THE APPLICATION OF A PERSONNEL MONITORING SYSTEM TO POPULATION DOSIMETRY OF BACKGROUND RADIATION*

JACOB SHAPIRO, ASCHER SEGALL and JANE WORCESTER
Departments of Industrial Hygiene, Epidemiology, and Biostatistics, Harvard School of Public Health, Boston, Massachusetts

Abstract—A field study was undertaken to evaluate the use of pocket ion chamber dosimeters for measuring population dose to background radiation. The chambers were charged to a low voltage to minimize leakage and read after exposure with a pulse-reading method. The method had a sensitivity reported to be 1 mr ± 0.2 mr.

Special tests were devised for selection of stable and reproducible ion chambers. The dosimeters were worn by individuals for a week at a time over a five-week period and calibrated and standardized after each week of use. Results of an analysis of variance on the standardization data obtained with 41 dosimeters over the period of use are presented. The tests showed that after field use, the system, including reader plus dosimeters, showed increased variability over the variability at the beginning of the tests. The leakage of the dosimeters was also apparently increased in field use over that found in laboratory experiments. The study showed the need of frequent testing in the field of any system used for population dosimetry at the low levels characteristic of background radiation.

The design of a study of population exposure to background radiation with personnel monitoring devices is discussed. Formulas are presented for determining the total number of dosimeters to use and the number of dosimeters to assign per individual, based on initial pilot studies.

The test data obtained in this survey should be useful for comparison with test data on other dosimeter systems, such as the thermoluminescent type in evaluating the performance of detection systems for the measurement of low-level population exposure.

INTRODUCTION

Interest in the measurement of background radiation for epidemiologic studies has, in recent years, stimulated efforts to develop methods that are capable of detecting differences in low-level gamma radiation and that are, at the same time, suitable for use in large-scale population studies. Such methods should be sufficiently sensitive to monitor the low dose rates characteristic of background radiation with a high degree of reliability. In addition, the dosimetric system should exhibit minimal energy dependence within the range of energies likely to be encountered in studies of natural background radiation and should be relatively dose-rate independent. The instruments should also be portable and sufficiently stable to ensure reliable operation under a variety of field conditions.

Of particular concern to epidemiologic investigations is the dose received by members of the population during the course of their normal activities. This may be estimated from spot measurements of the potential exposure in the environment as recorded by a pressurized ionization chamber or a geiger or scintillation detector. If a detailed mapping of the environment is made over the time period of interest and knowledge of the time spent by the subjects in areas of different exposure rates is obtained, the personnel dose may be calculated.

Environmental measurements provide a satisfactory method of determining population dose, and estimates based on their use have been

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presented in several studies.[1] Where the main information desired is the exposure of a selected group of individuals, or the difference in exposure of individuals in different areas, personnel monitoring devices provide an attractive alternative approach to background measurements, since they measure personnel exposure directly.

Personnel monitoring devices may also be particularly useful when the background levels, which are affected by rainfall, fallout, and barometric pressure, change significantly over the period of time of interest.

The two detection devices which have been used most extensively to date for monitoring of individuals occupationally exposed to radiation are pencil condenser ionization chambers and personnel monitoring film. Because of their widespread use and commercial development, both types of detectors are available at sufficiently low unit cost to enable their use by large numbers of individuals. However, the usual methods of using these detectors for radiation protection purposes are not sufficiently sensitive to enable their direct application to the low levels generally accumulated in population exposure studies.

The sensitivity of the personnel monitor film can be improved vastly by surrounding it with scintillation material, and the performance of this unit has been studied in detail by Henson.[2] It turns out that the film is highly dose-rate and temperature dependent when the exposure is produced by light from the scintillator rather than by background radiation directly.

The sensitivity of pencil ionization chambers may also be greatly increased by the use of a special read-out system designed in 1958 by Roesch, McCall and Rising.[3] In this method, a precision, stable voltage supply is used to charge the ion chambers. After exposure, the chamber is recharged to the same voltage through a resistor. A voltage pulse is produced across the resistor proportional to the differences in voltage between the ion chamber and charging voltage and, therefore, proportional to the measured dose. According to McCall, this system has several advantages as compared to the conventional method of reading condenser ion chambers.[4]

First, the method is a differential one; and the difficulties of measuring a small difference between two large numbers is avoided. Second, the method uses pulse measurements rather than direct current, and it becomes much simpler to obtain high sensitivity and stability. Selected single pencil dosimeters can measure 1 mr levels with an accuracy of ± 0.2 mr in 95% of the trials. The pencils are mechanically stable and undergo little change due to thermal cycling.

