Effect of a Nighttime Magnetic Field Exposure on Sleep Patterns in Young Women

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Since poor sleep quality is associated with multiple health problems, it is important to understand factors that may affect sleep patterns. The purpose of this study was to determine the effect of a continuous, 60-Hz, nighttime magnetic field exposure on sleep outcomes in young women sleeping at home. The study was a randomized crossover trial, comparing intervention (0.5–1.0 υT above ambient levels) with ambient magnetic field levels, during two 5-night measurement periods. Subjects lived in the Seattle, Washington, area and were 20–40 years of age, had regular menstrual cycles, were not taking oral contraceptives, and had not breastfed or been pregnant during the previous year. The study was conducted between March and September of 2001. Sleep outcomes were measured via actigraphy. The range of magnetic field exposure was 0.001–0.50 υT during the ambient period and 0.41–1.21 υT during the intervention period. Sleep outcomes were not significantly different between the intervention and the ambient measurement periods. The intervention magnetic field had no effect on sleep patterns, suggesting that this exposure may not be an important factor in predicting sleep of young women who sleep at home.

cross-over studies; electromagnetic fields; premenopause; sleep

Abbreviation: CI, confidence interval.

Poor sleep quality is associated with decrements in memory and learning, gastrointestinal disorders, depression, and exacerbation of existing chronic disease (1, 2). A recent study suggested that too little or too much sleep may increase the risk of cardiovascular disease in women (3). Thus, it is important to determine the risk factors for poor sleep.

Recently, several studies reported that extremely low frequency magnetic field exposure might disrupt normal sleep (4–7). Among 5,078 Taiwanese women, ambient magnetic field exposures of greater than 0.2 μT were associated with disrupted sleep initiation and maintenance (7). Experimental studies, conducted in sleep laboratories, have reported that exposure to nighttime magnetic fields was associated with less total sleep time (4–6), more wake time (5, 6), and lower sleep efficiency (4–6), compared with sham exposure, among young men (4, 5) and older women (6). One study used a continuous 1-μT, 50-Hz magnetic field (4), while the other two used an intermittent 28.3-μT, 60-Hz magnetic field (5, 6). Conversely, a randomized trial of a continuous 5-μT, 4-Hz magnetic field in 101 insomniacs sleeping at home reported that those in the exposed group had significant improvements in self-reported sleep outcomes compared with placebo (8).

The purpose of this study was to determine the effect of a continuous, 60-Hz, nighttime magnetic field exposure on sleep outcomes in young women. This study is unique in that it measures sleep at home using actigraphy, which is an objective measure of sleep outcomes.
MATERIALS AND METHODS

Subjects

Subjects were identified from participants in a randomized crossover trial investigating the effect of a nighttime magnetic field on melatonin and reproductive hormone levels in premenopausal women. Eligibility criteria included being 20–40 years of age, not taking oral contraceptives or other hormones in the past 6 months, having regular menstrual cycles, having a body mass index of less than 30.0 kg/m², not being pregnant or breastfeeding during the previous year, not being a shift worker, and not taking melatonin supplements. Subjects lived in the greater Seattle, Washington, area.

Between February and September of 2001, 131 eligible women were invited to participate in the parent study. Of these, 43 subjects did not complete any measurement period (all refused participation), 12 subjects completed only one measurement period, and 76 completed both. Of the 88 women completing at least one measurement period in the parent study, 85 were asked to participate in an additional component to measure sleep (three women completed one measurement period before obtaining institutional review board approval for the sleep component).

Subjects who contacted the study telephone line in response to posted advertisements for the parent study completed an initial screening interview and, if eligible, were scheduled for a home visit. Written consent, approved by the Fred Hutchinson Cancer Research Center Institutional Review Board, was obtained at this visit.

At the first home visit, a technician taught subjects to determine their ovulation date using a menstruation calendar and a commercial ovulation kit (Assure LH [luteinizing hormone] Ovulation Predictor; Conception Technologies, San Diego, California), which detects the luteinizing hormone surge 24–48 hours before ovulation. Subjects tracked one complete menstrual cycle, including the detection of a luteinizing hormone surge before proceeding to the intervention phase. After the next two detectable luteinizing hormone surges, the subject was scheduled for the two measurement periods in which the study intervention was applied. Both measurement periods were 5 nights and started 2 days after the luteinizing hormone surge. Half the women were randomly assigned to the intervention and half to the sham exposure (ambient) during the first measurement period; exposure status was switched for the second period.

