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Comparison of extremely low frequency (ELF) magnetic field personal exposure monitors

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The MultiWave® System III (MW III), a recently developed personal monitor for extremely low frequency (ELF) magnetic fields, was compared with the standard EMDEX Lite (Electric and Magnetic Field Digital Exposure System), the type of monitor widely used in epidemiology and other exposure assessments. The MW III captures three-axis magnetic field waveforms for the calculation of many exposure metrics, while the EMDEX monitors measure only the root-mean-squared (RMS) vector magnitude (or resultant). Thirty-eight partial period personal samples were monitored in six different job classifications. The sampling time for each personal sample ranged from 90 to 133 min, with a mean sample time of 110 min. The EMDEX Lite and MW III were evaluated by comparing the maximum and partial period time-weighted average (TWA) of the ELF magnitude. TWA exposures measured for the 38 partial period samples by the EMDEX Lite ranged from 1.2 to 65.3 mG, with a mean of 18.1 mG, while corresponding values for the MW III ranged from 1.1 to 65.8 mG, with a mean of 17.7 mG. The maximum magnetic field exposures measured for the 38 partial period personal samples by the EMDEX Lite ranged from 27.0 to 420.2 mG, with a mean of 216.3 mG, while corresponding values for the MW III ranged from 40.2 to 1311.8 mG, with a mean of 368.4 mG. The maximum and TWA ELF magnetic field exposures measured by the EMDEX Lite and MW III were compared using a two-tailed, paired t-test. Analyses indicate that there was no significant difference in the TWA magnetic field magnitude measured by the EMDEX Lite and MW III. On the other hand, the EMDEX Lite reported significantly lower ($P=0.002$) maximum magnetic field measurements compared to the MW III. From a detailed analysis of the time traces, the EMDEX Lite appears to measure the ELF magnitude inaccurately when the field changes rapidly over a 4-s sampling interval. The results of this comparison suggest that the standard EMDEX Lite and MW III provide similar measure of the TWA magnetic field in a variety of occupational settings and ELF magnetic field magnitudes. However, the EMDEX Lite underestimates maximum exposures when compared to the MW III.
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Introduction

The association between extremely low frequency (ELF=3–3000 Hz) magnetic fields, such as those generated by 60 Hz AC electrical current, and disease has been studied in residential and occupational settings (Bracken, 1993; Savitz, 1993; NIEHS, 1998). Some of this research suggests that AC magnetic field exposures might cause leukemia, brain cancer, breast cancer, and other types of cancer (Bracken, 1993; Savitz, 1993; Breysse et al., 1994b; NIEHS, 1998). However, the mechanism for interaction of ELF magnetic fields and the human body is not understood (Savitz, 1993; Bowman et al., 2000). Therefore, determining safe levels or acceptable dose is difficult. To date, ELF magnetic field exposure assessments have focused on measuring the root mean square (RMS) magnitude of the magnetic field vector (Bracken, 1993; Bowman and Methner, 2000). Exposure analysis has typically been limited to examination of the mean, median, and maximum values along with other basic descriptive statistics associated with the RMS magnetic field vector. The use of other biologically and physically based exposure metrics has been considered based on biophysical mechanisms associated with disease such as induced currents, free radical production, magnetosome interactions, ion parametric resonance, and temporal consistency (Bracken, 1993; Bowman et al., 2000). However, these biological and physical metrics have not been widely investigated due to limitations of personal exposure monitoring equipment. If EMF causes disease, risk estimates should be greater with a biologically based metric that is directly associated with causality than with the time-weighted average (TWA) RMS magnitude, which may be only loosely correlated with the biologically based metric.

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Table 1. Calculable exposure metrics based on MW III measurement data.

