Applied Occupational and Environmental Hygiene

ISSN: 1047-322X (Print) 1521-0898 (Online) Journal homepage: https://www.tandfonline.com/loi/uaoh20

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Power-frequency magnetic fields were measured with two types of instruments at a large automobile transmission plant and the results were compared. A group of machining and assembly workers (n = 57) wore a datalogging three-axis personal monitor, and also had each of their work locations measured with a hand-held meter. Time estimates at each of these locations were combined with averages of the meter readings to give surrogate daily-weighted average (DWA) exposures, which were compared with measures of central tendency derived from the personal monitor. Nonparametric correlation coefficients were used to compare the two estimates. Closer agreement was found between the DWA and the datalogger's geometric mean (Spearman coefficient, $r_s = 0.85$) than between the DWA and the arithmetic mean ($r_s = 0.77$), apparently because both the geometric mean and DWA were relatively insensitive to brief peaks. Principal sources were identified and their distances from the usual work position were estimated. Demagnetizers were unexpectedly found to be important sources in some jobs. Median distance from source to worker was about 1 m. For one cluster of demagnetizers, which influenced exposures up to 15 m away, the power law exponent (b) for falloff with distance was estimated with measurements in four directions. We found $1.9 < b < 2.6$, consistent with physical principles for sources which are small relative to the distances measured.
WENZL, T.B.; KRIEBEL, D.; EISEN, E.A.; MOURE-ERASO, R.: A COMPARISON OF TWO METHODS FOR ESTIMATING AVERAGE EXPOSURE TO POWER-FREQUENCY MAGNETIC FIELDS. APPL. OCCUP. ENVIRON. HYG. 10(2):125–130; 1995.

Intense public interest and conflicting scientific results oblige epidemiologists to determine whether excess risk is associated with exposure to extremely low frequency magnetic fields (MF). The accurate estimation of risk depends on exposure assessment that must be both reasonably accurate and efficient. Efficient strategies are needed to characterize this ubiquitous workplace exposure, to assess many locations, and to avoid misleading results that fail to capture the important aspects of exposure variability.

Both residential and occupational epidemiology studies have suggested that excess cancer risk may be associated with estimated exposure to MF. In the residential case, childhood leukemia and brain cancer appear to be elevated near high current neighborhood wiring, which generates higher MF exposure.[1,2] Case control studies of brain cancer across diverse occupations have shown somewhat consistent elevations in risk among electrical and engineering workers.[3,4] It is not known if this is due to MF exposure, as only one large case control study of adults has assigned exposures based on measurements.[5] It showed an association between MF exposure and risk of chronic lymphocytic leukemia. Most cohort studies have not shown such an effect.[6,7]

Small datalogging instruments and software are now available to record MF personal exposure profiles and generate various exposure indices. But it can be very expensive and time consuming to evaluate variability both within and across jobs in a large workplace if each measured worker must wear this instrument. If exposure estimates derived from spot measurements (with a hand-held device) yield results equivalent to averages from the datalogger, then such a strategy should be considered when resources are scarce or many work locations are to be surveyed. If such equivalence were shown, it might be useful in residential exposure assessments as well.

In a large automobile transmission plant, a survey of worker exposure to MF was conducted using both datalogging dosimeters and a single-axis spot meter as part of an epidemiologic study of brain cancer. This report describes the comparison of estimated exposure averages computed from spot measurements, with average MF exposures derived from data recorded by the datalogging instrument. In addition, the magnitude of exposure variability within individual work locations was evaluated, since spatial variability was expected to be very large. This was done by evaluating exposure differences among multiple spot measurements at given work locations.

Exposure variability from place to place was expected to be higher for MF than for airborne contaminants, since there is no smoothing of exposures caused by dilution effects. Within individual work locations, both vertical and horizontal exposure variability were evaluated with the spot measurements. In a few locations we also computed the rate of decrease in field strength with distance.

Since we were interested in estimating exposure to the head for a study of brain cancer, we evaluated whether head versus waist exposure differences were significant. Because of the rapid falloff in field strength with distance, it was possible that for some very close sources a waist-mounted dosimeter would not accurately measure exposure to the head. The hand-held device allowed us to compare estimated exposures at the head and waist, and to incorporate these results into the exposure estimates which were provided to the epidemiologists. These estimates were primarily based on measures from a personal dosimeter worn at the waist, but the spot measurements allowed for the possibility of adjustments based on this microspatial evaluation at each workstation.