Intervention

The intervention consisted of a continuous, 60-Hz magnetic field, 0.5–1.0 μT above the ambient levels, at the subject’s normal head location on the bed, such that the exposure was primarily directed at the head. Exposure to the rest of the body was minimal, since the magnetic field was directionally oriented toward the center of the pillow and dropped off rapidly when the subject moved laterally from the pillow. Using a detailed protocol, we administered the exposure by placing a common household appliance (an electric toothbrush charger) that was plugged into a power strip in the off or on position underneath the bed. There was no indication of whether it was on or off; thus, subjects, but not technicians, were blinded to exposure status. Measurements of magnetic field exposure were collected at 30-second intervals using an EMDEX II meter (Enertech Consultants, Campbell, California). Meters were calibrated for a 60-Hz frequency at the factory; the measurement error at this calibration is ± 2 percent. Meters were also checked weekly using a standard protocol to ensure proper functionality. The meter was placed under the bed at an appropriate distance from the exposure device, such that the magnetic field reading was within 0.05 μT of the reading at the subject’s normal head location on the bed, using a strict protocol to ensure accuracy.

Sleep data

Subjects wore an Actiwatch-16 actigraph (Mini Mitter Company, Inc., Bend, Oregon) on their nondominant wrist (9) from bedtime to rise time all nights of both measurement periods. Written and oral instructions for using the actigraph were provided at each measurement period.

The actigraph is designed for long-term monitoring of gross motor activity in humans, and it has an accelerometer capable of sensing motion with a minimal resultant force of 0.01 g (10). Actigraphs were programmed with a calibration coefficient to normalize data between watches, thus removing most, if not all, variation between devices due to sensor differences; this calibration occurred at the factory. The actigraph collected data in 1-minute sampling intervals. When possible, the same actigraph was used at both measurement periods. Actigraph data were downloaded onto a personal computer and analyzed via a FORTRAN software program using the method of Cole et al. (11). Using polysomnographic validation data provided by Mini Mitter Company, Inc. (10), we assessed the sleep/wake status of each minute of the night as follows:

\[ D = 0.025 \times (0.04 A_{12} + 0.20 A_{1} + 1.0 A_{0} + 0.20 A_{1} + 0.04 A_{12}) \]

where \( A_{i} \) is the number of detectable motions in that minute. If \( D \geq 1 \), then the subject was considered to be awake during minute \( A_{1} \); otherwise, the subject was considered to be asleep. To increase accuracy, we applied the five rescoring rules outlined by Cole et al. (11) that correct for the problem that subjects falling asleep after waking up during the night tend to stop moving a few minutes before polysomnography indicates the onset of sleep. Initial sleep onset was considered to be the beginning of the first 20-minute interval in which no more than 1 minute was scored as “wake”; this criterion had the highest correlation with polysomnography (11). Sleep data were scored by one of the authors (S. S. T.), who was blinded to exposure status.

Other data collection

At both measurement periods, a technician collected height to the nearest 0.1 cm and weight to the nearest pound (1 pound = 0.45 kg) and administered a structured interview collecting demographic information, job status, and exercise...
habits. Subjects also completed a nightly diary, including bedtime, rise time, medication use, and alcohol consumption, each night of the measurement period. Hours of daylight were determined via sunrise/sunset tables calculated by the National Research Council (Herzberg Institute of Astrophysics, Victoria, British Columbia). On the last night of the measurement period, subjects collected all urine excreted during the night after sleep onset plus the first morning void. To determine whether the cycle was ovulatory, pregnanediol-3-glucuronide was measured in urine by enzyme immunoassay (12) at the University of Southern California under the direction of Dr. Frank Z. Stanczyk.

Data analysis

The primary purpose of this study was to determine the effect of the intervention magnetic field versus ambient exposure on total sleep time, sleep efficiency, total wake time, minutes awake after sleep onset, the number of awakenings, the number of awakenings greater than or equal to 3 minutes’ duration, and sleep onset latency. Sleep efficiency is the total sleep time divided by the time in bed. The primary linear model regressed each sleep outcome on exposure (intervention vs. ambient), night in intervention period (night 1, 2, 3, 4, or 5), order of exposure (ambient-intervention, intervention-ambient), and measurement period (period 1 or 2). Because of the correlated nature of the data, we used generalized estimating equations with an independent working correlation matrix (13). In a separate model, we included a linear interaction term between night and exposure to determine whether the magnetic field effect on sleep changed across nights. However, we found no significant interactions, so data from all nights were combined.