Physical metrics	Biological metrics
ELF magnitude (mG)	Induced brain currents (mA/m^2)
Static magnitude (mG)	Full-band (0–3000 Hz) intensity (mG^2)
ULF magnitude (mG)	ELF component perpendicular to static field vector (mG)
Maximum harmonic (Hz)	ELF component parallel to static field vector (mG)
Polarization (%)	
Total harmonic distortion (%)	

Past use of EMDEX meters demonstrates reliability for measuring the RMS magnitude of the magnetic field vector, but the EMDEX does not have the capacity to collect data needed for evaluating more sophisticated biophysical metrics. The newly developed MW III personal dosimeter has the capabilities and offers a means of collecting the data necessary for calculating the biological and physical exposure metrics listed in Table 1. Since one or more of these metrics may capture the biophysical mechanism(s) associated with ELF magnetic field exposure, understanding the relationship between these metrics and historical TWA ELF magnetic field magnitude measurements is needed. It is therefore important to evaluate how exposures determined using the MW III compare to more commonly used EMDEX meters with respect to more traditional metrics (i.e., maximum and TWA RMS magnitudes).

The purpose of this study is to compare measures of EMF magnetic field magnitude between the EMDEX Lite and MW III in multiple job classifications and a variety of magnetic fields. The comparison is needed to validate the use of the MW III with respect to these parameters, and will allow comparison with past exposure assessments.

Methods

Magnetic fields vary over space and time and are directly related to electrical current levels. The magnetic field more accurately refers to magnetic flux density and is reported in the units of milliGauss (mG) or microtesla (μT). The instruments used in this study measured the RMS magnetic field components along three orthogonal directions in the ELF band and calculated the RMS vector magnitude of the ELF magnetic flux density from the resultant function (Bowman et al., 1998):

$$B_{ELF} = \sqrt{B_x^2 + B_y^2 + B_z^2} \quad (1)$$

where B_{ELF}=RMS vector magnitude of the ELF magnetic field; B_x, B_y, B_z=RMS components along their respective axes.

With the EMDEX, the RMS components are measured directly by the analog circuitry; with the MultiWave, the magnetic field signal for each component is digitized at a 7680-Hz analog–digital (A/D) rate and the RMS component calculated (Bowman et al., 1998). All ELF magnetic field data presented in this paper are RMS vector magnitudes.

EMDEX Lite

The EMDEX Standard Lite (Enertech, Campbell, CA), herein referred to as EMDEX Lite, is a small, portable, personal data collection system that measures 2.5×6.0×12.0 cm and weighs 170 g. Due to its light weight and small size, the EMDEX Lite can be placed in a shirt pocket or worn on the belt. Internal orthogonal induction coil sensors are located within the top right corner of the instrument case. Over sampling intervals (programmable from 4 s to 20 min), the EMDEX Lite measures the RMS magnetic field component from each sensor coil sequentially, digitizes these three measurements, calculates the resultant, and stores the data in its 128-kilobyte random access memory. Using a 4-s sampling interval, the EMDEX Lite can log data for up to 24.3 h. The data were downloaded to a laptop computer and analyzed using EMCALC software (Enertech). EMDEX Lite operating parameters are shown in Table 2. EMDEX Lite calibration was checked by placing the instrument into a Merritt coil magnetic field generator located at the National Institute for Occupational Safety and Health (NIOSH) and comparing its display to the coil's known magnetic field magnitude.

MultiWave System III (MW III)

The MW III (Electric Research and Management, State College, PA) is a portable personal waveform capture system. The main unit measures 17×14×6 cm and weighs 1050 g and can be worn in a belt pack or vest

Table 2. MW III and EMDEX Lite operating specifications.

Specification	MW III	EMDEX Lite
Magnetic sensor	three-axis, fluxgate magnetometer	three orthogonal induction coils
Frequency response	0–3000 Hz	40–1000 Hz
Range of RMS magnetic field[a]	0.02–6700 mG[b]	0.5–700 mG
Accuracy[a]	±2%	±8% (typical) ±10% (worst case)
Sample interval	1 s	4 s
Sample length	33 ms	~2.1 s[c]

[a]Single axis.
[b]Assumes 500 mG geomagnetic field.
[c]Each RMS component is measured for ~100 ms with 1 s between measurements.

with large pockets. A small (2 cm diameter×5 cm), three-axis fluxgate magnetometer is attached to the main unit with a 1-m cable. A 6-V video camera type battery provides power to the MW III. At 1-s intervals, three-dimensional waveforms are simultaneously captured for a 33.33-ms period, and stored on an 8-megabyte static random access memory (SRAM) card. The SRAM and battery required changing at 90-min intervals due to data storage and battery voltage limitations. Once full, the SRAM card was downloaded to a laptop for quality control checks and analysis *via* multiple software packages. The MW III was calibrated by the manufacturer prior to the investigation.

