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Exposure of Welders and Other Metal Workers to ELF Magnetic Fields

Jørgen H. Skotte[1]* and Henrik I. Hjøllund[2]

[1]*National Institute of Occupational Health, Copenhagen, Denmark*
[2]*University Hospital of Aarhus, Aarhus, Denmark*

This study assessed exposure to extremely low frequency (ELF) magnetic fields of welders and other metal workers and compared exposure from different welding processes. Exposure to ELF magnetic fields was measured for 50 workers selected from a nationwide cohort of metal workers and 15 nonrandomly selected full-time welders in a shipyard. The measurements were carried out with personal exposure meters during 3 days of work for the metal workers and 1 day of work for the shipyard welders. To record a large dynamic range of ELF magnetic field values, the measurements were carried out with ''high/low'' pairs of personal exposure meters. Additional measurements of static magnetic fields at fixed positions close to welding installations were done with a Hall-effect fluxmeter. The total time of measurement was 1273 hours. The metal workers reported welding activity for 5.8% of the time, and the median of the work-period mean exposure to ELF magnetic fields was 0.18 μT. DC metal inert or active gas welding (MIG/MAG) was used 80% of the time for welding, and AC manual metal arc welding (MMA) was used 10% of the time. The shipyard welders reported welding activity for 56% of the time, and the median and maximum of the workday mean exposure to ELF magnetic fields was 4.70 and 27.5 μT, respectively. For full-shift welders the average workday mean was 21.2 μT for MMA welders and 2.3 μT for MIG/MAG welders. The average exposure during the effective time of welding was estimated to be 65 μT for the MMA welding process and 7 μT for the MIG/MAG welding process. The time of exposure above 1 μT was found to be a useful measure of the effective time of welding. Large differences in exposure to ELF magnetic fields were found between different groups of welders, depending on the welding process and effective time of welding. MMA (AC) welding caused roughly 10 times higher exposure to ELF magnetic fields compared with MIG/MAG (DC) welding. The measurements of static fields suggest that the combined exposure to static and ELF fields of MIG/MAG (DC) welders and the exposure to ELF fields of MMA (AC) welders are roughly of the same level. *Bioelectromagnetics 18:470-477, 1997.*

Key words: magnetic fields; welding processes; shipyard

INTRODUCTION

Electric arc welding is known to cause considerable exposure to extremely low frequency (ELF) magnetic fields. Welders handle cables that carry current in the range of 100–500 amperes very close to their bodies. Normally the welder directly grasps a handle with the cable during welding, and sometimes the cable is in contact with other parts of the body (wearing the cable over the shoulder is common). A survey, including spot measurement of magnetic fields around 22 arc welders, showed levels of several hundred microtesla 10 cm from the trunk of the welders [Stuchly and Lecuyer, 1989]. Another survey reported magnetic field levels from 4 to 90 μT around eight Tungsten inert gas (TIG) welders [Bowman et al., 1988]. It is easily calculated by Ampere's law that within a few centimeters of a welding cable the magnetic field is in the order of millitesla.

In industrial countries 0.2–2% of the working population is engaged in welding, but there are wide national differences in the distributions of welding activity by technology and material [Stern, 1981]. There are large differences in the amount of time that a welder spends actually welding, ranging from welding nearly all the day to welding only occasionally. Some studies of exposure to magnetic fields and epidemiological studies include groups of welders, but normally no information is found about the actual welding processes

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*Correspondence to J. Skotte, Arbejdsmiljøinstituttet, Lersø Parkallé 105, DK-2100, Copenhagen, Denmark. E-mail: js@ami.dk

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used or time spent in welding. Average workday exposures for groups of welders have generally been reported in the range 0.5 to 2 μT [Kromhout, 1994; London et al., 1994; Sahl et al., 1994; Bracken et al.,1995; Floderus et al., 1995]. Most of the data reported refer to welders in the electric utility industry.

The purpose of this study was to assess the exposure to ELF magnetic fields of welders and other metal workers, to assess the exposure from the most widely used welding processes, and to report on the actual time spent in welding.

