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Effect of Short-Wave (6–22 MHz) Magnetic Fields on Sleep Quality and Melatonin Cycle in Humans: The Schwarzenburg Shut-Down Study

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This paper describes the results of a unique ''natural experiment'' of the operation and cessation of a broadcast transmitter with its short-wave electromagnetic fields (6–22 MHz) on sleep quality and melatonin cycle in a general human population sample. In 1998, 54 volunteers (21 men, 33 women) were followed for 1 week each before and after shut-down of the short-wave radio transmitter at Schwarzenburg (Switzerland). Salivary melatonin was sampled five times a day and total daily excretion and acrophase were estimated using complex cosinor analysis. Sleep quality was recorded daily using a visual analogue scale. Before shut down, self-rated sleep quality was reduced by 3.9 units (95% CI: 1.7–6.0) per mA/m increase in magnetic field exposure. The corresponding decrease in melatonin excretion was 10% (95% CI: −32 to 20%). After shutdown, sleep quality improved by 1.7 units (95% CI: 0.1–3.4) per mA/m decrease in magnetic field exposure. Melatonin excretion increased by 15% (95% CI: −3 to 36%) compared to baseline values suggesting a rebound effect. Stratified analyses showed an exposure effect on melatonin excretion in poor sleepers (26% increase; 95% CI: 8–47%) but not in good sleepers. Change in sleep quality and melatonin excretion was related to the extent of magnetic field reduction after the transmitter's shut down in poor but not good sleepers. However, blinding of exposure was not possible in this observational study and this may have affected the outcome measurements in a direct or indirect (psychological) way. Bioelectromagnetics 27:142–150, 2006. © 2005 Wiley-Liss, Inc.

Key words: radiofrequency; electromagnetic fields; insomnia; complex-cosinor-analysis; epidemiology; broadcast antenna

INTRODUCTION

Despite a growing number of experimental and epidemiological studies on the interaction between non-ionising electromagnetic fields (EMF) and biological systems, the effects of radio-frequency (RF) EMF on health remain controversial. Recent reviews have reported a wide variety of phenomena [Roberts and Michaelson, 1985; Juutilainen and Seze de, 1998; Repacholi, 1998; Röösli et al., 2003]. Sleep disorders, a frequent clinical symptom, have been hypothesized to be related to electromagnetic field exposure. So far sleep studies have focused on effects from mobile phone radiation but not from other sources in the high frequency range, such as broadcast transmitters, diathermy devices, radar etc. Randomized controlled cross-over trials examining electroencephalogram (EEG) changes during sleep have found altered amplitude, mostly in the alpha range, when study subjects were exposed to mobile phone handset antennae [Mann and Röschke, 1996, 2004; Borbely et al., 1999; Huber et al., 2000, 2002; Lebedeva et al., 2001]. Two of these studies found evidence of an association with changes in the distribution of the sleep stage during exposure [Mann and Röschke, 1996; Lebedeva et al., 2001]. Only two laboratory studies did not find an effect on EEG under exposure [Wagner et al., 1998, 2000]. There was little evidence that self-rated sleep quality was impaired but these studies were not designed to study such an effect.

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Previously the effects of amplitude-modulated short-wave broadcast transmitters on sleep quality were investigated in two cross-sectional studies of people living around the Schwarzenburg broadcast transmitter in Switzerland from 1992/1993 [Altpeter et al., 1995] and 1996 [Madarasz and Sprenger, 2002]. An increased prevalence of self-reported sleep disturbances with decreasing distance from the emitting antennas and increasing exposure to magnetic field was found, after controlling for several confounders. This was also the case for various unspecific symptoms of ill health, e.g., nervousness, restlessness, limb pain. However, in a multivariate path analysis (graphical modeling), it has been shown that these latter associations might have been due to difficulties with staying asleep and not directly associated with measured electromagnetic field strength. Similar findings have been reported in a study from the surroundings of a short-wave radio transmitter in Austria [Haider et al., 1992].