MW III operating parameters are shown in Table 2. Since the MW III responds to both the static and ELF magnetic fields, the upper limit of its dynamic range is 10,000 mG peak for a single component over the entire frequency range. For ELF fields, the upper limit of each RMS component is therefore $(10{,}000\ \text{mG} - B_o)/\sqrt{2}$, where B_o is the static field component. For geomagnetic fields alone, a reasonable upper limit on B_o is 500 mG (Bowman and Methner, 2000), in which case the dynamic range for the ELF magnitude is 6700 mG RMS or higher.

Since static magnetic fields are perturbed by proximity to steel objects, the waveforms measured by the MW III are affected by any motion of the probe (Bowman and Methner, 2000) or by steel objects in the environment. To eliminate any static field perturbations due the MW III measurement process, a custom-made vest without any steel fittings was developed to hold the its fluxgate probe motionless on the worker's body. Probe mountings are placed on the vest's chest and hip, so investigators can monitor the site most relevant to the health outcome. The MW III vests also have large pockets to hold the data collection unit and a second instrument.

Magnetic Field Measurement

Workers sampled as part of this comparison were divided into electrical and non-electrical job categories. Electrical jobs were selected from a list of standard occupational classifications (SOC) for electrical occupations used to assess ELF–EMF exposures in previous epidemiological studies (NIEHS, 1998). The occupations, SOCs, and number of samples for each category are shown in Table 3. The SOC codes were chosen to represent standard electrical worker job classifications used in epidemiologic studies. The number of workers sampled within each category was based on availability during the course of the study. A minimum of three workers within each category was targeted, with 5–10 being the goal. Each worker was briefed on the purpose of the evaluation and given an appropriately sized vest containing the EMDEX Lite and MW III. The vest's design ensured that the orientation of the MW III probe was fixed relative to the trunk of the body and within 6 in. of the EMDEX Lite. The EMDEX Lite was placed in the right, front pocket of the vest located near the worker's waist. The MW main unit was placed in the corresponding left pocket. However, the MW III cable was routed through the back of the vest, allowing the MW III probe to be fixed on the right hip, directly next to the pocket containing the EMDEX Lite.

The instrument serial numbers, date, start time, sample ID, worker ID, job category, and scheduled work activity were recorded on pre-printed forms prior to sample collection. When permitted, the worker was observed and notes were recorded regarding work activities and time of occurrence. In addition, AC field magnitudes were surveyed in the work area with a handheld EMDEX Lite to identify electrical power sources. When it was not possible to directly observe the worker, the worker was interviewed after the sampling period. At the end of the monitoring period, the stop time was noted and the meters were turned off and data were downloaded to a laptop computer. If the sample period exceeded 90 min, the battery and SRAM card were removed from the MW III and replaced with a fresh battery and blank SRAM card.

The time period (AM *versus* PM) for monitoring was determined based on worker availability. A target sampling time of 180 min during normal working hours was established to represent approximately one half of a work

Table 3. Occupational classifications, numbers of workers, and sample time studied.

Occupation	SOC code	Number of workers monitored	Average sample time (min)
Non-electrical	–	8	98 (12.4)[a]
Line workers	6433	11	98 (48.8)
Electronic repairers	6153	8	133 (50.6)
Electricians	6432	5	125 (49.9)
Welders and cutters	7714	3	123 (53.2)
Engineering technicians	3711	3	90 (0.5)
		Total=38	Mean=110 (42.5)

[a](Standard deviation).