From the point of view of a target tissue such as the brain, spatial and temporal variability are both seen as temporal changes in exposure. Changes in personal exposure may be due to source changes or to worker movement relative to the source, but biologically speaking they are both changes over time. For choosing a measurement strategy, spatial variability and the relation of the worker to the source may both affect the accuracy of the averages derived from spot measurements. This might be the case if exposure variability caused systematic error in how built-up average exposures were computed from spot measurements.

Probable magnetic field sources were identified with the spot meter by moving the coil along each of three orthogonal axes to note the direction in which field strength increased. In this way we evaluated the hypothesis that the principal magnetic field sources would be the large electric motors powering the machine tools.

Methods

The site of this investigation was an automobile transmission plant which has been in operation since 1943. Electrical power is supplied to machine tools via a 440-V three-phase wiring system. About 8000 people are presently employed there, although many more have worked there in the past. Equipment in the plant is continuously being upgraded, with some departments (in 1990) consisting entirely of new (post-1989) machines. One purpose of this exposure evaluation was to use present-day measurements to estimate past exposures, so workers were selected from those departments having older machinery (relative to the rest of the plant).

Instruments for MF Measurement

The principle of operation of each measuring instrument is the same, that is, a time-varying MF induces a current in a loop of wire which cuts across it. The single-axis meter was used by twisting the hand while seeking the maximum on the analog meter, in order to position the loop across the direction of the field. This method has been found to give results equivalent to those obtained using the single-axis loop in each of three orthogonal planes and then computing the square root of the sum of the squared readings.[8]

The EmdexC dosimeter (EFM Inc., West Stockbridge, Massachusetts) has loops in three perpendicular planes, with the associated electronics to combine the readings, computing a resultant MF strength which is independent of the orientation of the device. This dosimeter can record up to 14,000 such measurements for downloading to a personal computer. For this survey the instrument was set to record a measurement every 4 seconds, and from these data 1-minute averages were computed. These averages provided the basis for deriving several summary exposure indices for each worker.

Measurement Strategy

The dosimeter was worn for one-half shift by 81 workers chosen from a variety of production, assembly, and maintenance jobs. Workers were chosen from jobs that were representative of those held by the cases and controls in the brain cancer study. Results of measurements by both instruments were used to assign exposures to study subjects.

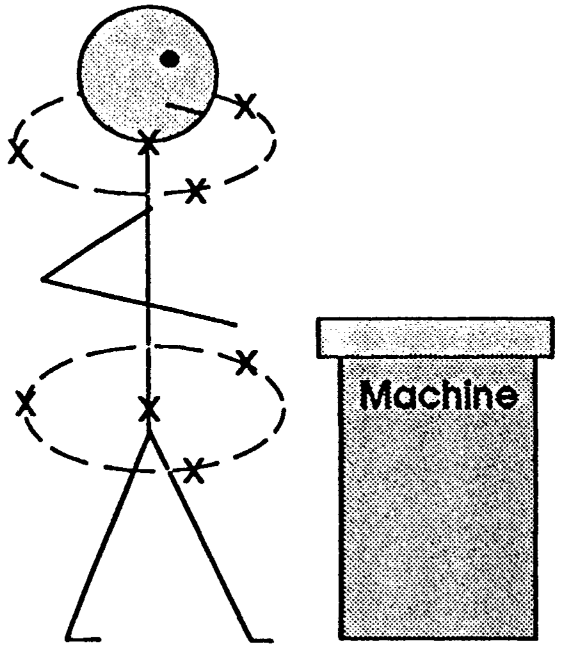

FIGURE 1. Measurement locations for spatial variability. Four measurements were made at waist and head, three around the circumference of a 1-ft radius disk.

This dosimeter was set to record a MF measurement every 4 seconds, and these data were downloaded and reduced to a series of 1-minute average exposures at the end of each day. From these exposure profiles, several exposure indices were computed, including the arithmetic mean (AM) and geometric mean (GM). This AM is the equivalent of the traditional time-weighted average (TWA) exposure, since both represent the area under the exposure versus time curve divided by the elapsed duration.

For those workers having semifixed workstations, including most of those in production and assembly jobs, spot measurements were taken at each location occupied by that worker for more than 10 percent of his or her work time. At each of these locations, three measurements were taken around the circumference and one at the center of a (horizontal) disk having a 1-ft radius around the head and waist. This was done to estimate the degree of microspatial variability in exposure (Figure 1).