Welding Processes

There exists a large number of different electric arc welding processes involving direct (DC), alternating (AC) or pulsed current. The most common processes are manual metal arc (MMA) welding, metal inert gas (MIG) or metal active gas (MAG) welding, tungsten inert gas (TIG) welding, and submerged arc (SA) welding. The parameters that primarily influence the exposure to magnetic fields are the type (AC/DC), the magnitude of current, and the distance to cables and current source. The processes can be manual or more or less automatic. Manual processes normally result in smaller distances between the welder and the cables than automatic processes. In MMA, MIG, MAG, and TIG welding the current is typically in the range of 50–400 amperes.

MMA welding, which is the oldest and has been the most widely used technology, uses short lengths of coated electrodes, which can be welded with AC or DC electricity. There can be considerable national differences in the use of AC or DC sources. In Denmark, normally AC has been used for MMA welding. Normal MIG/MAG welding employs a continuous wire electrode and uses only DC. However, a variant of the MIG welding process using a pulsed DC source has been developed (frequencies 0.2–3 kHz). TIG welding uses a nonconsumable tungsten electrode and a DC or AC source, depending on the material being welded (DC for steel and AC for aluminum/magnesium alloys). Some TIG processes require a superimposed high frequency current for starting the arc. SA welding is a fully or semi-automatic process that uses a continuous wire electrode and currents typically in the range of 500-1500 amperes (AC or DC).

Current sources for welding are constructed in several ways. Normally three-phase equipment is used, but low-power equipment may be designed with one-phase connection. The simplest source consists of a transformer giving an AC output with the frequency determined by the country's power frequency (60 Hz in North America and Brazil and 50 Hz in the rest of the world). A source with a three-phase transformer and diode rectifiers normally produces a DC output with a small ripple (roughly 4%) dominated by the sixth harmonic (300–360 Hz). Adjustable current sources equipped with thyristor control yield more AC ripple. Current sources with a low frequency chopper-inverter produce almost a pure DC output. Accordingly, depending on the welding process and current source, the frequency spectrum of the magnetic fields from welding equipment generally involves static and/or alternating fields ranging from ELF to HF for special processes. Furthermore, the welding arc emits intense optical radiation.

The distribution of exposure to the welder's body is very inhomogeneous because of the differences in distance between various parts of the body and the sources of the magnetic fields, i.e., the welding arc, the electrode, the cable, and possibly the power source. The individual's welding technique might cause large differences in exposure. It is clear that wearing the cable over the shoulder will cause a much higher exposure to the head and trunk than having the cable on the floor. Thus, the exposure to magnetic fields when welding is generally very complex and is characterized by inhomogeneous, fluctuating, and multifrequency fields.

SUBJECTS AND METHODS

Subjects

Exposure to ELF magnetic fields was measured for 65 workers, 50 workers selected from a nationwide cohort of metal workers and 15 full-time welders in a shipyard. The cohort of metal workers was originally created for a prospective study on couple fertility. The cohort consisted of 25,191 members of the Danish Metalworker Union. Cohort members were picked at random for the present study, regardless of welding duties with the purpose of selecting a group representative of the entire workforce in the Metalworker Union. A large number of different branches and types of jobs were represented: smiths, mechanics, technicians, fitters, operators, toolmakers, specialist workers, erectors, shipbuilders, and welders.

It appeared that the metal workers were considerably less engaged in welding than was expected during the planning of the study. To get more data on exposure to ELF magnetic fields from the widely used welding processes, MMA, MIG/MAG, TIG, and SA, the study was enlarged with a group of shipyard welders. A considerable proportion of the workers in a shipyard are welders working most of the time in welding activities. Fifteen shipyard welders were selected who worked all day with one of the processes: MMA, MIG/MAG, TIG, or SA welding. In this way the total time of welding activity in the study was doubled. The shipyard welders were not picked at random, but were selected to acquire data on process-specific exposure. Approximately half of the welders were using the MIG/MAG process.

Methods

The exposures were measured with personal exposure meters. Because of the large dynamic range of magnetic field levels expected from welding processes, the measurements were carried out with pairs of exposure meters/one for the 0.01–70 μT range (Emdex Lite standard) and another for the 1–7000 μT range (Emdex Lite high field). Both instruments recorded the root mean square (rms) magnetic fields in the 40-1000 Hz frequency range for the same measurement period. The metal workers' recordings were done on 3 successive workdays with a 10-s sampling rate, yielding approximately 24 total hours of work. Recordings were also done in nonwork periods, but these measurements are not reported in the present paper. The shipyard welders' recordings were done during 2 successive workdays with a 4-s sampling rate. The shipyard measurements were started the first day and stopped at roughly the same time the second day, yielding about 8 h of work-time measurement. In the nonwork period the instruments were kept operating in the wardrobe of the worker. During all work-time measurements both instruments were placed close together in a leather case attached to a belt worn at the waist. No data was displayed on the instruments during the recordings. The calibration was checked regularly during the measurement program. A few ''high field'' recordings were lost for technical reasons.