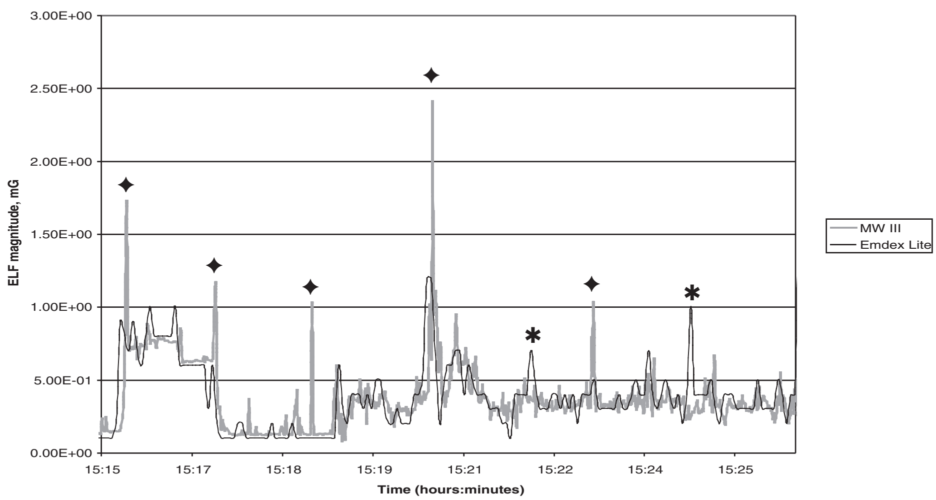


Figure 1. Representative plot of ELF magnetic field magnitude *versus* time for the EMDEX Lite and MW III. In the marked peaks, either the MW III (◆) or the EMDEX (*) took a measurement that was above the other meter by a margin greater than instrumental error.

shift, as well as minimize the battery and SRAM card change requirements for each monitoring period.

Results

The average sampling time for each occupational category is shown in Table 3. These times represent the period for which the MW III and EMDEX Lite were simultaneously in operation, and data from time intervals in which both instruments were not operating were not included in the analysis. In all cases, sampling times were less than the 180-min target due to worker availability and MW III faults. The MW III faults were attributed to the "on/off" switch locations, faulty low-voltage circuitry algorithms, battery pack connections, and other unidentified problems.

A graph of typical magnetic field magnitude as a function of time is shown for the EMDEX Lite and MW III in Figure 1. The plot is an excerpt from sampling of a lineman installing an electrical control panel at a transformer location. Figure 1 is representative of magnetic field magnitudes encountered and demonstrates the general agreement between the response of each instrument. In some cases, maximum responses of the meters varied, but followed the same general patterns.

The mean TWA and maximum magnetic field magnitudes for the 38 partial period samples are summarized for each occupational category in Tables 4 and 5, respectively. The standard deviation of the mean for each estimate is shown in parentheses. The lowest TWA values were measured in non-electrical occupations (mean of 1.2 mG for the EMDEX and 1.1 mG for the MW III), while the highest average TWAs were measured in engineering technician occupations (mean of 65.3 mG for the EMDEX and 65.8 mG for the MW III). The box plots of all measurements, shown in Figure 2a, illustrate the similarity in data distribution between TWA values measured by the EMDEX Lite and MW III. In the box plots, the bottom and

Table 4. Summary of *average* magnetic field magnitudes for job categories measured by EMDEX Lite and MW III.