Although a biological explanation for an association between exposure to RF-EMF and impaired sleep quality has not been identified, it has been hypothesized that nightly melatonin excretion is suppressed by electromagnetic field exposure [Stevens, 1987]. Melatonin is related to the day–night cycle with higher blood levels during night. Melatonin supplements have been shown to be effective in treating sleep problems due to jet lag, in the blind and to some extent in old people [Arendt et al., 1981; Dahlitz et al., 1991; MacFarlane et al., 1991; Reiter, 1991; Lewy et al., 1992; Jan et al., 1994; Garfinkel et al., 1995; Brzezinski, 1997; Burch et al., 1999]. Two recent observational studies have found evidence of an association between decreased excretion of melatonin during night and increasing use of mobile phones [Burch et al., 2002; Jarupat et al., 2003]. However, four cross-over trials have found no association between exposure to mobile phone handset and melatonin excretion [Mann et al., 1998; de Seze et al., 1999; Radon et al., 2001; Bortkiewicz et al., 2002].

In March 1998, the Swiss government decided to close down permanently the shortwave radio transmitter at Schwarzenburg. We used this opportunity to examine possible chronic and acute effects of radio frequency exposure on sleep quality and salivary melatonin levels in humans, with the hypothesis that an effect would be more pronounced among poor sleepers.

MATERIALS AND METHODS

Study Design

The shortwave transmitter of Schwarzenburg was scheduled to shut down on 29 March 1998 at 2:00 a.m. Our study took place for 1 week before (from 23 March 1998 at noon) and 1 week after the shutdown (until 3 April 1998 at noon). We contacted all participants of two previous studies [Altpeter et al., 1995; Abelin et al., in press] by post and invited them to participate in this study. Study participants recorded sleeping times and self-rated sleep quality in a sleep diary every morning. Salivary melatonin levels were sampled five times a day.

Fifty four participants of the previous studies agreed to participate and gave written consent. The study was approved by the Research Ethics Committee of the Medical Faculty, University of Bern. The participants were between 24 and 70 years (mean

TABLE 1. Descriptive Statistics of the Study Population

	1998	1996
	n (%)	n (%)
Total number of participants	54 (100)	446 (100)
Sex		
Male	21 (39)	199 (45)
Female	33 (61)	247 (55)
Occupation	n (%)	n (%)
General farming	15 (28)	149 (33)
Household work	19 (35)	121 (27)
Other	20 (37)	176 (39)
	Mean (SD)	Mean (SD)
Age	52.8 (12.3)	49.3 (16.8)
Magnetic field strength [mA/m]	1.5 (1.5)	n.a.
Distance to transmitter [km]	1.88 (1.32)	2.27 (1.63)
Years of education (without kindergarten)	12.9 (2.6)	11.8 (2.5)
Socioeconomic status (magnitude prestige scale[a])	39.2 (34.9)	39.0 (29.5)

Schwarzenburg shut-down study [1998] and Schwarzenburg survey [1996].
[a]From Wegener [1992].

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52.8 years, Table 1). The characteristics of this study population were similar to those from the previous study with respect to age, sex, and socioeconomic status but it tended to live closer to the transmitter.

Exposure Assessment

The transmitter was situated about 20 km south of the Swiss capital Berne and was built in 1939 to transmit information worldwide. It operated at frequencies of 6.1 to 21.8 MHz, with a maximum power of two times 150 kW. The signal was amplitude modulated. The direction of the transmission beam changed about every 2 h according to the local time in the target areas (America, Asia, Africa, Australia). The beam was elevated by 11° above the horizontal to reach its target by repeated reflection between the stratosphere and the ground.

We used an isotropic sensor system (EH 30KW, EMC-Baden Ltd., Dättwil, made available by Swisscom, operator of the Schwarzenburg transmitter) that had been developed during the previous studies [Altpeter et al., 1995] and took continuous measurements in a hayloft of a cattle stable which was located 925 m north of the shortwave transmitter's star shaped antenna, for the whole study period. The probe had been previously validated and reported [Altpeter et al., 1995; Madarasz and Sprenger, 2002].