The metal workers were instructed to start the measurement themselves at a prearranged time, in most cases Monday morning before the beginning of work. The measurements could be started by pushing a single switch on the exposure meters, and after that no further operation of the meters was required throughout the measurement. After finishing the measurement, the exposure meters were mailed to the investigator. For the measurements on the shipyard welders, the recordings were started and finished by the investigator at the workplace. All the workers were asked to complete a logbook with information on the work-time, the total time spent with different welding processes, the type of current source, and the type (AC/DC) and magnitude of welding current. The workers were asked also about their use of other sources of potential strong ELF magnetic fields, especially the use of electrical handtools, work with resistance welding equipment or induction heaters. The range of activities that could be recorded was determined in advance by the investigators.

By means of the logbook information, the work periods were selected from the recordings, and several summary measures were calculated for each worker: arithmetic mean (AM), geometric mean (GM), median (MD), 90% percentile (P_{90}), 99% percentile (P_{99}), maximum (MAX), fraction of measurement values exceeding 0.2 μT ($F_{0.2}$), fraction of measurement values exceeding 1.0 μT ($F_{1.0}$), standard deviation (SD), and geometric standard deviation (GSD).

When measurement values for a worker exceeded the recording capacity of the standard instrument (0.01–70 μT), the recordings from both the standard and high field instruments were used in the analysis. First, the distribution of data from both the measurements was obtained by calculating separate histograms. The histograms were calculated by grouping the data in 50 logarithmic-scaled classes from 0.01 to 1000 μT (class intervals $0.01 \times 10^{i/10}$ for $i = 0, 1, 2, \cdots 50$). Then the two histograms were combined in one histogram by joining levels below 63 μT (38th class interval) from the standard measurement and levels above 63 μT from the high field measurement. From this resulting distribution the above summary statistics were calculated.

Because different combinations of DC and AC currents are found in welding equipment, the static and alternating fields were also measured close to the welding equipment for some of the shipyard welders. Short-term (1 min) measurements were done very close to seven welding installations. These measurements were taken with a Hall-effect fluxmeter (type T2B, Heme International, Lancashire, UK), which determines both the static and ELF/VLF fields in the frequency range 15 Hz to 10 kHz. The sensitivity of the instrument is low, i.e., exact measurements cannot be made at levels below roughly 100 μT, and the static field due to the earth (50 μT) is barely detectable. To ensure reliable measurements it was necessary to measure very close to the cable connecting the current source and the welding electrode, where magnetic fields were in the order of millitesla. A plastic spacer held the fluxmeter's axial probe 1 cm from the welding cable. The probe, cable, and box of the fluxmeter were completely shielded against interference from electrical fields by metallic shields.

RESULTS

Typical instantaneous ELF magnetic field values were on the order of 100 μT during work with MMA (AC) and on the order of 10 μT for MIG/MAG (DC) welding. The active welding periods ranged from few seconds to several minutes. Figures 1 and 2 show examples of records from the ''standard'' and ''high field'' exposure meters for the same worker in the same measurement period. This worker reported 13 h of welding (MMA and MIG/MAG) during the 3 days of work. From the standard measurement in Figure 1 the