The characteristics of this system suggest that it may be adaptable for use in epidemiologic studies of background radiation. The present study was designed to assess this possibility.

INSTRUMENTATION

Specially selected Victoreen Model 36 Z pocket ion chamber dosimeters and a commercial reader were used. The reader is of the type described by Roesch *et al.*[3] and was supplied by Controls for Radiation, Cambridge, Massachusetts. A photograph of the reader is given in Fig. 1. It consists essentially of three parts—input circuit, amplifier, and peak-reading voltmeter. The input circuit is a high-impedance cathode follower using an electrometer tube. Long time constants are used to minimize the effect of electrical noise caused by the insertion of the ion chamber. The amplifier is a low-gain circuit with a choice of attenuators to provide high and low ranges. The peak-reading voltmeter converts the pulse into a very long high-current pulse whose amplitude can be displayed on a meter. The rest of the circuitry includes a highly stable power supply for charging the ion chambers and a system for simulating various doses on the ion chambers. This latter system makes it possible to check quickly the calibration and linearity of the reader.

Since a broad spectrum of gamma rays is encountered in the measurement of background radiation, it is desirable to have detectors as nearly energy-independent as possible. The Victoreen pencil dosimeters used were reported by their manufacturer to have a dose response which varied only a few percent with energy between 0.1 MeV and 1 MeV.

A seven-day period was chosen as a convenient time interval for measuring exposure. Readings of approximately 2–4 mr were expected for this period. The reader had two ranges and was adjusted so that the lower range was 0–5,

and the meter read directly in mr. The high range of 0–50 mr was not used in this study. To avoid excessive leakage, the chambers were charged to only 20 V. At this voltage, saturation is obtained up to dose rates of at least 50 mr/hr, and this saturation continues down to about ten volts. Leakage was reported to increase the reading by about 1 mr/month at 20 V.[3, 5]

SELECTION OF DOSIMETERS

The use of pencil chambers for measurement in the 1 mr range required special care in their selection. Residual mechanical strains in the insulators, loose connections, and excess dust or moisture may produce erratic and nonreproducible readings. It was therefore necessary to establish criteria for screening dosimeters prior to field evaluation.

During the course of initial screening, it was noted that even those dosimeters which appeared to be functioning in a reliable manner would occasionally give readings which differed appreciably from the average, e.g. as much as 0.5 mr when the average was 1.1 mr. Consequently, selection criteria were based on the average results of several readings rather than on a single reading. After several preliminary trials, the following empirical criteria for acceptance of dosimeters for field use were adopted.

1. Dosimeters were tested as a set, and the whole set was accepted or rejected depending on their meeting the prescribed conditions.

2. All the dosimeters were given a constant exposure of approximately 1 mr, and the exposure time was 5 min. The value chosen for the reference exposure was the average of all the readings of the dosimeters suitable for field use.

3. Each set of dosimeters was exposed for five times in succession. At least 90% of the readings had to be within 0.3 mr of the average reading, and each dosimeter had to read within 0.3 mr of the average in three out of five trials.