We calculated 24 h average H field exposure [mA/m] for each subject's home using Maxwell equations, taking into account the relative position of the residencies to the centre of the antenna (azimuth and distance), the previous exposure measurements (1992, 1993, 1996), and the present broadcasting scheme. The calculations were performed by Swisscom (U. Herrmann and B. Eicher). Before shut down of the transmitter H-field exposure of the study population was in the range of 0.2 to 6.7 mA/m (mean 1.5 mA/m, median 0.92 mA/m). We divided the study population in to groups according to median exposure value. Average exposure level in the low exposure group was 0.4 mA/m (median = 0.40 mA/m), in the high exposure group 2.6 mA/m (median = 2.1 mA/m). After shut-down, there were no emission sources left in this frequency range.

Outcome Measurements

Saliva was sampled using plain, citrate-free spongy polystyrol sticks (Salivetten®; Sarstedt) of 10 mm diameter and 35 mm length. These were kept in the mouth for about a minute and removed when filled with saliva. Salivary sampling times were as follows: before breakfast (median 6:40 AM, interquartile range 65 min), noon (median 12:00 AM, interquartile range 35 min), tea time (median 4:10 PM, interquartile range 60 min), dinner time (median 7:00 PM, interquartile range 75 min), and before bed (median 10:10 PM, interquartile range 70 min). In principle, two samples were taken at the same time point. The saliva samples were stored at below 8 °C in the participant's home refrigerator. Every morning between 8:00 AM and noon samples from the previous 24 h were collected and transferred on dry ice to IBL Laboratories in Hamburg (Germany) where they were stored at −20 °C before saliva melatonin levels were determined by radio-immuno-assay (RIA) tests. Sampling times were specified as before breakfast, noon, tea time, dinner time, and before bed, without giving exact times, in order to improve compliance. The subjects reported the actual sampling times on a form. Participants were requested to complete a standardized sleep log (VIS-M, Collegium Internationale Psychiatriae Scalarum, 4th edn.) every morning. They recorded morning tiredness and sleep quality, time of falling asleep, and duration of sleep. We calculated sleep efficiency as the duration of sleep divided by duration of staying in bed. The primary sleep quality outcome was morning tiredness, which was measured on a 100 arbitrary unit visual analogue scale with low values referring to freshness and high values to tiredness. Every morning the volunteers were supplied with new Salivetten® and new sleep logs. Questionnaires were collected daily so that participants did not compare their daily ratings.

Statistical Analysis

For the data analysis, we divided the study time into two 4-day periods, starting on Monday at noon and ending on Friday at noon. Period 1 (baseline exposure period) lasted from 23 March, 12.00 to 27 May. Period 2 (after shut down) from 30 March, 12.00 to 3 April.

Morning tiredness, melatonin excretion (log transformed), and acrophase (peak time of melatonin excretion) are the main outcome measures of the study. Total melatonin excretion and the acrophase for each period were estimated using a complex-cosinor-model (termed CCA by Lerchl and Partsch, 1994). This corresponds to a cosine-shaped diurnal melatonin excretion pattern. In Figure 1 are shown exemplarily salivary melatonin samples from one individual and the corresponding fitted curve before and after shut down of the transmitter. The total salivary melatonin excretion was then obtained for each individual from the area under the modeled curve (AUC) for both periods. The acrophases were obtained by finding the point in time of the daily maximum of the fitted melatonin cycle. All models were fitted by median regression of the logarithm of the salivary melatonin concentration, implemented in Splus 4.5 for Windows NT by the

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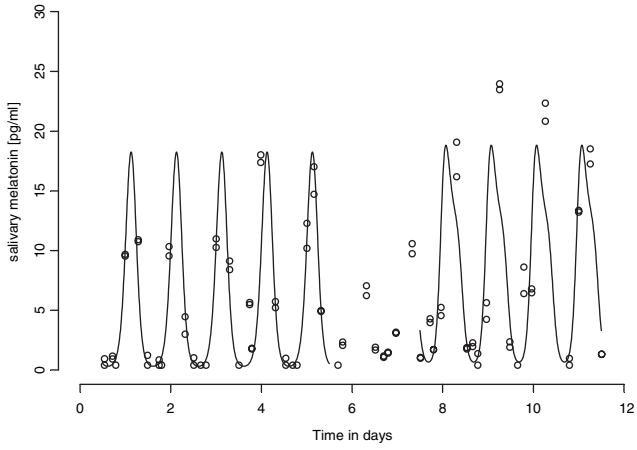


Fig. 1. Salivary melatonin samples from one individual and curve, fitted using a complex-cosinor-models, on workdays before and after shut down of the transmitter. The tick of the day number corresponds to the start of the day: 0:00.

function 'l1fit' [Birkes and Dodge, 1993]. Values beyond the laboratory detection limits, i.e., below 0.4 pg/ml and above 250 pg/ml, were excluded. The statistical methods have been described previously [Altpeter and Abelin, 2002].

