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Household appliance use and residential exposure to 60-Hz magnetic fields

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We characterized the distribution of exposure to magnetic fields (MFs) during daily activities and during household appliance use, and estimated the relative contribution of various activities and appliances to total daily exposure. One hundred sixty-two subjects provided information on their patterns of appliance use and wore personal monitors for 24 h to collect MF exposure data. Of total exposure, 27% accumulated while subjects were in bed; 41% while at home but not in bed; 9% at work; and 24% elsewhere. Less than 2% of the total MF exposure accumulated during the use of each of the eight individual appliances considered, except computers, during the use of which 9% of the total exposure accumulated. Of the time subjects spent at exposure levels higher than 2 μT, 8% accumulated while they were using microwave ovens, and 4% and 3% while using computers and electric stoves, respectively. Mean MF measurements tended to be lowest when subjects were in bed and highest at work and during the use of microwave ovens, coffee grinders, hair dryers, and electric shavers. Results from questionnaires on household appliance use in the past year were not useful in predicting the total mean exposure level and over-threshold exposures measured by 24-h personal monitors. Significant MF exposure accumulates at home, at work, and elsewhere; therefore, accurate exposure assessment needs to consider residential, occupational, and other sources together. Questionnaire-based information on appliance use has limited value in the assessment of average and over-threshold exposure to MFs. *Journal of Exposure Analysis and Environmental Epidemiology* (2001) **11,** 41–49.

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Introduction

Numerous epidemiologic studies have investigated whether exposure to magnetic fields (MF) affects the risk of cancer and other diseases. Investigations have been limited, however, by difficulties in assessing exposures and especially in developing estimates of exposures that occurred in the past. Among the crudest estimates are those of exposure to household appliances, which have been based largely on questionnaires. In general, risk estimates have been made for one appliance at a time (Preston-Martin et al., 1988, 1996; Savitz et al., 1990; London et al., 1991; Vena et al., 1991, 1994; Lovely et al., 1994; McCredie et al., 1994; Gurney et al., 1996; Dockerty et al., 1998; Hatch et al., 1998). Variations in the design and type of appliance, as well as in the pattern of use, have not been considered in most studies and have likely led to a large degree of misclassification. Additional difficulties are posed by missing data and infrequent use of many appliances.

Few of the several approaches to improving estimates of residential MF exposure have focused sufficiently on contributions from household appliances, and fewer still on developing a methodology to combine exposure from individual appliances and other sources. In fact, little is known about either the magnitude and distribution of exposures from appliances or the relative importance of exposures accrued at home and elsewhere.

The primary aims of this study are to describe in adults (1) the distribution of MF exposures during a variety of daily activities at work, at home, and elsewhere, and during sleep; (2) the distribution of MF exposures from certain key household appliances; and (3) the relative contribution of various activities and specific household appliances to total daily MF exposure. The study also explores the comparability of exposure assignment based on questionnaire data with that obtained from measurements by meters worn for 24 h.

Methods

Study Population

The study population consisted of couples residing in three northern California communities (Palo Alto, Menlo Park, and Redwood City) between April and September 1996 who met the following eligibility criteria: (1) either married or living as partners; (2) aged 20–79 years, according to the man's age; and (3) able to be interviewed in English (both members of the couple). Subjects were recruited

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through random digit dialing and through advertisements in local newspapers. (For a more detailed description of methods, see Mills et al., 2000.)

Interview Procedures

At study entry, two trained interviewers conducted structured interviews with both members of each couple simultaneously. Each member of the couple provided personal information as well as information about the spouse or partner. Two months after the initial interview, we conducted a repeat interview. We asked both members of the couples not to discuss the content of the survey until the second interview was completed.

Table 1. Appliance use during the past year based on the questionnaire, and Spearman rank correlation coefficients for associations between estimated duration of reported appliance use during the past year and measured MF exposure level (μT) during the observation day.