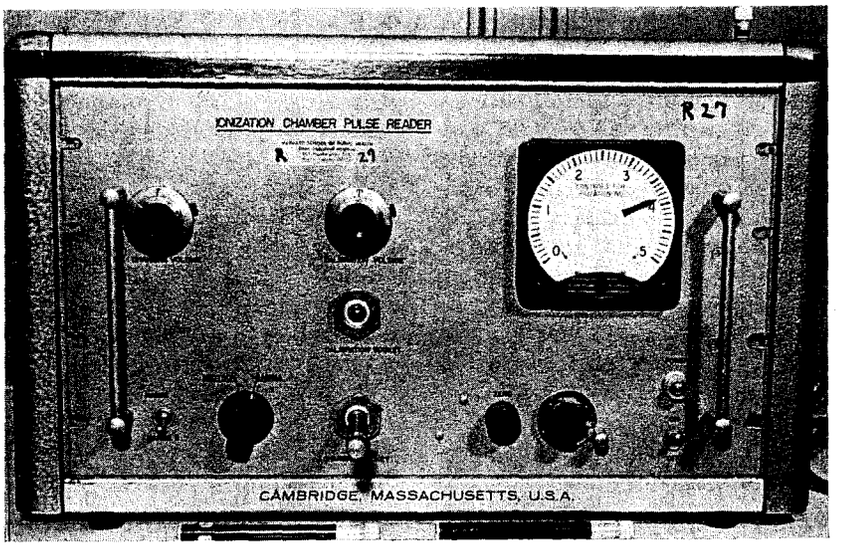

FIG. 1. Ionization chamber pulse reader.

The initial set of dosimeters tested could not meet these criteria. Another set of 50 dosimeters which was tested gave a mean reading of 1.03 mr, and the numbers of dosimeters giving all five, four, and three readings within the prescribed range were 39, 8, and 3 respectively. These readings represented 92% of the total taken. A third set gave a mean value of 1.24 mr and was rejected. Some dosimeters which gave erratic results because of induced charges on the insulator were improved and found suitable for use after exposure to 100r of X-radiation.

Table 1. *Screening of Dosimeters Prior to Field Use*

Instrument number	Trial 1 (mr)	Trial 2 (mr)	Trial 3 (mr)	Trial 4 (mr)	Trial 5 (mr)	Mean (mr)
14,508	1.10	1.20	1.10	1.00	1.10	1.10
14,532	1.10	1.10	1.20	1.00	0.95	1.07
14,544	1.00	1.00	1.10	1.00	0.90	1.00
14,743	1.00	1.10	0.80	1.00	0.60	0.90
14,817	1.10	1.10	0.80	0.90	1.20	1.02
14,897	1.00	0.90	0.70	0.80	1.00	0.88
14,946	1.00	0.70	0.90	1.10	0.90	0.92
14,961	1.05	1.00	1.10	1.00	1.20	1.07
15,175	0.80*	0.70	0.80	0.90	0.80	0.80
15,208	0.80	0.60	0.10	1.70	0.80	0.80
15,338	1.30	0.90	0.10	1.00	1.10	1.08
15,605	0.90	1.30	1.00	1.00	0.90	1.02
15,639	1.20	1.00	0.60	1.00	1.20	1.00
15,688	1.20	1.20	1.00	1.20	1.00	1.12
15,704	1.00	1.20	0.80	1.30	1.10	1.08
15,734	0.95	1.00	1.00	1.10	0.90	0.99
15,805	0.95	1.00	0.70	0.70	0.90	0.85
15,903	0.90	1.20	1.10	1.20	1.00	1.08
15,918	1.20	1.10	0.90	1.00	0.95	1.03
15,946	1.10	0.90	1.00	1.20	1.20	1.08
16,023	1.00	1.30	0.80	1.10	1.00	1.04
16,059	1.20	0.60	0.80	0.90	0.85	0.87
16,310	1.00	0.80	0.80	0.80	1.00	0.88
16,337	1.50	1.00	0.90	1.00	1.10	1.10
16,368	1.10	1.00	1.00	1.20	1.10	1.08
16,397	1.50	1.10	1.00	1.20	1.10	1.18
16,478	1.20	1.30	1.10	1.50	1.00	1.22
16,629	0.90	0.90	1.00	0.70	0.70	0.84
16,662	0.90	0.80	0.90	0.80	0.90	0.86
16,705	0.85	0.80	1.00	0.90	1.00	0.91
16,842	0.90	0.70	0.90	0.80	1.00	0.86
16,868	0.90	1.00	0.80	0.90	0.90	0.90
16,959	1.00	1.10	0.90	1.00	1.00	1.00
17,046	1.10	1.30	1.10	0.90	1.10	1.10
17,127	1.20	1.10	0.90	1.00	1.30	1.10
17,169	1.10	0.90	1.10	0.70	1.00	0.96
17,173	1.10	1.10	0.90	1.20	1.00	1.06
17,185	0.80	0.90	0.60	1.00	0.70	0.80
17,291	1.20	1.80	1.10	1.40	1.20	1.34
17,303	1.10	1.00	0.80	1.10	1.00	1.00
17,404	1.00	0.83*	0.83*	0.90	0.60	0.83

* Instrument mean substituted for missing reading.