Chronic effects of short wave radiation were investigated by comparing outcome measurements during the baseline period in association with the magnetic field exposure. Melatonin excretion levels were log transformed. Age and sex were taken into account as possible confounding factors. In order to obtain robust coefficients, a linear median regression model was fitted (L1-norm).

Acute RF effects were studied in a within subject analysis where every subject served as his/her own control. For this analysis, we fitted the outcome measurements in period 2 using a random effects model taking into account the respective baseline value. All models were adjusted for age and sex. We also investigated interaction between sleep quality at baseline and acute exposure in stratified analyses to determine whether EMF exposure affects sleep quality more in poor sleepers than in good sleepers. Sleep quality at baseline was obtained by a principal component analysis (PCA) on diary data from the first period (baseline). Thus, a compound variable was derived as an overall measure of sleep quality at baseline. We constructed two equally sized groups using the median value of the compound variable to classify the study participants as either poor or good sleepers. Mean age of poor and good sleepers was 54 and 50 years, respectively. The sex ratio was similar in both groups (63 and 59%, respectively).

In order to get hints with respect to the biological mechanism, we modelled possible association between rating of sleep quality (freshness vs. tiredness) and the melatonin cycle. We performed two different analyses. First we compared sleep quality at baseline with the melatonin cycle at baseline. Second, we compared change in sleep quality from the period after shut down to the baseline period with the respective change in melatonin excretion at peak time.

The chronic and acute disease models were calculated using Stata 8.1 (Stata Corporation, Austin, TX). $P < 0.05$ was considered statistically significant.

RESULTS

Raw Outcome Measurements

The median melatonin concentrations were 7.02 pg/ ml (interquartile range 13.60) before breakfast, 1.76 pg/ml (interquartile range 2.12 pg/ml) at noon, 1.56 pg/ml (interquartile range 2.54 pg/ml) at tea time, 2.00 pg/ml (interquartile range 3.40 pg/ml) at dinner time, and 10.91 pg/ml (interquartile range 21.53 pg/ml) before bed. One baseline value of a high exposed individual was excluded because there were too few salivary samples. One outlying peak time value (11:30 AM) in a 69-year-old individual was considered as implausible and thus omitted from the analyses.

Table 2 shows the raw outcome measurement during baseline period and after shut-down stratified by exposure status. Morning tiredness was the same before and after shut down in the low exposure group, but the high exposure group reported considerably less tiredness after shut-down. Melatonin excretion (AUC) remained relatively constant in the group with low exposure and increased in the group with high exposure after shut-down of the transmitter. Note that the data distribution of the AUC is skewed and thus logarithm transformed for further data analysis. The peak time for excretion of melatonin in both groups was delayed after shut-down, corresponding to the switch from winter to summer time, when the clock is put forward by one hour. Mean age and sex ratio in the low and high exposure group were similar (51 and 53 years; 63 and 59%, respectively).

Chronic Effects

Table 3 shows the chronic effects of magnetic field exposure. During the baseline period, morning tiredness increased with increasing electromagnetic field values, after controlling for age and sex. Melatonin excretion decreased by a factor of 0.90 for every 1 mA/m increase in magnetic field exposure (95% CI: 0.68–1.20). The peak time of melatonin excretion was put backward by 4.4 min for every 1 mA/m increase in magnetic field exposure (95% CI: −25.4 to 16.6).