	Number of subjects reporting use of appliance	Mean duration (range) of appliance use (h/year) among subjects reporting use of appliance	Spearman correlation coefficient between duration of reported appliance use by questionnaire (h/year) and mean daytime exposure level (μT) among subjects reporting use during the past year	Spearman correlation coefficient between duration of reported appliance use by questionnaire (h/year) and mean daytime exposure level (μT) among all subjects
Refrigerator	162	167 (9–2078)	0.01	0.01
Telephone	160	948 (7–5144)	−0.04	−0.04
Microwave	*143*	*83 (9–134)*	*0.09*	*0.08*
Toaster	140	28 (0.2–1273)	0.04	0.00
Vacuum cleaner	138	38 (0.4–520)	−0.11	−0.06
Washer	129	27 (1–182)	0.04	0.06
Answering machine	124	380 (0.4–3637)	0.09	0.16
Computer	*122*	*469 (1–4365)*	*−0.21*	*−0.13*
Electric clock	119	2053 (0.1–6001)	0.10	−0.01
TV	112	139 (0.1–2598)	0.06	−0.01
Stereo	109	144 (0.1–4365)	0.07	−0.02
Blender	108	17 (0.1–520)	0.12	0.03
Garbage disposal	105	21 (0.3–364)	0.05	0.07
Printer	103	239 (0.1–4365)	−0.16	−0.15
Iron	101	47 (0.3–2078)	−0.09	0.02
Dishwasher	99	35 (1–364)	0.08	−0.06
Electric stove	*97*	*182 (3–2078)*	*0.00*	*−0.12*
Coffee maker	*93*	*37 (0.2–416)*	*0.24*	*0.06*
Hair dryer	*93*	*30 (0.1–208)*	*0.07*	*0.06*
Clothes dryer	92	26 (1–182)	0.04	0.01
Electric range hood	87	54 (0.3–520)	0.11	0.00
Fan	85	128 (0.1–5144)	0.07	−0.07
Power tools	77	43 (0.1–1039)	0.08	−0.03
Coffee grinder	*59*	*6 (0.1–39)*	*0.37*	*0.02*
Electric shaver	*54*	*18 (0.1–130)*	*0.24*	*0.06*
Fax machine	41	211 (0.4–2078)	−0.02	−0.05
Hair curler	36	35 (0.1–520)	0.04	−0.01
Can opener	29	11 (0.4–104)	0.05	−0.14
Sewing machine	28	13 (0.1–104)	0.38	−0.03
Electric blanket	27	517 (2–2910)	0.01	−0.02
Cellular phone	*25*	*367 (0.1–5820)*	*−0.17*	*0.07*
Massager	25	12 (0.1–52)	−0.16	0.02
Jacuzzi	14	47 (0.1–520)	0.49	0.00
Electric mower	12	30 (0.4–104)	0.15	−0.01
Vanity mirror	11	46 (1–208)	−0.42	0.03
Water bed	10	2723 (1819–3118)	−0.17	0.00
Washer/dryer	4	14 (1–32)	−1.00	0.02

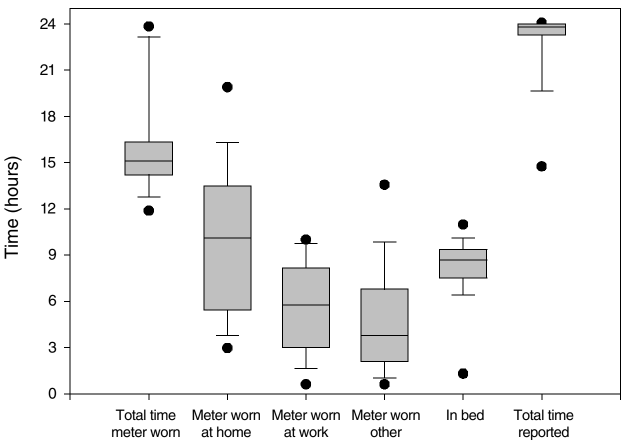

Figure 1. Number of hours spent in different partitions during the observation day. The shaded area represents the interquartile range; the horizontal line in the center represents the median; vertical bars represent the 10th and 90th percentiles; dots represent the 5th and 95th percentiles.

The structured interview included information on demographic factors (age, gender, race/ethnicity, marital status, education, household income, years lived with spouse or partner), occupational history, household appliance use, residential history, smoking history, physical activity, and sleep patterns.