Each worker's location was observed repeatedly over one-half shift to form the basis for the time percentages in the calculation of the built-up daily-weighted average (DWA) exposure. This DWA was computed separately for the head and waist by averaging the four measurements at each height and summing the averages weighted by the estimated percentage of time spent at each position (Table 1). This computation was done for each worker who wore the dosimeter and for whom it was possible to take spot measurements at from two to five locations. For some workers, primarily those with maintenance jobs, it was not possible to identify their locations and no DWAs were computed.

TABLE 1. Calculation of DWA Exposure to Power-Frequency MFs for a Typical Job

Location	Percent Time	Spot Readings				Average Reading	(%) * (Average)
I	50	0.30	0.30	0.22	0.42	0.31	0.16
II	15	2.6	3.9	2.5	2.6	2.90	0.44
III	10	1.1	1.9	2.6	1.05	1.67	0.17
IV	10	0.22	0.35	0.26	0.32	0.29	0.03
V	15	0.8	4.2	2.3	0.9	2.05	0.31

Department: 356
Job title: machine operator-general (drill and ream)
Date: 10/10/90
Identifier: J.
Height: head
Readings in milligauss; 10 mG = 1 microtesla.

Sum = DWA = 1.11 mG.

These estimates of duration (as a percentage of the work period) spent at each location were made without knowledge of the measured average exposure, since duration percentages were assigned to each location while the dosimeter was being worn and before the data were downloaded later that day.

In addition, by moving the spot meter in each of three orthogonal directions at each measured location, estimates were made of the identity of the principal source(s) of the MFs. Distances from the apparent source to head and waist were also estimated and recorded.

Statistical Analysis

To learn whether this DWA method adequately estimates the actual MF exposure, correlations were computed between the waist DWA and the AM and GM derived from the datalogger records. The nonparametric Spearman correlation coefficient was used to examine the degree of association between the pairs of exposure measures, since the distributions of each were found to be nonnormal and skewed to the right.[9]

These two central tendency indices derived from the datalogger, the AM and GM, have also been compared with several other plausible exposure indices derived from the datalogger records, since little is known of the biological mechanism of harm.[10]

To estimate horizontal (within-disk) variability at each measured location, the coefficient of variation (CV) was computed for the four readings at head and waist. Across all the head readings, the shape of this distribution of CVs was evaluated with the Shapiro-Wilks test[11] and its central tendency estimated by the median, since a right-skewed distribution was expected.

Source Distance and MF Strength

For selected strong MF sources the degree of field strength falloff with distance was investigated to compare actual results to those predicted by physical principles. This was useful because in a workplace the complex geometry of current-carrying wires makes direct application of these principles uncertain. If the MF (B) falloff is assumed to follow a power law,

$$B_i = B_o r^{-b},$$

to estimate the exponent (b), the distance versus field strength data were log-transformed and a linear regression of log(field strength) on log(distance) was carried out:

$$\log(B_i) = \log(B_o) - b*\log(r).$$

Results

For 57 workers it was possible to estimate fractions of time spent at each of several workstations and to measure the MFs at both head and waist. The remaining 24 workers (among the 81 wearing dosimeters) were in maintenance and other jobs without fixed workstations, so no DWA exposure could be computed.

Both calculated DWAs and dosimeter measures of central tendency of MF strength showed a wide range of values, reaching two orders of magnitude. Because the spot measurements did not detect brief peak exposures to which the AM is quite sensitive, the upper end of the range of both DWAs (at head and waist) was lower than that of the AMs (Table 2). Many of these peaks were due to demagnetizers in the vicinity of workers' normal work locations (see below). The GM was less sensitive than the AM to these peaks, and showed approximately the same range as both DWAs.

The lower range of MF values was also of interest. The background exposure in the plant was less than 0.2 milligauss (mG), below the 25th percentile of average residential exposures (approximately 0.45 mG in a large national survey).[12]

Comparison Between the DWA and Dosimeter Averages

Spearman correlation coefficients were found to be relatively high between built-up averages (DWAs) and dosimeter-

TABLE 2. Summary Statistics for Exposure Estimates

Within-Worker Indices	Between-Worker Statistics					
	AM	GM	Median	Min	Max	IQR*
Dosimeter						
AM	2.7	1.4	1.2	0.16	38.	0.77–2.4
GM	1.2	0.86	0.84	0.14	9.1	0.56–1.3
Spot meter						
DWA (W)	1.2	0.82	0.84	0.17	7.6	0.45–1.4
DWA (H)	1.4	0.94	0.98	0.20	9.4	0.57–1.5

Dosimeter-derived indices and DWAs at head and waist (in milligauss; 10 mG = 1 microtesla); n = 57.
AM = dosimeter-derived arithmetic mean of approximately 200 1-minute averages;
GM = dosimeter-derived geometric mean of the same 1-minute averages;
DWA (W) = DWA, based on spot measurements at the waist;
DWA (H) = DWA, based on head measurements.
* IQR = interquartile range, the 25th and 75th percentiles.