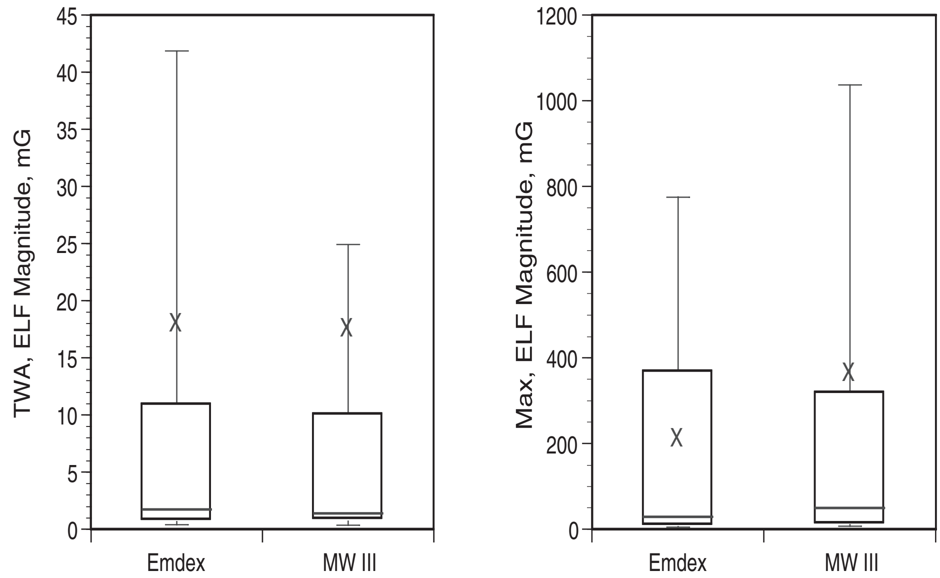
Job category	Average TWA (mG)	
	EMDEX Lite	MW III
Non-electrical (n=8)	1.2 (1.1)[a]	1.1 (1.1)[a]
Line workers (n=11)	30.1 (62.0)	31.7 (69.3)
Electronic repairers (n=8)	4.6 (4.0)	4.6 (4.2)
Electricians (n=5)	10.1 (9.2)	8.5 (8.5)
Welders and cutters (n=3)	21.8 (25.3)	12.8 (12.6)
Engineering technicians (n=3)	65.3 (110.5)	65.8 (111.9)
Overall average (n=38)	18.1 (45.6)	17.7 (48.7)

[a](Standard deviation).

Table 5. Summary of *maximum* magnetic field magnitudes for job categories measured by EMDEX Lite and MW III.

Job category	Average maximum (mG)	
	EMDEX Lite	MW III
Non-electrical (n=8)	27.0 (28.0)[a]	40.2 (39.3)[a]
Line workers (n=11)	314.5 (431.2)	613.9 (968.1)
Electronic repairers (n=8)	100.2 (202.5)	106.1 (187.8)
Electricians (n=5)	251.9 (239.5)	230.6 (235.7)
Welders and cutters (n=3)	407.2 (398.4)	328.8 (269.9)
Engineering technicians (n=3)	420.2 (590.1)	1311.8 (2109.6)
Overall average (n=38)	216.3 (332.9)	368.4 (800.8)

[a](Standard deviation).



a) TWA Magnetic Field Distribution b) Maximum Magnetic Field Distribution

Figure 2. Box plots of TWA maximum distributions for the EMDEX Lite and MW III for all jobs sampled.

top box edges represent the 25th and 75th percentiles of the distribution. The horizontal line through the box represents the sample median, and the mean is shown with an "X". The central vertical lines extending from the box represent the range of data falling within the 10th and 90th percentiles. The mean, median, and interquartile percentiles appear in agreement with the only difference being outlying (high) data measured by the EMDEX Lite. A comparison of the log-transformed means of the TWA data using a paired, two-tailed t-test did not indicate a significant difference (P=0.111). Additionally, a scatter plot and regression analysis between the transformed means measured by the