Measurement of Household Appliance Use

For each of 37 appliances (listed in Table 1), we asked study subjects how many months of the past year they had spent at least some time within 3 ft of the appliance while it was in use, and how much total time per week (in hours and minutes) during these months they had spent within 3 ft of the appliance while it was in use. Based on this information, we estimated the hours per year of exposure to each appliance. To refer to time periods when subjects reported being within 3 ft of an appliance in use, even if someone else was using it, we use the term "appliance use."

Before data collection began, we selected nine key appliances (electric can opener, coffee maker, electric coffee grinder, electric blanket, electric stove or range, hair dryer, microwave oven, electric shaver, and lighted vanity mirror) for more detailed inquiry. Because only 6% of the subjects reported ever having used a lighted vanity mirror during the past year, this appliance was dropped from the list, leaving eight key appliances. The selection of key appliances was based on high MF levels immediately surrounding the appliances when in use (as determined from previous studies); the relatively high proportion of the population thought *a priori* to use the appliances; and the close proximity of the person typically using each appliance during at least some of the time it is used.

Exposure Measurement

At the time of the second interview, we asked each subject to wear an EMDEX Lite™ meter (Enertech Consultants, Campbell, California) to collect personal MF exposure data for 24 h on the following day, whether it was a weekday or a weekend day. We instructed subjects to wear their meters hanging on lanyards at chest level while they were awake, and to place them at their bedsides at night. If an appliance was situated within 3 ft of a subject in bed, the meter was to be placed at an equal distance from the appliance and the subject. We programmed the meters to sample and record power-frequency MF along three orthogonal axes every 4 s. We supplied subjects with small diaries to record the start and stop times of their presence at home, at work, and elsewhere, as well as times when their meters were not worn. We also instructed subjects to record the time periods they spent within 3 ft of any of the eight key appliances while in use. In addition, we asked participants to record the amount of time they spent within 3 ft of computers and cellular phones while in use, since the use of these appliances was thought to be rapidly increasing in the U.S. population. Because no subjects reported using electric can openers, and only two reported using electric blankets during the observation day, we included measurements for eight appliances in the analyses.

We checked the calibration of the meters before each 24-h period of data collection. We transferred the measurement results to a computer and examined them for readability and quality. Specifically, we inspected the data for each axis for characteristic patterns of meter failure from various hardware malfunctions; we detected none.

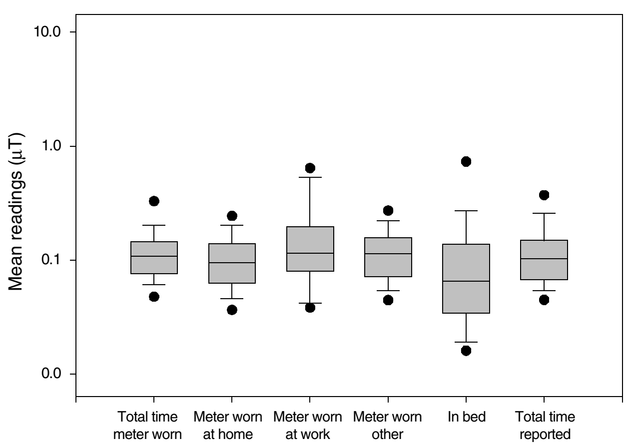

Figure 2. Mean MF readings in different partitions. The shaded area represents the interquartile range; the horizontal line in the center represents the median; vertical bars represent the 10th and 90th percentiles; dots represent the 5th and 95th percentiles.

Table 2. Percentage of participants according to mean MF readings during the total exposure period and during periods of exposure at home (daytime), at work, in places other than work and home, and in bed.

Mean (μT)	Total (N=162) (%)	Meter worn, at home (N=153) (%)	Meter worn, at work (N=47) (%)	Meter worn, other (N=143) (%)	In bed[a] (N=142) (%)
0.000–0.099	48.8	52.3	40.4	39.9	64.8
0.100–0.199	37.7	37.3	34.0	46.2	21.8
0.200–0.299	7.4	6.5	10.6	10.5	4.2
≥0.300	6.2	3.9	14.9	3.5	9.2

[a]Subjects were instructed to place their meters near their bedsides, but not next to an appliance, while in bed.