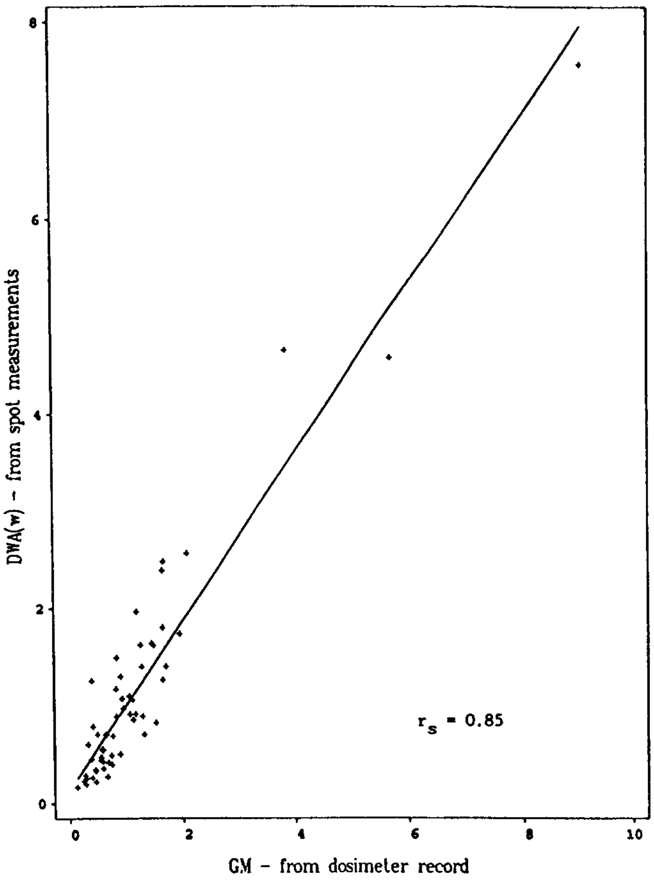

FIGURE 2. Scatter plot of DWA(w) versus GM. DWA(w) = daily weighted average, at the waist, derived from averaged spot measurements and time estimates. GM = geometric mean, computed from the sequence of 1-minute averages which were derived from the dosimeter record.

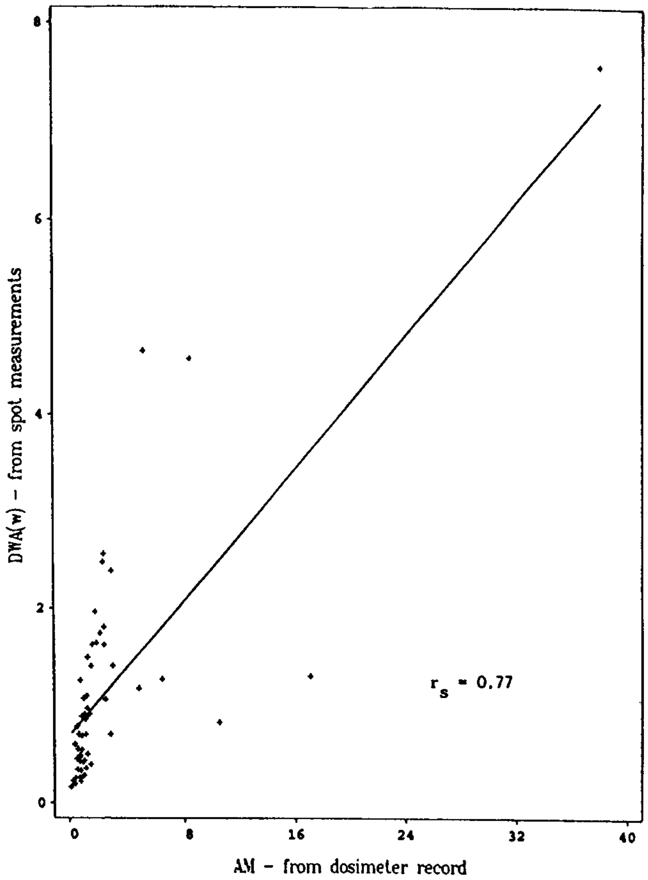

FIGURE 3. Scatter plot of DWA(w) versus AM. DWA(w) = daily weighted average, at the waist, derived from averaged spot measurements and time estimates. AM = arithmetic mean, computed from the sequence of 1-minute averages which were derived from the dosimeter record.