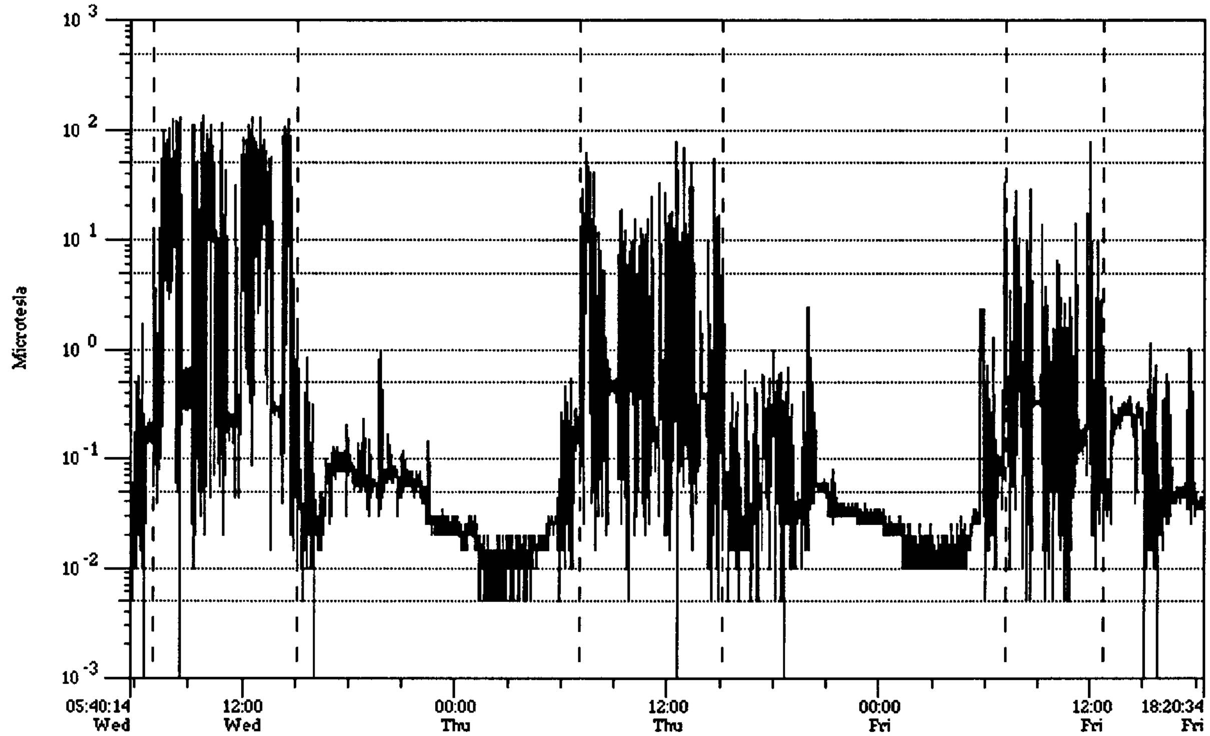

Fig. 1. Three days of measurement for a metal worker reporting: First day, 5 h of MMA welding; second day, 5 h of MIG/MAG welding; last day, 3 h of MIG/MAG welding. The vertical dashed lines indicate the beginning and finishing of work periods. The record comes from a ''standard'' exposure meter (0.01–70 μT in three axis) and some overloading of the instrument is found in the first day of measurement.

average exposure for the first workday was calculated to 17.9 μT, but some overloading was found in the record. The overloading could be detected by comparing the occurrence of peak exposure levels in the ''standard'' and ''high field'' records. By using the high field record in Figure 2, a corrected average value was calculated to 21.6 μT, which was one of the highest average exposures found for one workday. Figure 3 shows the combined distribution of magnetic field values for the three days of measurement shown in Figure 1 and 2. For 9 of the 65 workers the magnetic field levels significantly overloaded the recording capacity of the standard instrument and the high field recordings were included in the analysis.

The total time of measurement (work-time) was 1273 h and the welding activities totalled 135 h. The mean measurement work-time was 23.0 h for the metal workers and 8.2 h for the shipyard welders. For the metal workers, the average and median exposure during the work period were 0.50 and 0.18 μT; for the shipyard welders, the average and median of the workday were 7.22 and 4.70 μT, respectively. A maximum workday mean of 27.5 μT was found. Details on the distributions of the exposure summary measures are given in Table 1. The distributions of the summary measures for the metal workers were very skewed. Of the 10 measures, 7 could be approximated with a lognormal distribution (Kolmogorov-Smirnov test, $P = .05$). As an example, the distribution of work-period means is shown in Figure 4. To examine relationships between the different summary measures for the metal workers, Spearman rank-order correlation coefficients of work-period exposures are calculated in Table 2.