Statistical Analysis

For each subject, we assigned MF readings, taken every 4 s, to various categories, or partitions, representing the subject's whereabouts according to the records in the activity diary: in bed, at home, at work, or neither at home nor at work. An additional partition included readings recorded when the meter was not worn. MF readings were also noted for time periods when subjects used the various appliances. For each partition or period of appliance use, we computed the length of time and the mean, median, maximum, and various percentiles of the MF readings, and the length of time of exposure to MFs higher than 0.5 and 2.0 μT.

Since the various measures were clearly not normally distributed, we calculated Spearman rank correlation coefficients, rather than Pearson correlation coefficients, to evaluate the strength of association between various measures. However, results were similar if Pearson correlation coefficients were used. We also calculated the proportion of the total MF exposure and the proportion of time spent in fields higher than 0.5 and 2.0 μT that was accumulated in various partitions and during the use of various appliances. To compare characteristics of subjects with high mean exposures ($\geq$0.3 μT) and low mean exposures ($<$0.1 μT), we used the t-test, Wilcoxon rank test, chi-square test, or Fisher's exact test, as appropriate.

We used multiple linear regression modeling with backward stepwise variable selection to predict overall mean, median, and maximum exposures based on frequency and duration of appliance use (as determined by questionnaire) and subject characteristics. Since exposure measurement values had skewed distributions, we also completed regression analysis with log transformation of the exposure variables. We calculated r^2 values for regression models to determine the portion of variability in the dependent variables explained by the included independent variables. We performed all statistical analyses using SAS software, version 6.12 (SAS Institute, Cary, North Carolina).

Results

Of the 184 subjects (92 couples) who participated in the first round of interviews, 170 (85 couples or 92%) also participated in the second round. Of these, 162 subjects (81 couples or 95%) had valid MF measurements. (The first four couples were treated as pilot participants for the MF measurement phase of the study and were not included in the analysis.) The mean age of the subjects was 49 years, with a range of 24–81 years; 83% was comprised of whites, and their average level of education was high: 88% had some post-secondary education, including 33% with post-graduate degrees.

The mean length of the total observation period, i.e., the nominal 24-h period, including time when meters were worn and time spent in bed, was 22.7 h [standard deviation (SD) 2.8], with a range of 11.3–24.3 h; 90% of the subjects covered at least 20 h. Subjects reported wearing personal meters for an average of 15.8 h (SD 3.5) (n=162) (Figure 1). One hundred forty-two subjects reported the amount of time they had stayed in bed, during which time they had been instructed to place their meters near their bedsides. These subjects spent, on average, 8.2 h (SD 2.3) in bed. Subjects spent an average of 16.9 h (SD 5.1) at home (n=153), an average of 5.8 h (SD 3.1) at work (n=47),

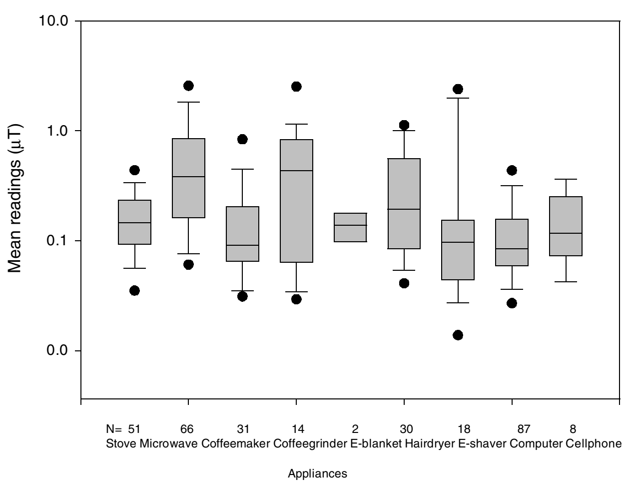

Figure 3. Distributions of mean MF readings while different appliances were used at any time during the observation day. The shaded area represents the interquartile range; the horizontal line in the center represents the median; vertical bars represent the 10th and 90th percentiles; dots represent the 5th and 95th percentiles.

Table 3. Measures of appliance use among study subjects during the observation day.