We also examined the relation between mean nighttime magnetic field exposure as a continuous measure and sleep outcomes, stratifying by exposure period, in a cross-sectional analysis. This analysis disregarded the experimental design of the study and treated the subjects as a random sample. We adjusted for job status (yes, no), body mass index (linear), usual hours of sleep over the previous month (linear), daylight hours (linear), alcohol servings (0, 1, 2, ≥2 servings), bedtime (linear), rise time (linear), age (linear), took a sedative (yes, no), and took another prescription or over-the-counter medication (yes, no).

Imputation of missing outcome data

Some subjects did not wear the actigraph for the entire night, put it on more than 30 minutes after bedtime, or took it off more than 30 minutes before getting up, resulting in at least partially missing data for 88 (14 percent) nights. Missingsness was nominally associated with order of exposure, and removing the actigraph early was associated with significantly worse sleep outcomes compared with nights with complete data; removing these records from the analysis could bias the results. Therefore, we performed multiple imputation using the regression method (described below) to estimate the uncertainty caused by the missing data (14, 15).

We imputed 10 data sets by generating a unique linear regression prediction model for each missing data point, chosen at random. The prediction model contained the following: exposure, order of exposure and their interaction, night of the measurement period, subject identification number, job status, exercise in the previous month (minutes/week), took a sedative, took an unknown medication, took another prescription or over-the-counter medication, daylight hours, weekday/weekend day, number of alcohol servings, body mass index, and usual hours of sleep over the previous month. If the subject wore the actigraph for part of the night, the sleep outcomes during that time were also included (by thirds of the night). Each missing data point was replaced by the predicted mean value based on the covariate data for its corresponding record plus a randomly sampled residual, determined from the prediction model. We assumed the data were missing at random (14, 15).

Point estimates were determined by fitting the model in all 10 imputed data sets and taking the mean of the resultant point estimates. Standard errors were determined by taking the square root of the sum of the within- and between-imputation variances (14, 15). All statistical tests were two sided.

RESULTS

Of the 85 eligible women, 77 (91 percent) consented. Nineteen subjects completed one measurement period, and 58 completed both. The reasons for having only one measurement period included the following: became ineligible (n = 10), dropped the study (n = 6), and no actigraph available (n = 3). We excluded measurement periods in which the subject used an electric blanket (n = 1), started menstruating (n = 1), took emergency contraceptive hormones (n = 1), had missing outcome data for 4 or 5 nights (n = 6), or had an anovulatory cycle (pregnanediol-3-glucuronide of 1.25 µg/mg of creatinine) (n = 9). Thus, 117 measurement periods from 71 subjects were available for analysis. No significant differences existed between subjects who contributed data for two (n = 46) versus one measurement period (n = 25) (data not shown).

On average, subjects were 31 years of age and had a normal body mass index (table 1). Subjects reported sleeping about 7 hours per night over the previous month and had an average bedtime of 11:18 p.m. and a rise time of 7:18 a.m. during the measurement periods. Most subjects were employed, about a third took a medication, and around 60 percent consumed alcohol on at least one of the measurement nights. Randomization yielded approximately equal numbers of subjects in each exposure order.

The mean magnetic field was about 0.7 µT higher during the intervention versus ambient period (table 2). One subject had ambient magnetic fields higher than the minimum intervention period exposure. Subjects slept an average of 6 hours and 58 minutes, with a sleep efficiency of 88.3 percent, during the ambient period and 7 hours and 1 minute, with a sleep efficiency of 88.4 percent, during the intervention period. Sleep outcomes were not significantly different between the intervention and ambient periods. Results were similar when excluding the subject with ambient magnetic fields higher than the minimum intervention period level or when excluding nights with any missing sleep data (data not shown).
In the observational analysis, a 0.1-µT increase in the mean magnetic field during the ambient period was associated with 8.9 fewer minutes of total sleep time (95 percent confidence interval (CI): –16.3, –1.5), 1.3 percent lower sleep efficiency (95 percent CI: –2.2, –0.4), 5.2 more minutes of total wake time (95 percent CI: 0.5, 9.8), 4.5 more minutes of wake after sleep onset (95 percent CI: 1.2, 7.7), and 0.6 more awakenings of greater than or equal to 3 minutes (95 percent CI: 0.1, 1.2). There was little association between the mean magnetic fields and sleep outcomes during the intervention period (data not shown).