PERFORMANCE TESTS DURING FIELD USE

Test results obtained with one set of dosimeters that was selected for field use are given in Table 1. This group consisted of 41 dosimeters. The mean reading of the exposure was 1.00 mr. Thirty-one of the dosimeters read between 0.7 and 1.3 mr; 9 dosimeters gave readings in this range in four out of five trials; and only 1 dosimeter exceeded these readings in two of five trials. Ninety-five percent of the readings were within the prescribed range.

Table 1 provides an indication of the extent to which the response characteristics of the 41 dosimeters varied, both within a single instrument and between instruments, when the instruments were exposed to a reference source under standard conditions. An analysis of variance based on the observations in Table 1 is shown in Table 2(a). The detailed methods for calculating the mean squares can be found in standard statistical textbooks.[6]

The mean square 0.0222 represents the error variance associated with reading and timing as well as those factors inherent in the nature of the individual instruments. The variability between instruments was significantly greater than the variability within instruments.

The dosimeters were worn by individuals for a week at a time over a five-week period to measure exposure from background radiation. The results of this study have been published elsewhere.[7, 8] Following each weekly read-out, the pencil chambers were exposed to two calibration trials with the same reference source and using the same technique employed prior to the field studies. The results of these calibration trials are shown in Table 2(b) and indicate a significant variation between the means of the five weeks.

The variation may have been caused by difficulties in accurate adjustment of the read-out system over an extended time period, as well as by possible changes in average dosimeter performance. As before, the variation between dosimeters was also significant. The interaction between weeks and dosimeters was not significant. Also worth noting is the fact that the error variance 0.0407 during field use is significantly larger than the error variance 0.0222 in the laboratory selection tests shown in Table 1. This may be due, in part, to the mechanical trauma to which the dosimeters were subjected when worn over a period of five weeks and to variations in leakage of the individual dosimeters.

Following the population survey, the dosimeters were returned to the laboratory where they were again exposed to four calibration trials. Table 2(c) gives the analysis of variance for the same set of 41 dosimeters following field use. The variation between dosimeters is no longer significant. However, the error variance has increased greatly. This increase was due presumably not only to the effect of handling

Table 2. Analysis of Variance

	Source of variation	Degrees of freedom	Mean square	F
(a)	*Before field use*			
	Between dosimeters	40	0.0770	3.45 $P < 0.01$
	Within dosimeters	164	0.0222	
(b)	*During field use*			
	Weeks	4	0.189	4.65 $P < 0.01$
	Dosimeters	40	0.157	3.84 $P < 0.01$
	Interaction	160	0.0415	1.02 not significant
	Within dosimeters	205	0.0407	
(c)	*After field use*			
	Between dosimeters	40	0.2604	1.37
	Within dosimeters	164	0.1893	

during field use on the dosimeters, but also to an unexpected difficulty encountered with respect to the read-out unit. This suggests the necessity of frequent testing of the entire system under actual survey conditions.

Experience acquired in repeated tests of the dosimeters indicated that the variance in dosimeter readings was significantly influenced by the method of handling the dosimeters and the method of inserting the dosimeters into the reader, and a proper technique had to be developed to give minimum variance in the readings. Apparently, as the limit of sensitivity of this system was approached, as much art as science was required in getting the best performance possible.

During the time the dosimeters were used to measure personnel exposure, a concurrent independent study of background radiation in the area was conducted by Lowder and Condon with the use of high-pressure argon ionization chambers and a gamma spectrometer system. [8]

The dosimeters averaged 1.1 mr/week higher than the personnel exposure calculated by Lowder and Condon in all areas. The higher exposure values obtained with the dosimeters indicated a systematic error which was attributed by Lowder and Condon to be due to leakage of the dosimeters in the field which was considerably higher than the expected value used to correct the readings. The expected value based on laboratory tests had indicated a leakage correction of 0.2 mr/week, so the average total leakage for pencil chambers when worn by individuals was of the order of 1.3 mr/week.*

Because the purpose of the dosimeters was primarily to measure a difference in levels between two areas, the leakage produced only a second order error in the desired results. This may be seen by comparing the differences in the weekly exposure for two regions as derived by Lowder and Condon based on ionization chamber and dosimeter readings. The two sets of results are presented in Table 3.