Appliance	Number of subjects using the appliance during the observation day	Mean duration of appliance use (min) among subjects using the appliance	Mean exposure levels during appliance use (μT)	Percentage of total exposure accumulated during appliance use in the total population (N=162)	Percentage of total exposure accumulated during appliance use among subjects who used the appliance	Percentage of daytime exposure accumulated during appliance use among subjects who used the appliance
Computer	87	176 (1–606)	0.14 (0.02–0.86)	8.6 (0–88.5)	15.9 (0.1–88.5)	21.2 (0.1–90.7)
Microwave oven	66	30 (0.2–756)	0.68 (0.03–3.07)	1.5 (0–59.7)	3.8 (0.01–59.7)	4.4 (0.02–60.2)
Electric stove	51	45 (1–541)	0.18 (0.02–0.68)	1.5 (0–45.2)	4.6 (0.1–45.2)	5.8 (0.1–59.9)
Coffee maker	31	12 (0.2–217)	0.19 (0.02–0.94)	0.2 (0–17.5)	1.1 (0.01–17.5)	1.5 (0.01–19.4)
Hair dryer	30	7 (0.4–25)	0.35 (0.04–1.37)	0.2 (0–8.6)	1.3 (0.01–8.6)	1.6 (0.01–8.6)
Electric shaver	18	3 (0.6–9)	0.42 (0.01–2.54)	0.06 (0–3.6)	0.5 (0.01–3.6)	0.7 (0.02–3.6)
Coffee grinder	14	4 (0.2–32)	0.60 (0.03–2.93)	0.06 (0–3.6)	0.7 (0.01–3.6)	2.1 (0.01–16.7)
Cellular phone	8	153 (2–584)	0.17 (0.04–0.40)	1.1 (0–78.0)	21.4 (0.01–78.0)	23.4 (0.1–88.3)

Values in parentheses represent ranges.

and an average of 4.9 h (SD 4.2) neither at home nor at work (n=143).

The mean of the MF measurements in the different partitions varied widely among subjects, but tended to be lowest while they were in bed and highest at work (Figure 2). For 49% of the subjects, the mean (time-weighted average) of the measurements for the total observation period was less than 0.1 μT, and for 6%, the mean was higher than 0.3 μT (Table 2). Low mean readings (<0.1 μT) were more common in bed (65%), and higher mean readings ($\geq$0.3 μT) were more common at work (15%). However, the second highest percentage of mean readings over 0.3 μT accrued in bed.

The means of readings during appliance use also varied widely within each appliance category, but tended to be highest during the use of microwave ovens, coffee grinders, electric shavers, and electric hair dryers (Figure 3). The mean exposure levels were 0.6 μT or higher for microwave ovens and coffee grinders, and higher than 0.3 μT for electric shavers and hair dryers (Table 3). For all other appliances, mean exposure levels were below 0.2 μT. Subjects used computers and cellular phones for at least 2.5 h on average, and at least 30% used computers, microwave ovens, and electric stoves. Overall, subjects were exposed to MFs higher than 0.5 μT for an average of 67 min (SD 146), and to fields higher than 2 μT for an average of 6.1 min (SD 36.8).

Of the total exposure (the sum of all readings) for all subjects, 26.6% accumulated in bed; 40.8% at home but not in bed; 8.9% at work; and 23.7% neither at home nor at work (Figure 4). Less than 2% of the total exposure accumulated while subjects were using the various appliances, except for computers, during the use of which 8.6% of the total exposure accumulated (Table 3). The low percentages of the total exposures accrued during appliance use resulted mainly from the relatively short use of the appliances. Among subjects who used specific appliances, the proportion of the total exposure accumulated during use was high for cellular phones and computers: 21% and 16%, respectively. While subjects were using electric stoves, 4.6% of the total exposure accrued; microwave ovens, 3.8%; and other appliances, less than 2%. These percentage values were similar, with only a slight increase, when we calculated these proportions for total daytime exposures (Table 3).