**DISCUSSION**

The purpose of this study was to determine the effect of a continuous, 60-Hz, nighttime magnetic field exposure on sleep outcomes in young women sleeping at home. Our results suggest that the intervention had no effect on sleep outcomes. This finding is inconsistent with results from laboratory-based studies, which reported significant reductions of total sleep time (range: 16–29 minutes) and sleep efficiency (range: 3–7 percent) during the exposed period (4, 6, 16), and from one home-based study, which reported

<table>
<thead>
<tr>
<th>Table 1: Characteristics of women (n = 71) who had complete data for the first (n = 67) and second (n = 50) data collection periods, Seattle, Washington, 2001</th>
</tr>
</thead>
<tbody>
<tr>
<td>Completed first period</td>
</tr>
<tr>
<td>Age (years) (mean (SD*))</td>
</tr>
<tr>
<td>Body mass index (kg/m²) (mean (SD))</td>
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<tr>
<td>Usual hours of sleep (mean (SD))</td>
</tr>
<tr>
<td>Daylight hours (mean (SD))</td>
</tr>
<tr>
<td>Bedtime (minutes) (mean (SD))</td>
</tr>
<tr>
<td>Rise time (minutes) (mean (SD))</td>
</tr>
<tr>
<td>Employed (no. (%))</td>
</tr>
<tr>
<td>Consumed alcohol† (no. (%))</td>
</tr>
<tr>
<td>Took a prescription sedative† (no. (%))</td>
</tr>
<tr>
<td>Took another medication†,‡ (no. (%))</td>
</tr>
<tr>
<td>Order of exposure</td>
</tr>
<tr>
<td>Exposed during second period (no. (%))</td>
</tr>
<tr>
<td>Exposed during first period (no. (%))</td>
</tr>
</tbody>
</table>

* SD, standard deviation.
† At least once during the measurement period.
‡ Any prescription or over-the-counter medication, except sedatives.

**Table 2: Mean sleep outcomes and magnetic field levels, stratified by measurement period, and the adjusted* difference in sleep outcomes between the ambient and intervention periods, Seattle, Washington, 2001**

<table>
<thead>
<tr>
<th></th>
<th>Ambient (n = 251)†</th>
<th>Intervention (n = 255)†</th>
<th>Adjusted* difference (n = 506)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (SD‡)</td>
<td>Range</td>
<td>Mean (SD)</td>
</tr>
<tr>
<td>Total sleep time (minutes)</td>
<td>417.9 (69.2)</td>
<td>226–689</td>
<td>421.2 (72.5)</td>
</tr>
<tr>
<td>Sleep efficiency (%)</td>
<td>88.3 (4.7)</td>
<td>62.6–97.3</td>
<td>88.4 (4.6)</td>
</tr>
<tr>
<td>Total wake time (minutes)</td>
<td>55.4 (24.9)</td>
<td>11–163</td>
<td>55.1 (23.1)</td>
</tr>
<tr>
<td>Minutes awake after sleep onset</td>
<td>40.6 (18.3)</td>
<td>6–109</td>
<td>39.6 (19.1)</td>
</tr>
<tr>
<td>Total no. of awakenings</td>
<td>22.3 (8.0)</td>
<td>3–51</td>
<td>22.1 (7.7)</td>
</tr>
<tr>
<td>Awakenings of ≥3 minutes</td>
<td>4.2 (2.9)</td>
<td>0–14</td>
<td>4.1 (3.0)</td>
</tr>
<tr>
<td>Sleep onset (minutes)</td>
<td>12.4 (13.9)</td>
<td>1–70</td>
<td>13.3 (16.3)</td>
</tr>
<tr>
<td>Mean magnetic field# (µT)</td>
<td>0.08 (0.08)</td>
<td>0.001–0.50</td>
<td>0.76 (0.17)</td>
</tr>
</tbody>
</table>

* Adjusted for order of exposure, night, and period; analysis used imputed data.
† Number of nights with nonmissing sleep outcome data; for sleep onset: nambient = 263 and nintervention = 262.
‡ SD, standard deviation; CI, confidence interval.
§ Average difference in sleep outcomes between the intervention exposure and ambient exposure only.
¶ p value for statistical significance of the regression coefficient using the Wald test.
# Includes 270 measured nights during the ambient period and 260 measured nights during the intervention period.
significant improvements in self-reported sleep outcomes for exposed insomniacs (8). Disparities between study results may be due to different exposure protocols, settings, subject populations, or statistical variation. The exposure protocols varied in the magnetic field frequency (4–60 Hz), level (0.5–28.3 µT), intermittency (continuous vs. intermittent), and exposure area (head vs. whole body). Such properties may have different effects on sleep (16).