The metal workers reported welding 5.8% of the time for the 3 days of work; half of them did not weld at all during the 3 days. On one workday (e.g., the second day), 22% of them reported welding activities. The shipyard welders reported welding 56% of the time, roughly 10 times more than the metal workers, and all of them did weld during the day of measurement. Table 3 shows the distribution of work time for different welding processes in the two groups. Workday mean exposures for full shift working with MMA (AC) and MIG/MAG (DC) welding are shown in Table 4, which includes measurements for welders and metalworkers working with just one welding process for more than 3 h during the day. The analysis in Table 4 included three measurements on MMA (AC) shipyard

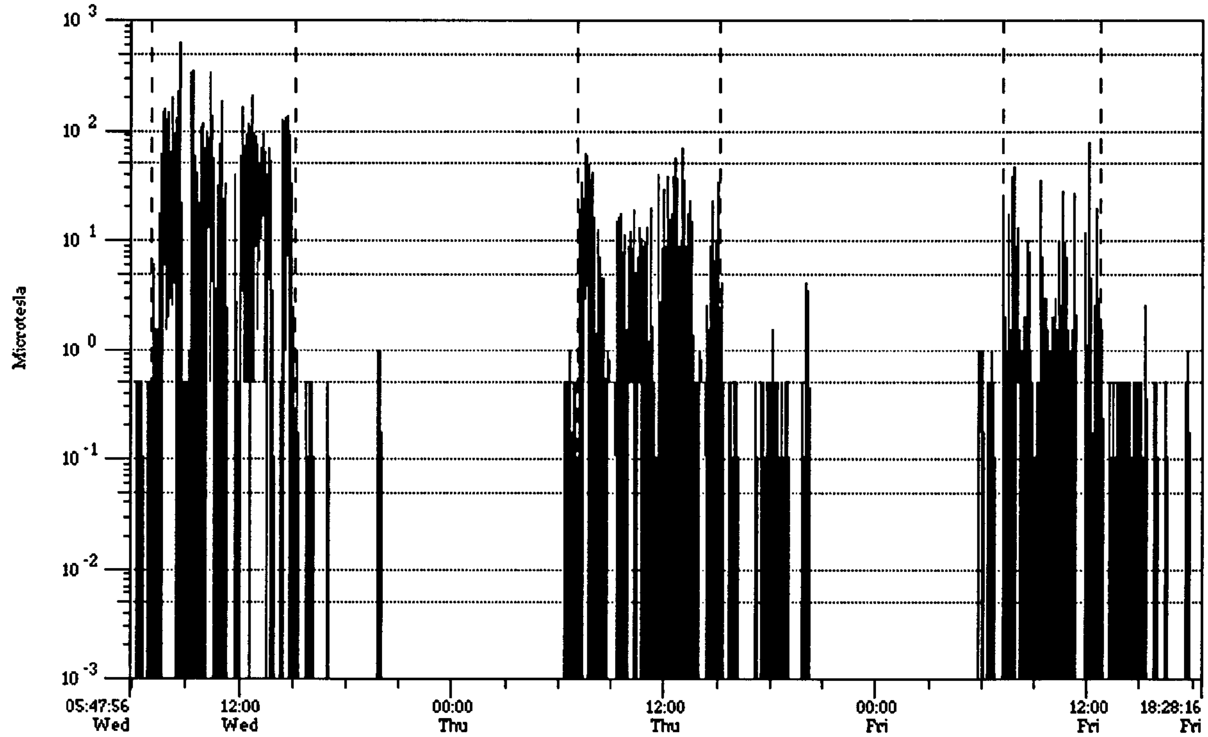

Fig. 2. Three days of measurement with a "high field" exposure meter (range, 1–7000 μT) same worker and measurement period as in Figure 1.

welders that were made with Positron exposure meters [Skotte, 1994]. There are some differences in the measurement principles (dynamic range and bandwidth) of these instruments that could cause a slightly lower reading of the Positron meter compared with the Emdex meter, but otherwise the procedure of the Positron and Emdex measurements was the same.