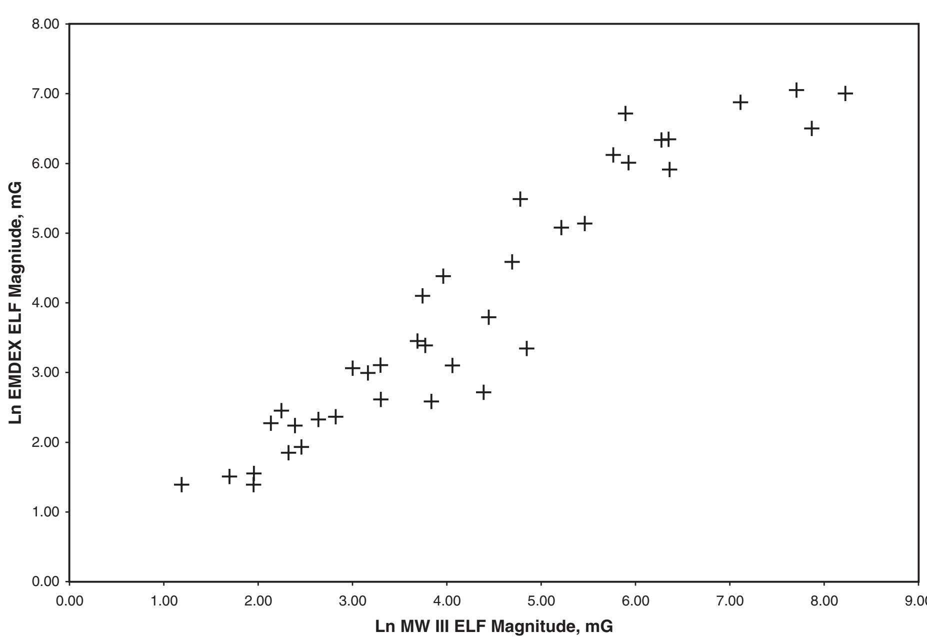


Figure 3. Scatter plot of EMDEX Lite and MW III maximum measurements.

EMDEX Lite and MW III (not shown) indicated a linear relationship with a slope near 1 (R^2=0.98; y=1.02x+0.04).

Similar to the TWA, the lowest maximum values were measured in non-electrical occupations (means of 27.0 mG for the EMDEX and 40.1 mG for the MW III), while the highest maximum values were measured in engineering technician occupations (means of 420.2 mG for the EMDEX and 1311.8 mG for the MW III). The EMDEX Lite reported lower maximum ELF magnitudes in 27 of 38 sampling periods (71.1%). The box plots presented in Figure 2b show that the MW III average, median, and 90th percentile values were elevated compared to the EMDEX Lite for maximum ELF magnitudes. A comparison of the log-transformed maximum measurements using a two-tailed t-test indicated a significant difference (P=0.002) between the maximum magnetic field measurements of the two meters. The scatter plot shown in Figure 3 and regression analysis indicates a linear relationship with slope of about 1 between the two meters (R^2=0.89; y=1.00x − 0.29). The meter responses differ over the entire range of ELF magnitudes.

Discussion

The sizes of the EMDEX Lite and MW-3 were convenient for personnel sampling. Workers were able to perform a wide variety of administrative, as well as physical, tasks while wearing each meter. Workers did note the increased size and weight of the MW-3 with respect to the EMDEX Lite. The disadvantages of increased weight and size of the MW-3 are offset by the instrument's significant waveform capture and recording capabilities.

The mean and maximum magnetic field magnitudes measured during this investigation were consistent with values found in previous studies of similar worker classifications at this location (Breysse et al., 1997). The ranges of values encountered were in general agreement between the two studies. We also noted that the average and maximum magnetic field magnitudes measured in non-electrical job categories were consistently lower than electrical occupations as noted in previous studies (Breysse et al., 1994a,b, 1997).

Despite the agreement of TWA magnetic field magnitudes measured by the two meters, the mean of maximum magnetic field magnitude measurements were significantly different in this study. Maximum magnetic field measurements were typically of short duration and, therefore, were poorly correlated with the TWA for the same monitoring period (Spearman correlation=0.36). As a result, the significant difference in the maximums between meters did not have much impact on the mean TWA.

The significant difference in the maximums from the two monitors could be due to (1) their different locations on the body, (2) inherent instrumental errors, and (3) their disparate operating characteristics: frequency response, operating range, and sampling procedures, including the interval and duration (Table 2). We examined our data in detail for evidence that would support any of these possibilities.