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TABLE 2. Average Daily Values of Melatonin Excretion (AUC), Peak Time, and Tiredness Before and After Shut Down of Transmitter Stratified by Exposure Status

		EMF low[a]				EMF high		
	Period	n	1st quartile	Median	3rd quartile	n	1st quartile	Median	3rd quartile
EMF [mA/m]	Baseline	27	0.25	0.40	0.57	27	1.47	2.10	3.55
	2	27	0.00	0.00	0.00	27	0.00	0.00	0.00
Morning freshness-tiredness	Baseline	27	41.3	45.0	50.3	27	44.3	54.5	62.3
	2	27	39.5	45.8	51.0	27	31.3	42.5	48.0
Melatonin excretion [pg/ml]	Baseline	27	5.3	12.5	37.9	26	4.9	9.5	17.8
	2	27	9.0	13.7	31.6	27	9.0	14.8	100.6
Peak time [min]	Baseline	26	0:34	1:44	2:20	27	0:37	1:43	3:11
	2	27	1:30	2:19	2:46	27	1:40	2:26	3:04

[a](cut-off = median).

Acute Effects

Table 4 shows the results of the random effects model comparing within subject changes in outcome measurements. After shut-down study, participants rated their condition in the morning on average 1.74 (95% CI: 0.11 to 3.36) units fresher for each mA/m reduction in magnetic field exposure. There was a tendency for melatonin excretion to increase after shut-down of the transmitter by a factor of 1.15 (95% CI: 0.97 to1.36) per mA/m decrease in magnetic field exposure. The observed change in peak time for melatonin excretion after shut-down of the transmitter was independent of the extent of change in the magnetic field exposure.

In analyses stratified by sleep quality we found evidence of an effect from electromagnetic fields on morning tiredness scores and melatonin excretion in poor sleepers but not in good sleepers (defined as sleep quality below the median for the group) (Table 5). Again, peak time was not related to magnetic field exposure in either good or poor sleepers.

Association Between Sleep Quality and Melatonin

With respect to the biological mechanism, we did not find evidence of an association between rating of sleep quality (freshness vs. tiredness) and the melatonin cycle (Table 6); but due to small numbers, no break-down by level of EMF exposure was possible.

DISCUSSION

This paper describes the results of a unique ''natural experiment'' on sleep related effects of the operation and cessation of a short-wave broadcast transmitter. We confirmed that during operation of the transmitter self-rated morning freshness as an indicator of sleep quality decreased with increasing exposure to short-wave magnetic fields. We found that sleep quality improved after the transmitter shut-down, and we found evidence suggestive of a rebound in nightly melatonin excretion in poor sleepers. We did not find any acute or

TABLE 3. Chronic Effects of EMF on Morning Tiredness, Melatonin Excretion (AUC) and Peak Time (Regression Models of Outcomes During Baseline Period)

	Model	Coefficient[a]	Lower 95%-CI	Upper 95%-CI
Morning freshness/tiredness	Crude	2.78	−0.02	5.58
	Adjusted[b]	3.85	1.72	5.99
Melatonin excretion [ratio][c]	Crude	0.86	0.68	1.09
	Adjusted[b]	0.90	0.68	1.20
Peak time [min]	Crude	−14.4	−36.1	7.2
	Adjusted[b]	−4.4	−25.4	16.6

[a]Coefficient refer to a change in outcome parameter per unit increase in EMF exposure [mA/m].
[b]Model includes EMF, age, and sex.
[c]Due to the logarithm transformation the coefficient refers to a change in the ratio (the presented model coefficient is back transformed: in case of statistical significance, the 95% confidence interval does not include 1).

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TABLE 4. Acute Effects of EMF on Morning Tiredness, Melatonin Excretion (AUC), and Peak Time

	Model	Coefficient[a]	Lower 95%-CI	Upper 95%-CI
Morning freshness/tiredness	Crude[b]	−1.98	−3.62	−0.34
	Adjusted[c]	−1.74	−3.36	−0.11
Melatonin excretion [ratio][d]	Crude[b]	1.14	0.97	1.35
	Adjusted[c]	1.15	0.97	1.36
Peak time [min]	Crude[b]	2.7	−8.1	13.5
	Adjusted[c]	2.7	−8.2	13.7

[a]Coefficients refer to a change in outcome parameter per unit decrease in EMF exposure [mA/m].
[b]Model includes EMF and outcome measurement at baseline.
[c]Model includes EMF levels and outcome measurement at baseline, age, and sex.
[d]Due to the logarithm transformation the coefficient refers to a change in the ratio (the presented model coefficient is back transformed: in case of statistical significance, the 95% confidence interval does not include 1).

chronic effects of magnetic field exposure on the acrophase of the melatonin cycle.