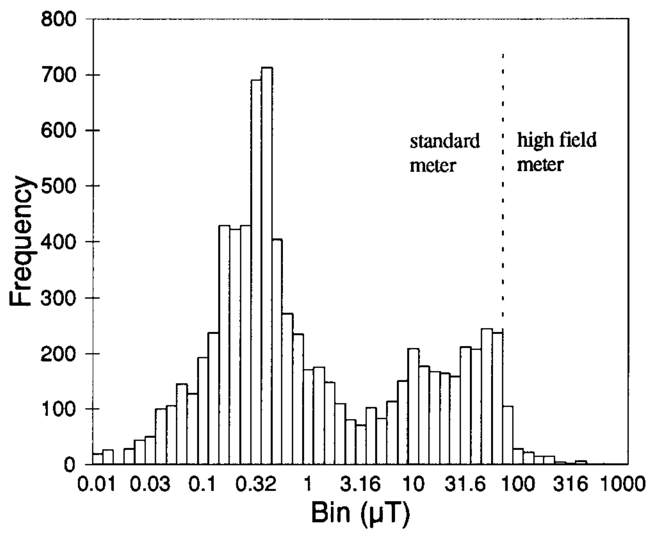

Fig. 3. Histogram of magnetic field values in the three work periods of the measurement presented in Figures 1 and 2. Values below 63 μT in Figure 1 and values above 63 μT in Figure 2 are combined. Number of measurement values 7844 (21.5 h). Arithmetic mean 9.73 μT.

The welding currents were in the 110-380 ampere range, with no clear differences between MMA (AC) and MIG/MAG (DC) welding.

The measurements of static magnetic fields with the Hall-fluxmeter 1 cm from the welding cables showed 5 mT for a SA (DC) welding installation, 0.9–1.9 mT for MIG/MAG (DC) installations and no detectable static fields for MMA (AC) welding installations. MIG/MAG welding equipment showed ELF/static fields ratios in the range 0.05-0.1, so from this welding process there was a static magnetic field roughly 1 order of magnitude higher than the ELF magnetic field measured by the exposure meters.

DISCUSSION

The exposure of the body to ELF magnetic fields during welding is very inhomogeneous. The measurements in this study represent a sample in one position (the waist), and measurements, at the chest for example, could yield other results. Considering the small size of the magnetic field exposure meters, it would be

TABLE 1. Statistics of Exposure Summary Measures for Metal Workers and Shipyard Welders

	Exposure summary measures[a]									
Group statistics	AM (μT)	GM (μT)	MD (μT)	P_{90} (μT)	P_{99} (μT)	MAX (μT)	$F_{0.2}$	$F_{1.0}$	SD (μT)	GSD
Metal workers (n = 50)										
Arithmetic mean	0.50	0.098	0.079	1.09	5.53	87.9	.19	.04	2.1	3.4
Median	0.18	0.068	0.055	0.24	1.38	40.3	.12	.02	0.7	2.9
Geometric mean	0.21	0.068	0.056	0.28	1.89	28.6	.11	—	0.7	3.0
Minimum	0.01	0.009	0.008	0.01	0.06	0.4	.00	.00	0.0	1.4
25% percentile	0.13	0.045	0.038	0.15	0.76	7.9	.09	.01	0.2	2.2
75% percentile	0.36	0.103	0.097	0.36	6.00	98.0	.25	.05	2.7	3.9
Maximum	9.73	0.955	0.422	32.1	77.3	893	.77	.38	24.3	9.5
Standard deviation	1.37	0.134	0.073	—	—	—	—	—	—	—
Geometric standard deviation	3.0	2.2	2.4	—	—	—	—	—	—	—
Shipyard welders (n = 15)										
Arithmetic mean	7.22	0.480	0.273	20.7	85.9	218	.53	.32	18.0	13.1
Median	4.70	0.360	0.253	10.2	63.3	189	.55	.32	11.7	10.1
Geometric mean	4.69	0.362	0.194	11.4	59.5	178	.52	.32	12.4	11.1
Minimum	1.35	0.064	0.013	3.12	13.5	56.8	.32	.24	3.0	4.5
Maximum	27.5	1.562	0.673	82.1	308	704	.87	.41	69.9	40.8
Standard deviation	7.88	0.383	0.190	—	—	—	—	—	—	—
Geometric standard deviation	2.5	2.2	2.8	—	—	—	—	—	—	—

[a]AM, GM, MD, P_{99}, MAX, $F_{1.0}$, and SD are approximately log-normal distributed. AM, arithmetic mean; GM, geometric mean; MD, median; P_{90}, 90% percentile; P_{99}, 99% percentile; MAX, maximum; $F_{0.2}$, fraction of measurement values exceeding 0.2 μT; $F_{1.0}$, fraction of measurement values exceeding 1.0 μT; SD, standard deviation; GSD, geometric standard deviation.

possible to conduct measurements at several different positions on the body to study the spatial distribution of the exposure.