Setting also may be important. The three laboratory-based studies controlled for the temperature, humidity, light exposure, bedtime, and rise time, while our study and the other home-based study did not. One study reported that young, normal sleepers have longer and more consolidated sleep in a laboratory versus home environment (17), suggesting that additional factors affecting sleep in a home environment could overshadow a potential effect of magnetic field exposure.

Further, different populations may not have the same sensitivity to magnetic field exposure. For example, older women, but not older men, had reduced sleep quality during magnetic field versus sham exposure (6). The authors theorized that the particularly poor sleep quality of the older men during the placebo condition might have masked a potential magnetic field effect. However, magnetic field exposure improved subjective sleep quality in insomniacs, a population with extreme sleep disruptions (8). Thus, it is possible that the effect of a nighttime magnetic field exposure on sleep differs between populations.

In an observational analysis, we found that higher ambient magnetic fields were associated with modestly worse sleep. Our results are consistent with those from a study in Taiwan, which reported that increased ambient magnetic fields in the bedroom were associated with self-reported disruptions in sleep initiation and maintenance (7). It is possible that the intervention and ambient magnetic fields may have distinct properties that could affect sleep differently. For example, Graham and Cook (16) reported that an intermittent, but not a continuous, magnetic field exposure disrupted sleep; in our study, the exposure device emitted a continuous field, while the ambient field fluctuated over the night. Another difference between the intervention exposure and ambient magnetic fields is that the intervention exposure was primarily directed at the head, while ambient exposure likely was more uniformly distributed across the entire body, which is similar to previous experimental studies. Further, it is possible that, since ambient magnetic fields are stable over time (18), the observed association with sleep may reflect the effect of long-term magnetic field exposure. However, given that we found no effect of the intervention on sleep patterns, it is likely that the results of the observational analysis are biased due to selection bias (e.g., women self-selected to participate in the study), the strict eligibility requirements, or residual confounding. Some possible confounders are family income, which may be inversely associated with both ambient magnetic field levels (19, 20) and poor sleep quality (21, 22), noise, or light.

The current study has several strengths. The sample size is larger than previous laboratory-based studies. We also accounted for the correlated nature of the sleep outcome data, which has the benefit of eliminating between-subject confounding. Our study examined young women, a group that was underrepresented in previous studies. Measurement periods were conducted during the same menstrual phase, thus eliminating the possibility that observed associations were due to different sleep patterns across the menstrual cycle (23, 24). Although the residential setting may increase sleep variability, it is important to understand the effect of magnetic field exposures outside of a laboratory environment.

The present study has several weaknesses. First, since women were measured while sleeping at home, we could not control for exposures that can affect sleep, such as light or bedtime. We also did not collect information about whether women slept alone or with another person or pet or whether they had small children living in the house. However, the randomized nature of the trial should remove the confounding effects of these factors. Second, we did not exclude women with medical conditions or who took medications known to affect sleep. This could affect the results if magnetic fields have a different effect in such individuals.

Third, although actigraphy is an objective measure of sleep, it overestimates total sleep time compared with polysomnography, because it cannot detect wake time in which no movement occurs (11, 25, 26). This overestimation may be larger among those with poor sleep quality (11, 27, 28), possibly causing an attenuation of the observed associations. Fourth, 14 percent of the nights had at least some missing data, which may limit the generalizability of our results. Rather than exclude these nights, possibly leading to biased results, we used a multiple imputation method that produces valid answers with respect to the uncertainty introduced by the missing data (15, 29).

Our study found that a continuous, 60-Hz, nighttime magnetic field, 0.5–1.0 µT above ambient levels, has no effect on sleep patterns. These results conflict with those from laboratory-based settings, highlighting the importance of assessing various exposure-sleep relations in a natural or home environment. Overall, our results suggest that magnetic field exposure is not an important factor in predicting sleep of young women sleeping at home.

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