The relative importance of the various appliances increased when we calculated the proportion of time subjects spent exposed to MFs higher than 0.5 and 2 μT while using the appliances, except for computers and coffee makers (Table 4). Among the total study population, 7.9%

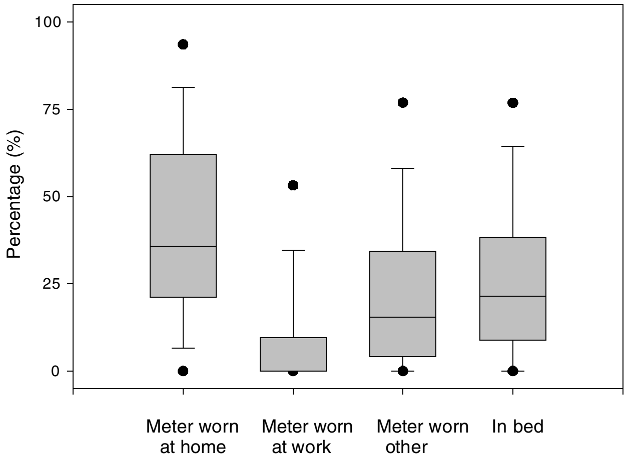

Figure 4. Percentage of total exposure accumulated in different partitions. The shaded area represents the interquartile range; the horizontal line in the center represents the median; vertical bars represent the 10th and 90th percentiles; dots represent the 5th and 95th percentiles.

Table 4. Proportion of time spent at MF exposure levels higher than 0.5 and 2 μT by appliance use among study subjects during the observation day.

Appliance	Percentage of time spent at levels >0.5 μT during which appliances were used among all subjects	Percentage of time spent at levels >0.5 μT during which appliances were used among subjects who used the appliance	Percentage of time spent at levels >2 μT during which appliances were used among all subjects	Percentage of time spent at levels >2 μT during which appliances were used among subjects who used the appliance
Computer	5.4 (0–98.8)	10.0 (0–98.8)	4.4 (0–100.0)	8.2 (0–100.0)
Microwave oven	3.6 (0–93.5)	9.0 (0–93.5)	7.9 (0–100.0)	19.3 (0–100.0)
Electric stove	3.4 (0–78.4)	10.9 (0–78.4)	3.3 (0–100.0)	10.6 (0–100.0)
Coffee maker	0.4 (0–33.2)	2.2 (0–33.2)	0.1 (0–14.0)	0.5 (0–14.0)
Hair dryer	0.9 (0–48.3)	4.7 (0–48.3)	1.7 (0–92.3)	9.1 (0–92.3)
Electric shaver	0.1 (0–13.8)	1.1 (0–13.8)	0.9 (0–82.6)	7.7 (0–82.6)
Coffee grinder	0.2 (0–9.5)	2.6 (0–9.5)	1.2 (0–88.9)	13.5 (0–88.9)
Cellular phone	1.2 (0–95.8)	24.8 (0–95.8)	1.4 (0–100.0)	27.8 (0–100.0)

Values in parentheses represent ranges.

of the time spent in fields higher than 2 μT accumulated during the use of microwave ovens, and 4.4% and 3.3% during the use of computers and electric stoves, respectively. Among subjects who used specific appliances, the proportion of the total time of exposure to MF higher than 2 μT was more than 7% during the use of all appliances except coffee makers, and more than 10% during the use of cellular phones, microwave ovens, coffee grinders, and electric stoves (Table 4).

The correlation between mean exposure during use of the included appliances and mean daytime exposure was low for all subjects; however, there was a good correlation for computers and electric stoves, with correlation coefficients of 0.74 and 0.66, respectively (Table 5). The duration of appliance use, determined from the diaries, did not correlate well with mean daytime exposure level either among all subjects or among those who used the appliances. The duration of use estimated for the previous year based on the questionnaires and that estimated for the observation day based on the diaries showed a poor correlation, except for cellular phone use among subjects who used cellular phones during the observation day (Table 5). However, the latter subgroup included only eight subjects.

The estimated amount of time each of the 37 appliances included in the questionnaire was used in the previous year is shown in Table 1. There was no correlation between questionnaire-based time estimates and mean daytime exposures. Similarly, no correlation was found between daytime mean exposure level during the observation day and either sum of usage time for all appliances or number of

Table 5. Spearman rank correlation coefficients for associations between various measures of appliance use determined by meter, diary, and questionnaire.