The exposure of welders to magnetic fields is characterized by periods of high levels during the active welding operations, interrupted by lower background levels. The histogram of magnetic field values for the welder during three workdays in Figure 3 shows a compound distribution, reflecting the intermittent character of exposure. The lower part of the distribution, with a peak around 0.3 μT, represents the background levels; above roughly 3 μT, the magnetic fields are caused by welding. The peak at 10 μT is caused by MIG/MAG welding and the peak at 50 μT is caused by MMA welding.

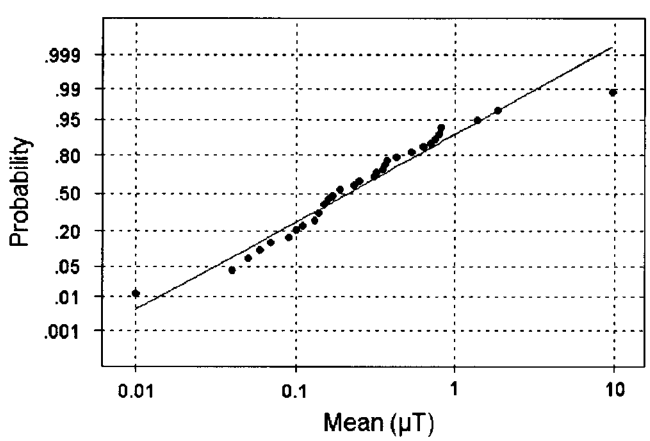

Fig. 4. Log-normal probability plot of work-period means for metal workers (number of measurements, 50; geometric mean, 0.21 μT; geometric standard deviation, 3.0).

For the metal workers the average of the work-period means was 0.50 μT, but because of the skewed distribution the average was highly influenced by one work-period mean of 9.73 μT. If this measurement is excluded the average value would be 0.31 μT. The medians of magnetic field exposure were low compared with the means. This reflects the high frequency of rather low background levels and the influence of peak exposures during welding.

The highest rank-order correlation coefficient between the summary measures for the metal workers was found between GM and MD (0.96). Exactly the same value has been found for a very large group of electric power utility workers [Savitz et al., 1994]. Very high correlations were found between P_{90} and $F_{0.2}$ (0.93), P_{99} and $F_{1.0}$ (0.95). These measures address the upper end of the distribution, so it is not unexpected that a high correlation is found between some of them. The high correlation (0.94) between MAX and SD is caused by the very skewed distributions. So it seems that several of the measures are more or less redundant, and, for instance, SD, P_{90}, P_{99}, and GM could be excluded without the loss of very much information. The correlation (0.43) of AM and MD is smaller than found

TABLE 2. Spearman Rank-Order Correlation Coefficients for Summary Measures of Workday Exposures for the Metal Workers, Number of Measurements-50[a]

	AM	GM	MD	P_{90}	P_{99}	MAX	$F_{0.2}$	$F_{1.0}$	SD
GM	0.55								
MD	0.43	0.96							
P_{90}	0.73	0.66	0.56						
P_{99}	0.85	0.25	0.13	0.53					
MAX	0.76	0.12	0.02	0.39	0.75				
$F_{0.2}$	0.71	0.74	0.67	0.93	0.42	0.34			
$F_{1.0}$	0.83	0.27	0.15	0.57	0.95	0.69	0.44		
SD	0.83	0.16	0.03	0.47	0.87	0.94	0.38	0.82	
GSD	0.65	−0.03	−0.14	0.54	0.79	0.68	0.40	0.78	0.74

[a]AM, arithmetic mean; GM, geometric mean; MD, median; P_{90}, 90% percentile; P_{99}, 99% percentile; MAX, maximum; $F_{0.2}$, fraction of measurement values exceeding 0.2 μT; $F_{1.0}$, fraction of measurement values exceeding 10 μT; SD, standard deviation; GSD, geometric standard deviation.