To examine the impact of instrumental errors, the accuracy of the ELF magnitude measurements was compared to the percent differences between the maximums from the two meters. To determine the accuracy of ELF magnitude measurements, the error bounds for a single sensor (Table 2) are multiplied by $\sqrt{3}$ (from the resultant in Equation 1), giving worst-case error estimates of ±17.3% for the EMDEX Lite and ±3.5% for the MW III. For the 38 sampling periods, the differences between maximums ranged from 1% to 137% (relative to the mean of the two measurements). Of the 38 pairs, 25 (66%) have differences greater than ±20.8%, which is the maximum conceivably due to combined measurement errors from the two instruments. Of those 25 pairs, the MultiWave's maximum reading is substantially greater than the EMDEX's in 20 cases (80%). This analysis suggests that the differences cannot be entirely due to inherent instrumental error.

The different frequency responses of the two meters (Table 2) were also investigated as a source of discrepancy between the maximum ELF magnitudes. Since the EMDEX Lite does not respond fully to frequencies from 1000 to 3000 Hz, it would underestimate peak magnetic fields with a high-frequency content. A review of the frequency time histories for each sampling period did not show any occupational exposures below 40 Hz and very few instances with occupational exposures above 1000 Hz. In those limited instances when the frequencies were above 1000 Hz, corresponding ELF magnetic fields were minimal and did not contribute to the maximum value.

A difference between the operating ranges of the two meters was also analyzed as a cause of the differences in maximum in ELF magnitudes. The upper operating limit for the ELF magnitude depends on the fields spatial orientation, and ranges up to $\sqrt{3}$ times the single axis limits (Table 2), i.e., 700–1212 mG for the EMDEX Lite and 6700–11,605 mG for the MW III. Fields encountered during this study definitely exceeded the upper limit of the EMDEX in 3 of 38 monitoring periods (8%), but were always below the upper limit of the MW III. (Note that the EMDEX Lite is also available in a "High Field" model with an upper operating range of 70 G. The EMDEX High Field Lite may be more suited to exposure assessments for high fields.)

When paired data sets with values exceeding 700 mG are excluded from the analysis of maximum values, the average maximum values measured by the MW III continue to be significantly higher compare to the EMDEX Lite

(P=0.004). Regression analysis for these maximum paired data sets below 700 mG also shows a linear relationship with a slope of about 1 (R^2=0.90; y=0.94x−0.09). In addition, analysis of error as a function of ELF magnitude for each monitoring period (not shown) did not show an association between error and ELF magnitude. The disparity in operating ranges between the two meters is apparently not the only cause of differing maximum responses between the two meters.

The monitors' different sampling procedures are another possible factor, especially when the field is varying more rapidly than their sampling intervals (Table 2). The EMDEX Lite is especially liable to such errors because its three orthogonal sensors are read sequentially for ~100 ms periods spaced 1 s apart. In comparison, the MultiWave's sensors are read together by synchronizing the multiplexing and digitization of their signals over 33 ms (Electric Research and Management, 1997). These readings are repeated at 1-s intervals.

To compare the signal processing from the two meters, we plotted 1-min intervals around maximum readings for all samples where their differences were greater than experimental error. In cases such as the lineworker (Figure 4), the fields changed so rapidly over 4-s intervals that the EMDEX's three-component measurements were apparently being taken with different field magnitudes. EMDEX measurements of the rapidly changing field will therefore be less accurate than the MultiWave, and will tend to underestimate maximum ELF magnitudes. On the other hand, the MW III captures the field magnitude for only 33 ms out of each 1-s sampling interval, and can therefore miss a peak that the EMDEX might capture inaccurately with a single sensor. Figure 1 shows such an episode when the EMDEX captured a peak that the MW III did not.