The strengths of this study are that we were able to exploit the closure of the transmitter to conduct a natural experiment. We compared the same time interval before and after shut-down of the transmitter to minimize data variability. The observed time period allowed us to investigate acute effects of shut-down of the transmitter with a latency of 2 to 6 days. We also collected biological specimens. Although we were particularly interested in melatonin excretion at night, we did not collect nocturnal samples because this might have interfered with sleep quality. Nightly excretion was modelled using the complex-cosinor-analysis model [Lerchl and Partsch, 1994], which fits a characteristic 24-h melatonin excretion curve based on the five samples taken each day. The model takes into account irregularly spaced time series and imperfect compliance, and by using the natural logarithm of salivary melatonin levels and estimating all regression models by L1-norm we could attenuate the influence of outlying observations and measurement error. The estimate of the dose-response relation between melatonin excretion and magnetic field exposure was consistent and independent of the type of model estimated, including a least square approach and a model based on absolute differences.

Some limitations in the study design were due to the natural characteristic of the experiment. First, exposure from short-wave transmitters can cause side effects such as radio sounds in electrical appliances. Thus, we could not blind participants to exposure. Observer bias in the ratings of sleep quality can therefore not be excluded. Melatonin excretion, however, cannot be altered on purpose. Nevertheless, a psychologically triggered interference through other hormonal substances, e.g., adrenaline, cannot be ruled out completely.

Second, it was unfortunate that the change from winter to summer time coincided with the transmitter shut-down. This event was clearly demonstrated by the time difference in the acrophase between the two study periods. On the one hand this observed time shift was not related to magnetic field exposure, which validates our data modeling process. On the other hand, the time change may have influenced sleep quality. This would be expected to increase morning tiredness in period 2 because subjects had to get up 1 h earlier. The observed

TABLE 5. Acute Effects of EMF on Morning Tiredness, Melatonin Excretion (AUC), and Peak Time Stratified by Baseline Sleep Quality

	Sleep quality	Coefficient [a]	Lower 95%-CI	Upper 95%-CI
Morning freshness/tiredness	Poor	−3.54	−5.37	−1.72
	Good	1.30	−1.33	3.93
Melatonin excretion [ratio][b]	Poor	1.260	1.081	1.468
	Good	1.008	0.733	1.386
Peak time [min]	Poor	5.6	−8.2	19.3
	Good	0.8	−16.4	18.0

[a]Coefficients refer to a change in the outcome parameter per unit decrease in EMF exposure [mA/m]. Coefficients are adjusted for age and sex.
[b]Due to the logarithm transformation the coefficient refers to a change in the ratio (the presented model coefficient is back transformed: in case of statistical significance, the 95% confidence interval does not include 1).

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TABLE 6. Association Between Freshness/Tiredness Level And Melatonin Excretion (AUC) as Well as Peak Time

	Model	Coefficient[a]	Lower 95%-CI	Upper 95%-CI
Melatonin excretion [ln(pg/ml)]	Baseline	−0.88	−3.96	2.19
Peak time [min]	Baseline	−19.00	−85.38	47.39
Melatonin excretion [ln(pg/ml)]	Difference	1.705	−3.695	7.105
Peak time [min]	Difference	4.0	−118.3	126.3

The baseline model relates baseline tiredness rating to melatonin excretion/peak time. The difference model relates change in freshness/tiredness level to change in melatonin excretion/peak time.
[a]Coefficients are adjusted for age and sex.

lower tiredness after shut-down is therefore more likely to be an underestimation. If a time shift of 1 h had affected melatonin excretion, this effect would not have been dependent on the magnetic field exposure of the study participants. Neither would a time shift explain a dose-response relationship. The same is true for the possible influence of light on the melatonin cycle. Light exposure was increasing during the study period in spring. However, this is unlikely to create a bias in a dose-response manner. The same holds for possible changes in light exposure due to changing weather conditions.