* A leakage rate of approximately 1 mr/week was also observed in tests at Harvard of dosimeters used as area monitors.

Table 3. Comparison of Differences in Weekly Exposures for two Regions as Determined from Pressurized Ionization Chamber and Pencil Dosimeter Measurements

Regions compared*	Difference in mr/week	
	Ionization chambers	Pencil dosimeters (average of 100 readings per area, 2 dosimeters/individual)
8–4	0.82	0.97
8–1	0.76	0.70
8–2	0.69	0.81
8–3	0.67	0.66
8–5	0.61	0.57
8–6	0.52	0.70
7–4	0.44	0.49
8–7	0.38	0.49
7–1	0.36	0.24
7–2	0.31	0.35
6–4	0.30	0.27
7–3	0.29	0.20
7–5	0.23	0.08
6–1	0.22	0.00
5–4	0.21	0.43

* Regions 1 through 8 were classified on the basis of underlying bedrock. The equivalent uranium bedrock concentration ranged from a minimum in region 1 progressively up to a maximum in region 8.

The results in Table 3 indicate good agreement between differences in exposure in different areas as determined from pencil chamber and pressurized ionization chamber measurements for differences greater than 0.3 mr. Lowder and Condon report a high degree of correlation between the two methods with a line of slope equal to one fitting very well a plot of dosimeter measurements versus ionization chamber measurements. It is not possible to determine to what extent the differences in results for the two methods reflect true differences in exposure or errors in the methods.

DETERMINATION OF SAMPLE SIZE

In planning a survey to measure differences in the population exposure between two regions it is necessary to determine the number of persons to be included in the sample as well as the number of dosimeters to be worn by each individual. For this purpose it is advisable to conduct a pilot study in order to obtain estimates of the magnitude of the variation between dosimeters worn by the same individual (inter-dosimeter variability) and of the variation between individuals within a region (interindividual variability).

Table 4, based on data obtained during a survey in northern New England, indicates the type of information which should be collected in a pilot study, preferably but not necessarily, in the two regions. In this case 20 individuals, 5 from the urban and rural parts of each region, wore 2 dosimeters each for a week. This period of exposure is such that readings were, for the most part, between 2 mr and 4 mr. Since the top scale reading is 5 mr, it is necessary to keep the exposure under this level.

The information of particular importance from the pilot survey is the within areas sources of variation. Dosimeters, when worn by individuals, show greater variation (0.3978) than they did when exposed to a constant source. Variations between individuals, (0.9248) is significantly greater than variation between dosimeters. Consequently, if the between areas mean squares are to be tested for significance, it must be against the between individuals' mean square rather than against that for dosimeters.

The general formula for the determination of sample size is:[10]

$$n = \frac{2s^2(t_\alpha + t_\beta)^2}{\Delta^2}$$

where n is the number of observations in each of the two groups, s^2 is the estimate of variance, Δ is the difference to be established, t_α is the t-value associated with the level of significance and t_β is the t-value associated with power. t_α, t_β and Δ are chosen by the investigator. The value of s^2 is determined from the pilot survey.

Table 4. Readings on Dosimeters Worn by Individuals in Pilot Study

Region A	Urban			Rural		
Individual	1	3.5	3.4	6	4.3	4.8
	2	4.2	4.6	7	5.0	4.4
	3	4.0	4.8	8	3.7	2.1
	4	5.0	5.0	9	5.0	4.2
	5	3.4	2.7	10	5.0	4.8
Region B						
Individual	11	2.6	2.6	16	2.1	1.8
	12	2.5	2.2	17	3.3	2.2
	13	3.3	3.3	18	3.0	2.8
	14	2.8	2.8	19	2.6	2.5
	15	2.8	2.6	20	2.5	5.0

The analysis of variance on these 40 observations is shown in Table 5.