A final explanation for discrepant maxima from the two meters could be their different sensor locations when the field has a large spatial gradient. Although the MW III sensor was mounted 2 cm from the pouch with the EMDEX, the 20-cm-wide pouch was big enough for the 6×12 cm EMDEX to move around, creating separations as large as 20 cm between the two sensors. A large spatial gradient between the probes is the most plausible explanation for cases such as the electrician in Figure 4 where the EMDEX consistently recorded higher values for many measurements. Circumstantial evidence for a spatial gradient in these cases is provided by their TWAs. A strong spatial gradient should affect a large part of the time trace, creating a significant difference in the TWAs as well as the maximums measured by the two instruments. For the entire study, the means test for the TWAs showed no significant difference, but the mean of the EMDEX's TWA was also significantly greater (P=0.03) in the five cases where the margin of the EMDEX's maximum over the MW III's was more than instrumental error. Furthermore, spatial magnetic field gradients across

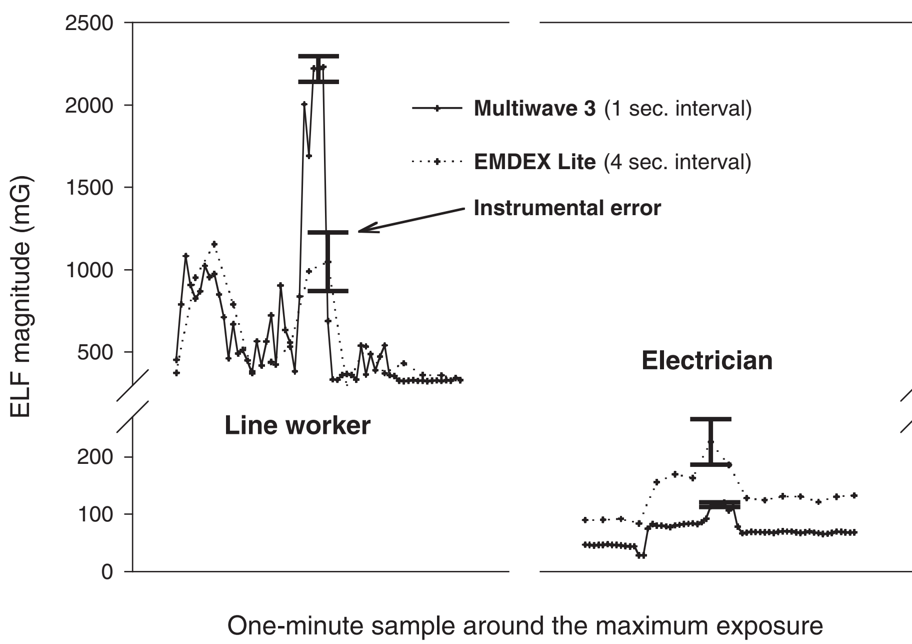


Figure 4. Traces of the ELF magnetic field magnitudes around the maximum in two cases where differences between the MW III and EMDEX Lite were greater than instrumental error. (Since the clocks on the two instruments were not synchronized, the relative times of the traces were shifted to maximize the between-instrument correlation of the ELF magnitudes.)

workers' bodies have been documented in several occupations (Delpizzo, 1993).

While spatial magnetic field gradients seem to account for the few cases where the EMDEX's maximum was substantially greater than the MW III's, a gradient's impact on the two meters should generally be random. Therefore, gradients between the probes would be unlikely to cause the significant difference in the maximums observed in the entire sample. Instead, this bias of the standard EMDEX Lite towards lower maximums would appear to be due to its limited operating range and sequential sampling procedure.

Conclusions

The EMDEX Lite and MW III provided comparable measures of TWA ELF magnetic field magnitudes in multiple job classifications and variety of magnetic field environments. Although there was no significant difference in mean TWA measures, our findings indicate the maximum ELF magnetic field magnitudes measured by the EMDEX Lite were significantly lower than those measured by the MW III.

The reasons for the discrepancies in the maximum ELF magnitudes between the EMDEX Lite and the MW III are not clear. However, some discordant maximums are clearly greater than experimental error, and can be plausibly explained by differences in the sensor's locations on the body and the meter's sampling procedures, plus the limited operating range of the EMDEX Lite. From the evidence in this study, the MultiWave's process of reading all three sensors in 33 ms appears to be generally more accurate in rapidly varying fields than the EMDEX's sequential sensor readings over a 4-s interval. However, the MultiWave's sampling procedure can underestimate peaks with duration <1 s. Further investigations are needed to confirm these hypotheses.

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