Due to the high natural variability of the melatonin cycle, large sample sizes are needed to obtain strong evidence that magnetic field exposure affects melatonin excretion. We found weak evidence of chronically suppressed melatonin excretion before shut-down of the transmitter. Evidence of an acute increase in melatonin excretion after withdrawal of magnetic field exposure was observed in poor sleepers in accord with our hypothesis. In this context it should be noted that the study had more power to detect acute effects than chronic effects because baseline values of each subject were taken into account.

Our findings are consistent with the hypothesis of a melatonin suppressing effect from magnetic field exposure and a rebound effect after the exposure has ended [Stevens, 1987]. The effect of short wave exposure (3–30 MHz) on melatonin has not previously been investigated except in the area of the Schwarzenburg transmitter [Altpeter et al., 1995; Stärk et al., 1997]. A finding there was an indication of a melatonin rebound effect in cows 3 days after temporary interruption of transmitter activity [Altpeter et al., 1995; Stärk et al., 1997].

A melatonin suppressing or a rebound effect has not been detected so far in randomized crossover trials of mobile phone exposure (radiation in the high frequency range, 900–1800 MHz) [Mann et al., 1998; de Seze et al., 1999; Radon et al., 2001; Bortkiewicz et al., 2002]. Three of those studies investigated melatonin in the night following or during the exposure only [Mann et al., 1998; Radon et al., 2001; Bortkiewicz et al., 2002]. The fourth analyzed melatonin excretion the night after a 4 week exposure had ended and 15 days later [de Seze et al., 1999]. Thus, none of those studies would have captured a 2 to 6 day latency, but a melatonin suppression effect due to a longer exposure period should have been detected, if present. Two recently published observational studies have found a reduction in nocturnal melatonin excretion with increasing use of mobile phones [Burch et al., 2002; Jarupat et al., 2003]. A further observational study found decreased 6-sulfatoxymelatonin urinary excretion in workers exposed to video screen emitting magnetic fields in the kilohertz frequency range [Santini et al., 2003]. However, extrapolating findings from different frequency ranges is still an uncertain endeavor as a common underlying biological mechanism is not known.

Of note, we found evidence that EMF exposure was associated with sleep quality and melatonin excretion, but in poor sleepers only. This suggests that there might be a group of people who are sensitive to electromagnetic field exposure. This phenomenon has been described as electromagnetic hypersensitivity (EHS) [Bergqvist and Vogel, 1997; Radon and Maschke, 1998; Hillert et al., 2002; Levallois, 2002; Mueller et al., 2002; Leitgeb and Schrottner, 2003; Röösli et al., 2004]. It is conceivable, however, that poor sleepers were more emotionally involved in the study and we cannot rule out the possibility of psychologically mediated effects on melatonin excretion.

Irrespective of the frequency, other studies support the hypothesis that melatonin suppression from EMF exposure or rebound effects after exposure termination require extended time to become manifest [Wilson et al., 1990; Pfluger and Minder, 1996; Burch et al., 1999; Graham et al., 2000]. A delayed effect might explain some negative results of short-term exposure trials [Graham et al., 1996a; Graham et al., 1996b]. Overall, the hypothesis of an association between melatonin cycle and EMF exposure requires therefore further investigation [Warman et al., 2003].

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In our study there was no shift in the acrophase of the melatonin cycle, although investigating this in detail was hampered by the change from winter to summer time. Our research was not suited to provide evidence of a plausible biological pathway for the effects of melatonin on EMF-associated sleep problems. Given that our results may be due to lack of blinding the question remains whether the present study could be repeated under well controlled laboratory conditions. This, however, is unlikely due to feasibility constraints. Who will accept staying in a sleep lab for more than a week? And where can enough sleep laboratories be found to investigate a sample size of more than 50 persons for several weeks?

CONCLUSIONS

Our findings support a relationship between operation of the radio transmitter under investigation and sleep disturbances in the exposed population, and they are compatible with a causal dose-effect model between radio frequency EMF exposure and sleep quality as well as melatonin excretion. Due to the observational nature of the study, a direct biological cannot, however, have been causality proven, and the possibility of a psychological (Nocebo) rather than a biological effect cannot be excluded. From a public health perspective our findings call for caution in exposing populations to EMF from short-wave radio transmitters. But they do not allow for any firm conclusions about the effects of mobile phone radiation, as short-wave frequency is different from mobile phone radiation. Further studies investigating this particular exposure are needed.

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