Appliance	Mean exposure level (μT) during appliance use *versus* mean daytime exposure level (μT)		Duration of appliance use during the observation day by diary (min) *versus* mean daytime exposure level (μT)		Reported use of appliance during the past year by questionnaire (h/year) *versus* duration of appliance use during the observation day by diary (min)		
	Among all subjects	Among subjects who reported use of the appliance during the observation day	Among all subjects	Among subjects who reported use of the appliance during the observation day	Among all subjects	Among subjects who reported use of the appliance during the observation day	Among subjects who reported use of the appliance during the past year
Computer	0.16	0.74	−0.05	0.09	0.48	0.20	0.37
Microwave oven	0.26	0.35	0.23	0.21	0.11	0.05	−0.06
Electric stove	0.03	0.66	−0.07	−0.14	0.59	0.15	0.28
Coffee maker	0.01	0.20	0.02	0.53	0.36	0.20	0.16
Hair dryer	0.08	0.22	0.06	−0.29	0.51	0.24	0.42
Electric shaver	0.06	0.45	0.05	−0.17	0.55	0.22	0.34
Coffee grinder	−0.01	0.15	−0.01	0.09	0.40	0.14	0.05
Cellular phone	0.09	0.43	0.09	0.31	0.47	0.98	0.24

Table 6. Comparison of subjects with high and low mean total exposure levels.

	Subjects with mean total exposure $\geq$0.3 μT (N=10)	Subjects with mean total exposure <0.1 μT (N=79)
Age (years)	55±16	47±15
Sex: female	60%	47%
Ethnicity: white	90%	82%
Education (years) <13	0	10%
13–16	60%	38%
>16	40%	52%
Income >US $60,000/year	30%	47%
Appliance use		
Computer	60%	57%
Microwave	50%	32%
Electric stove	20%	35%
Coffee maker	20%	19%
Hair dryer	30%	18%
Electric shaver	30%	9%
Coffee grinder	10%	8%
Cellular phone	0	1%
Number of appliances used during the observation day (based on measurements, 0–8)	2.2±0.9	1.8±1.1
Number of appliances used during the past year (based on questionnaire, 0–37)	17.8±4.3	18.3±4.1

appliances used in the previous year, as assessed by the questionnaires (Spearman rank order correlation coefficients −0.04 and −0.05, respectively). There was either a weak correlation or no correlation between the amount of time spent in MFs above 0.5 or 2 μT and the estimated amount of time the various appliances were used during the past year, based on questionnaires, or during the observation day, based on diaries (Spearman rank order correlation coefficients ranged between −0.36 and +0.41).

A comparison of subjects who had mean total exposure levels of over 0.3 μT to those who had mean total exposure levels of less than 0.1 μT revealed no significant difference between the two exposure groups in either their demographic characteristics or in their observed and reported use of appliances, although microwave ovens, hair dryers, and electric shavers were more frequently used among subjects in the high-exposure group (Table 6).

Results from the questionnaires were not useful in predicting the observed total mean exposure levels as measured by the meters. When we used multiple linear regression with backward stepwise variable selection to identify predictors for the logs of the mean measured exposure levels from the questionnaire-based estimated duration of use of various appliances over the previous year, the final model included 5 of 37 appliances: toaster, coffee grinder, electric blanket, electric can opener, and iron. The model explained only a small fraction of the variation in mean measurements (R^2=0.14).

A model including demographic variables (age, sex, ethnicity, education, and income) showed that none of these variables was a significant predictor for the logs of the mean exposure levels. Use of these variables resulted in a model that explained only a very small portion of the variance of the outcome variables (R^2=0.02).

We obtained similar results when we repeated the analyses using the log of the highest reading or the log of the median of the readings instead of the log mean. Analyses without log transformation or those using time spent in MFs above 0.5 and 2 μT as dependent variables had similar results.

Discussion

Our study found a wide variation in mean (time-weighted average) MF readings among study subjects. Readings tended to be lowest while subjects were in bed and highest at work and during the use of microwave ovens, electric coffee grinders, hair dryers, and electric shavers. Mean MF readings during different daily activity periods showed a similar distribution to mean MF readings for corresponding periods in a nationwide survey of residential MF measurements (Zaffanella and Kalton, 1998). Mean measurements taken during appliance use were also comparable to values in previous reports attempting to describe MFs measured at specified distances from domestic appliances (Mader and Peralta, 1992; Preece et al., 1997). Mean readings for microwaves and computers fell largely in the range reported by Preece et al. (1997) for distances of 50 and 100 cm, but were somewhat higher than the range given by Mader and Peralta (1992) for distances from 30 to 305 cm. Values for hair dryers, electric shavers, and coffee grinders were generally within the range of Preece et al. (1997) for distances of 5 and 50 cm, but tended to be lower than the range of Mader and Peralta (1992) for distances from 3 to 30 cm. When comparing these values, however, it is important to remember that measured MFs decrease rapidly with distance from appliances. In our study, we did not make measurements at specified distances from appliances, but rather made measurements during ordinary appliance use, with subjects wearing their meters at chest level. Therefore, the resulting exposures, although largely dependent on the way subjects used specific appliances, are probably more representative of typical exposures.