TABLE 3. Distribution of Time (%) Working with Different Welding Processes

Process[a]	Metal workers (%)	Shipyard welders (%)
MMA	10	22
MIG/MAG	80	56
TIG	5	9
Other	5	13
Total	100	100
	66.7 h	68.5 h

[a]MMA, manual metal arc; MIG/MAG, metal inert gas/metal active gas; TIG, tungsten inert gas.

by Savitz et al. [1994] for electric utility workers (0.80), but the general trend for high correlations between several of the measures of exposure to ELF magnetic fields is the same.

It seems that welding generally causes exposure to magnetic field levels above at least 1 μT. If no other powerful sources of magnetic fields are found, then the total time of active welding could be estimated by the total time with levels above 1 μT. The average time with levels exceeding 1 μT ($F_{1.0}$) was 4% for the metal workers and 32% for the shipyard welders (Table 1). This is somewhat lower than the time spent welding reported by the workers in the two groups (5.8 and 56%). However, this was expected because the workers reported the time spent in welding activities and not just the time of active welding. The total time spent in welding activities includes the intervals between active welding periods and the time for other activities relevant to the work of welding, e.g., preparations, fittings, or cleaning the weld seam. However, 25 of the metal workers did not report any welding activities, but their time of exposure to levels above 1 μT averaged 2%. Therefore, these workplaces must have sources of exposure above 1 μT other than welding operations, e.g. motors and electrical tools. So it is probable that the effective welding time of the metal workers was less than 4%. Nevertheless the time of exposure above 1 μT seems to be a useful indicator of the extent of welding operations in groups with welders.

MIG/MAG welding was the most widely used process: the metal workers used this process 80% of the time they were welding. For 85–90% of the time, a DC process was used. The original MMA (AC) welding process, was only used 10% of the time. Because of the method of subject selection and the different branches and types of jobs found, this distribution is presumed to be representative for metal workers in general. The distribution for the shipyard welders is not as representative, because they were nonrandomly selected on the basis of the welding process. This selection procedure could have biased the exposure estimate.

For full shift welders, the average workday mean ELF magnetic field exposure was 21.2 μT for MMA (AC) welders and 2.3 μT for MIG/MAG (DC) welders (Table 4). Because the average effective time of welding, which could be estimated by the time exceeding 1 μT, was approximately one-third of the working hours for these welders, the average exposure during the effective time of welding can be estimated as 65 μT for the MMA (AC) welding process and 7 μT for the MIG/MAG welding process. However, according to the fluxmeter measurements MIG/MAG (DC) welding also produced a static magnetic field that can be roughly 10 times higher than the ELF field. If the static magnetic fields were included in the measurements, the exposures from MMA and MIG/MAG welding would be approximately the same.

There are significant differences between the exposure of shipyard welders and welders in electric utilities reported in other studies. A study including 42 workday means for welders in electric utilities

TABLE 4. Exposure to ELF Magnetic Fields from MMA (AC) Welding and MIG/MAG (DC) Welding Processes*

Process	Number of workdays	AM (μT)	SD (μT)	Maximum (μT)	Minimum (μT)
MMA (AC)	7[a]	21.2	11.9	43	5.3
MIG/MAG (DC)	16	2.3	1.5	4.9	0.59
Other	3[b]	4.2	2.0	6.2	2.2

*Arithmetic mean (AM), standard deviation (SD), maximum, and minimum of the workday means for production welders working more than 3 hr per day with welding. MMA (AC), manual metal arc (alternating current); MIG/MAG (DC), metal inert gas/metal active gas (direct current).
[a]Three of the measurement were carried out with Positron exposure meters in a previous study [Skotte, 1994].
[b]One tungsten inert gas (DC) and two submerged arc (DC) welders.

[Bracken et al., 1995] reported AM of 0.54 μT and GM of 0.28 μT. The exposure of these utility welders corresponds roughly to the exposure of the metal workers in this study (AM of 0.50 μT, GM of 0.21 μT), even though half of the metal workers did not weld at all. On the contrary the exposure of shipyard welders in this study was about 15 times higher than in the study of Bracken et al. It is very likely that this difference is caused by the time actually working with welding and the welding technology.

This study has shown that there are significant differences between exposure to magnetic fields in different subgroups of welders and that information on welding time and technology is important for evaluating measurements of exposure to magnetic fields of welders.

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