derived indices. For example, the correlation between the dosimeter GM and the DWA at the waist was $r_s = 0.85$ ($p < 0.0001$ from a test of H_o: $r_s = 0$). A less strong correlation was found between the AM and DWA ($r_s = 0.77$, $p < 0.0001$); this was expected because brief peak exposures had more significant effects on the AM than the GM, and these were not detected in the DWA computation. Figures 2 and 3 show scatter plots of these associations.

MF Sources

Unexpected types of MF sources were encountered. Motors were expected to be the principal sources, but they were the primary source in only 28 percent of locations measured. Power panels, fluorescent light ballasts, and wiring were the other principal sources identified (Table 3).

The presence of demagnetizers was not anticipated. The friction of grinding operations magnetizes some steel parts, which then must be demagnetized for several reasons. In some cases small parts must have no magnetism so that, once assembled in an automobile transmission, they will not pick up metal shavings which would interfere with proper functioning. Similarly, cutting tools and dies must have magnetism removed to prevent them from picking up shavings which would interfere with the intended metalworking operation. Additionally, magnetism in parts can interfere with the alignment of some electron beam welders, which are used for the very precise joining of parts prior to assembly. Parts are demagnetized by placing them in a continuously reversing magnetic field whose field strength is gradually diminished to zero.[13]

A total of 21 demagnetizers were identified in the plant, of which 10 were in production departments. This identification depended heavily on interviews with electricians and experienced machinists, since most demagnetizers were not listed as machines in the computerized list maintained by the plant

TABLE 3. Principal Magnetic Field Exposure Sources Identified

Source Type	Percent of Work Locations
Power panels	34
Motors	28
Fluorescent light ballasts	23
Wiring	19

Other sources, which influenced MF strength at fewer work locations, included demagnetizers, cathode ray tubes, and apparent ground return currents. Sources were identified by moving a hand-held spot meter in three perpendicular directions at each of 156 work locations.

engineering department. Thus there may be other demagnetizers in the plant that were not identified by this process. A few of these devices operate continuously, including those on conveyors which feed parts to a group of electron beam welders. In this case several workers who happen to be stationed in this area are regularly exposed. More commonly a demagnetizer will be activated manually, when it is used to remove magnetism from a cutting tool or die which has been ground. Other demagnetizers in production areas are activated only when a basket of parts has reached them in its path down a conveyor. As a result, workers in a variety of job titles and departments are exposed to the fields from the demagnetizers.

In addition to motors being important sources, power distribution panels were major sources at about 34 percent of the measured sites (Table 3). These panels are metal boxes, sometimes with switches on their face and sometimes not, from which electric current is distributed to the machines in the area. Because wiring is not paired in these panels, they tend to be important sources of MFs. External fields from two-conductor wires tend to cancel, since opposite fields are generated by the current in each conductor. Another 23 percent of the locations measured had a significant influence from fluorescent light ballasts.

Field Strength Versus Distance

Multiple measurements were taken in each of several directions from a cluster of demagnetizers, at estimated distances ranging from 2 to 11 m. The exponent for the power law falloff with distance was found to vary from 1.93 to 2.64 ($r^2 > 0.90$) across the four different directions in which measurements were taken. This is consistent with what would be expected from the physical principles, which suggest that such an exponent should be between 2 and 3 when the distance is much greater than the dimensions of the current-carrying coils generating the fields.[14] Figure 4 shows this falloff for one of the sets of measurements.

Fields apparently due to ground return currents were encountered in a few locations in the plant, but in only one case were data available to estimate the exponent as above. In this case the estimated exponent was 0.46, lower than the expected value of 1.0.[14]

Most sources identified did not have influence past several feet, except for some demagnetizers whose fields retained strength at considerable distances (e.g., 11 mG at 10 m from the cluster of four demagnetizers). (Background MF strength at this plant is below 0.2 mG, with median exposure across the measured group of 1.3 mG.)

Local Variability

For individual workers, DWA exposures at the head and waist were found to vary in both directions, with the head exposure sometimes higher and sometimes lower. The magnitude of the differences was not large, with only 10 of 57 workers having differences greater than 0.7 mG. Instances in which head exposures were found to be higher than exposure at the waist were sometimes found to be due to fluorescent light ballasts, or less frequently to switch panels and overhead ground return currents. Higher waist exposures were also due to a variety of sources, including a fluorescent light table and machine motors. There appeared to be no job or department as a whole that had consistent differences between head and waist exposures.