Table 5. Analysis of Variance from the Pilot Survey

Source of variation	Degrees of freedom	Mean square
Between Areas	3	6.5396
Regions	1	19.1822
Urban–Rural	1	0.0562
Interaction	1	0.3802
Within Areas	36	
Between individuals	16	0.9248
Between dosimeters within individuals	20	0.3978

From the within areas mean squares, it is possible to determine the components of variance σ_D^2 and σ_I^2 associated with dosimeters and individuals. In general, the between individuals mean square is $\sigma_D^2 + D\sigma_I^2$ where D is the number of dosimeters worn by an individual. The between dosimeters mean square is σ_D^2. In this case

$$\sigma_D^2 + 2\sigma_I^2 = 0.9248, \sigma_D^2 = 0.3978$$

This gives $\sigma_I^2 = 0.2635$.

The variance s^2 in the sample size formula is the variance between individuals, $\sigma_D^2 + D\sigma_I^2$, which becomes $0.3978 + 0.2635D$. The number of observations per group is ID where I is the number of individuals in each area.

The formula for the determination of sample size becomes

$$ID = \frac{2(t_\alpha + t_\beta)^2}{\Delta^2} (\sigma_D^2 + D\sigma_I^2)$$

Putting in the values from the pilot survey, this becomes

$$I = \frac{2(t_\alpha + t_\beta)^2}{\Delta^2} \left(\frac{0.3978}{D} + 0.2635\right)$$

As an illustration of the use of the formula, let us assume the investigator considers the establishment of differences, Δ, of 0.55 and 0.30, to be significant at the 5% level and that he wishes to be 90% sure of establishing such a difference if it exists. Under large sample theory $t_{0.05} = 1.96$ and $t_{0.10}$ (one tail) $= 1.28$.

CONCLUSIONS

Field experience with a pencil ionization chamber type of personnel monitoring system for measuring weekly exposures to background radiation produced results with considerably greater variability and additional systematic errors than were expected on the basis of laboratory studies.

Table 6. Number of Dosimeters Required to Establish Differences of 0.55 and 0.3 mr between two Areas, based on Results of Pilot Survey

	$\Delta = 0.55$ mr			$\Delta = 0.3$ mr		
Dosimeters per individual, D	1	2	3	1	2	3
Individuals required in each area, I	46	32	27	154	108	91
Observations per group in each area, ID	46	64	81	154	216	273

The main source of error in field application of the pencil chambers was excessive leakage, which probably precludes the application of the pencils for absolute measurements at their limits of sensitivity. However, the pencil chambers were effective in measuring differences in exposure because the effects of leakage were to a large extent cancelled out.

The procedures employed in the field study were able to detect differences of greater than 0.3 mr/week when 100 observations were made at each point.

The evaluation data presented in this paper for pencil dosimeters should be useful to investigators interested in using this method at the limit of its sensitivity. The statistical and experimental methods of testing these dosimeters as outlined in this paper are indicative of the type of information which should be obtained with other systems for personnel dosimetry at radiation background levels if useful evaluations and comparisons of their performance are to be made.

REFERENCES

1. J. A. S. Adams and W. M. Lowder, ed. *The Natural Radiation Environment*, University of Chicago Press, 1964.
2. P. W. Henson. A photographic dosimeter for the measurement of personal doses of environmental radiation, *Phys. Med. Biol.* **8,** No. 4, 423–438 (1963).
3. W. C. Roesch, R. C. McCall and F. L. Rising. A pulse reading method for condenser ion chambers, *Health Physics* **1,** 340–344 (1958).
4. R. C. McCall. Personal communication. Controls for Radiation, Inc., Cambridge, 1962.
5. F. L. Rising. Experience with the ionization chamber pulse reader at Hanford. Paper presented at Health Physics Society, Las Vegas, June 1961, unpublished.
6. W. J. Dixon and F. J. Massey, Jr. *Introduction to Statistical Analysis.* McGraw-Hill, 1957.
7. A. Segall. Radiogeology and population exposure to background radiation in northern New England, *Science* **140,** 1337, 1963.
8. W. M. Lowder and W. J. Condon. Measurement of the exposure of human populations to environmental radiation. *Nature* **206,** 658–662, May 15, 1965.
9. A. Segall and R. Reed. Human exposure to external background radiation, *Archives of Environmental Health* **9,** 492–499, 1964.
10. J. Worcester. The statistical method, *New England Journal of Medicine* 274, No. 1, January 6, 1966.