to the relatively high field strength produced by these devices, the close proximity of the field in relation to the body, and the long period of exposure, (e.g., 8 hr/day for 120 days/year or more) (*72*). Future research directed toward either occupational or residential ELF field exposures should address electric blanket use as a potentially significant exposure variable.

Epidemiologic Evidence. Evidence of adverse reproductive effects among humans due to exposure to electromagnetic fields has been reported in two epidemiologic investigations. In one study, a retrospective survey of reproductive experience was conducted among 524 Swedish electrical substation workers (*76*). Data on birth weight, spontaneous abortion, perinatal mortality, and congenital defects were ascertained by questionnaire and verified through review of hospital records. Reproductive data were compared for periods of time the men were employed at electrical substations with the reproductive experience for those times the men worked at other occupations. This research indicated a significantly increased frequency of birth defects associated with employment in electrically related occupations. Heart defects, facial clefts, and hydrocele were among the reported malformations. No evidence of an increased risk of spontaneous abortions was observed among the substation workers.

An ecologic study of adverse reproductive outcomes in Denver examined the frequency of abortion and length of gestation among women using electric blankets or heated waterbeds during pregnancy (*77*). The study population was identified through birth announcements published in the local newspaper. Data on electric blanket and heated waterbed use were ascertained by telephone interview. Data on gestation length and abortion history were collected by review of birth records. In this analysis, spontaneous and induced abortions were not differentiated. The authors reported a significant seasonal variation in abortion frequency and fetal gestation length among women who reported using electric blankets or heated waterbeds while pregnant. This seasonal trend was not observed in a comparison group. The authors suggested that use of these heating devices during pregnancy may be a factor in the seasonal variability of abortion and gestation length.

The findings from these exploratory studies should be interpreted with caution. The significant findings observed among the substation workers were based on only 26 cases (17 of which occurred among exposed men). Moreover, the types of defects observed were varied and many appear to be unrelated to sperm abnormalities. In the Colorado study, bias may have resulted from the use of published birth announcements to recruit study subjects, although it is difficult to predict the magnitude and direction of such a bias if indeed one does exist. In addition, an unknown proportion of induced abortions comprised the total number of abortions analyzed in this study. Unless the number of therapeutic abortions was disproportionately distributed among electric blanket users and nonusers, one would expect that a true association might be missed due to the increased random variability introduced into the data. More definitive research is needed to address these issues.

Discussion

Epidemiologically, studies of noise and ELF fields are quite complex. Both agents involve difficult exposure assessments because there are so many sources for these agents—sources that individuals may choose or reject. Exposure is highly variable from person to person. This variability limits greatly the use of exposure categories that are derived by ecologic criteria such as job title or place of residence. Further, the possible reproductive effects are varied and uncertain, thereby making it difficult to focus epidemiologic studies on specific end points that are biologically relevant to the exposure. The suspected risks associated with these physical agents are quite low and are confounded by recognized chemical exposures such as smoking. Each of these factors (poorly defined exposure, uncertain end points, low magnitude of risk) can reduce the statistical power of epidemiologic studies.

Several suggestions for improving exposure characterization of noise and ELF fields have been presented above. Further experimental animal research may yield

some insights regarding the possible range of end points associated with each agent; however, appropriate animal models will first need to be identified. Until appropriate test species can be found, some clues may be gleaned from the present literature. For both noise and ELF fields, intrauterine growth retardation may be the best candidate reproductive outcome in terms of both the existing evidence and the prevalence of the disease. Neural tube defects (and perhaps other midline defects) are among the most likely congenital anomalies associated with maternal exposure to noise and possibly to ELF fields. Spontaneous abortion is a plausible end point for both exposures; however, substantial problems exist with respect to ascertainment, particularly in retrospective studies (*78*).

The presumed low magnitude of risk requires (in addition to detailed exposure assessment and well-focused end points) large study populations, adequate control for confounding variables, consideration of potential sources of bias, and powerful analytic techniques. Because of these methodologic constraints, the options for current epidemiologic study designs are few. Owing to the ubiquity of noise and ELF fields, even occupational studies would require residential monitoring to account for potential confounding exposures such as electric blanket use. Residential studies are feasible from a sample size perspective and may be facilitated by state or regional birth defects registries (*79,80*). If further research is to provide additional insights into these potential reproductive health risks, improved study designs that address these methodologic considerations are needed.

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