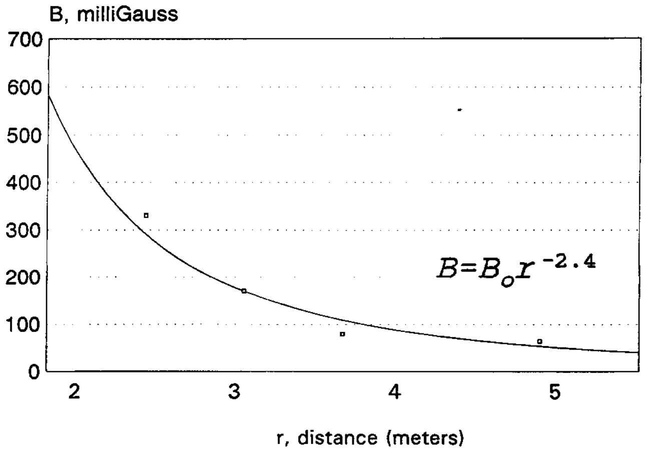

FIGURE 4. Magnetic field falloff with distance from a cluster of demagnetizers.

With few exceptions variability within the (horizontal) disks at head or waist was remarkably low, as shown by the CV of the four readings in each disk. Distributions of the CV across the 136 measured locations were tested and found to be more lognormal than normal. Their median at the head was 28 percent and at the waist 23 percent, meaning that about half the locations had standard deviations across the 1-ft radius disks less than one quarter of the mean.

This finding is apparently due to most MF sources not being close enough to the worker for a rapid falloff to occur within the 1-ft radius disk which we used to mark the worker's position.

Discussion

We have shown that it is possible to construct a surrogate exposure average, the DWA, which agrees remarkably well with indices of central tendency derived from the repeat measurements recorded by a three-axis personal monitor. Agreement is better with the GM and reasonably good with the AM of the individual's exposure pattern, as computed from 1-minute mean exposures. This latter index, the AM, is the equivalent of the traditional TWA exposure.

The usefulness of this finding will depend somewhat on whether exposure indices sensitive to peaks (e.g., the AM) are found to be consistent with the unknown mechanism of harm. Since the DWA agrees more closely with the GM, an index which is less influenced by brief peaks, a strategy relying on spot measurements will be more dependable if these peaks play little role in the disease process.

It is not clear to what extent these findings may be generalizable to other workplace exposure evaluations. In our strategy, the estimates of time spent at each location were based on judgments from repeated observations of each worker's location. Whether the same result would follow based on worker interview reports, or on estimates based on less intense observation, should be investigated further.

In the estimation of household exposures, it has been shown that single spot measurements weakly predict ($r^2 = 0.25$) 24-hour measured average exposures despite time of day differences and within-house variability.[15] In our case we used from 8 to 20 spot measurements to estimate measured averages over 200 minutes, and found a much higher percent of the variance explained ($r^2 = 0.73$). Exposure variability across workers having the same job title can also be expected but was not evaluated in detail here. This DWA method would allow the estimation of the GM exposures of many persons working in the same area, at lower cost (in equipment or time) than with the use of dosimeters on each person. Such a group of workers in the same part of the plant could all have their activity patterns observed by one person, who could take spot measurements at each of their work locations. This could be a major benefit in evaluating variability in exposure across a group in the same department.

Since measures of horizontal exposure variability at given work locations are not large, we can say that this strategy can be used effectively with no more than four measures per location. A strategy which used a larger number would appear to be redundant. In case of doubts concerning the generalizability of this finding, a conditional strategy could be described to identify which situations might require more than four spot readings, based, for example, on the largest range between any pair of measurements in a disk of radius 25 cm.

The degree of error which might be expected from greater horizontal (within-location) variability awaits further identification of which strong sources are commonly close enough to contribute to this problem. Fluorescent ballasts and color monitors (CRTs) close to the head are sources which may fall into this category. Such arrangements may be common in electronic assembly and at some office desks, where future exposure strategy evaluations should take this spatial variability into account.

Acknowledgments

This work was supported in part by funds from the United Auto Workers/General Motors National Joint Committee on Health and Safety, and by grant RO1 OH 02820 from the National Institute for Occupational Safety and Health.

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