Mean MF measurements made during the use of the above appliances correlated poorly with mean daily exposure levels, probably both because the appliances were used for a short time and because only a relatively small portion of study subjects used them during the observation day. There was a good correlation for computers and electric stoves, but only when subjects who actually used these appliances during the observation day were included. Thus, studies focusing on a single appliance or a small number of appliances do not give a good indication of total MF exposure.

Questionnaire-based data estimating the amount of time the various appliances were used during the past year did not predict the mean exposure level measured by meter during the observation day. This finding is consistent with the conclusion of Preece et al. (1999) that questionnaires have little or no value for time-weighted average MF exposure estimation. The amount of time subjects were exposed to over-threshold MF was also poorly correlated with questionnaire-based exposure estimates. Similarly, the amount of time certain appliances were used during the observation day correlated poorly with questionnaire-based estimates for their use in the past year. The only exception was usage time for cellular phones for subjects who actually used them during the observation day, but this subgroup included only eight subjects.

Several factors may explain the poor correlation between questionnaire-based estimates of usage time and mean daily MF readings. The questionnaire referred to the average amount of time subjects used certain appliances during the past year, and the accurateness of these estimates could be affected by poor recall. Even if recall was accurate, present behavior does not necessarily reflect the past year's experience. Similarly, since measurements were taken for only one day, the degree of misclassification depends on the representativeness of that particular day for the whole period. In addition, subjects' behavior could have changed as a result of wearing their meters, or they may have failed to record or inaccurately recorded all instances when they were within 3 ft of an appliance.

An additional limitation of our study that may restrict our ability to generalize its findings is that the study population was self-selected and was recruited, in part, through newspaper advertisements. Also, ethnic minorities were underrepresented among study subjects, and subjects tended to be more highly educated than the general population.

Our results showed that although a large portion of the total exposure was accumulated at home, a significant portion occurred outside the home (9% at work and 24% in other places). These findings indicate that a comprehensive exposure assessment protocol needs to include exposure determination at home, at work, and in other places. Including only home or only work exposure may result in substantial exposure misclassification.

With regard to the contribution of individual appliances to total exposure, only computers contributed significantly (8.6%), while other appliances each contributed less than 2%. Most of the time, low contribution was caused by infrequency and short duration of appliance use. When limited to only those subjects who actually used certain appliances, the analysis showed that computers (16%) and cellular phones (21%) could contribute significantly to total daily exposure. It is important to note, however, that exposure associated with an individual appliance cannot be separated from exposures to other sources where the appliance was used. The notable contribution of computers and cellular phones to total daily exposure resulted mainly from their extended use during the day, and may reflect ambient exposure to MF rather than appliance-related exposure.

A different picture arose when we examined the contribution of individual appliances to MF exposures above 0.5 and 2 μT. The relative contribution of appliances with associated high MFs, such as microwave ovens, electric stoves, and electric coffee grinders, increased while the relative contribution of computers, which have lower associated MFs, decreased.

In summary, significant MF exposure accumulates at home, at work, and elsewhere. Exposure assessment methods should therefore include residential, occupational, and other sources of exposure. Variability in MF exposure among individuals is large for each daily activity and for periods of use for each appliance, and this variability cannot be captured with the use of questionnaires. Certain appliances that may be used for extended periods of time, such as computers and cellular phones, should be considered when assessing mean MF exposure, since a significant portion of total daily exposure may accumulate during their use. Also, some appliances with higher associated MFs, such as microwave ovens and electric stoves, may be significant determinants of exposures to high, over-threshold exposures.

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