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ESTIMATING INDIVIDUAL AND COLLECTIVE DOSES TO GROUPS WITH 'LESS THAN DETECTABLE' DOSES: A METHOD FOR USE IN EPIDEMIOLOGIC STUDIES

DANIEL J. STROM
Department of Radiation Health, Graduate School of Public Health,
University of Pittsburgh, Pittsburgh, PA 15261

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Abstract—Distributions of annual external doses to worker populations are often found to be distributed lognormally below 15 mGy (1.5 rad). Using the properties of the lognormal distribution, and starting from individual dosimeter results, a method is presented whereby estimates can be made of collective and individual doses "missed" due to the fact that dosimeters have a threshold of detection or minimum detectable dose (MDD). For the case where only annual dose totals are available for a population, if MDD results were recorded as zero and if monitoring was done on a quarterly basis, the method developed is shown to yield reasonably good estimates of "missed" collective dose. For the other cases of only annual totals being available (i.e. monitoring was done more frequently than quarterly, or MDD results were recorded as equal to the MDD), it is shown that the method does not yield useful results. The estimates developed here may be useful in radiation epidemiology, employee relations, and in probability-of-causation calculations.

INTRODUCTION

EPIDEMIOLOGIC studies of persons occupationally exposed to external radiation have been undertaken by many groups (Ch83; Lu83; Ri83). Such studies may require an estimate of the collective dose received by individuals whose dosimetry results were "less than detectable," "below the minimum detectable dose," or "minimal," especially when there is a large proportion of persons given dosimeters for administrative rather than radiation protection reasons.

Grimson *et al.* have reported nonparametric statistical methods for estimating upper bounds on doses to unmonitored individuals in a group where some persons were monitored (Gr83). By contrast, the method presented here permits estimation of notional doses (Re82; UN82) for individuals and of the collective doses received by groups under a variety of conditions, for persons who were monitored but whose dosimetry results included one or more records of the type described above. The collective dose estimated here is that which was "missed" by the occupational monitoring program because the dosimeters being used have a threshold of detection.

In addition to their use in epidemiology, the estimates described below may be used in litigation where actual numbers are needed as input to probability-of-causation calculations.

THE RECORDING OF MINIMUM DETECTABLE DOSES

Before dose data can be cumulated to annual totals for individuals or for populations, the question of minimum detectable doses (MDDs) must be addressed. For the purposes of this paper, the MDD is considered to be the maximum dose that cannot be distinguished from zero, so that if a dosimetry calibration algorithm returns a value of MDD (an "MDD result"), then all that is known is that $0 \leq D_d \leq$ MDD, where D_d is the dose registered by that dosimeter. If the algorithm returns a value of MDD + Δ, then it is known that $D_d >$ MDD and that the best estimate of the dose is D_d = MDD + Δ. MDD results may have been recorded in occupational records in three distinct ways: (1) as zero or "minimal"; (2) as equal to the MDD for a given dosimeter type; or (3) as some other value, such as half the MDD or a value selected by the procedure outlined below.

If MDD results are recorded as equal to the MDD (Case 2, above), a positive bias is introduced into the data (Wai80), causing overestimation of both individual doses and of collective dose when individual doses are summed over a population. As an example of this, consider a film badge dosimeter with an MDD equal to 300 μGy (30 mrad) issued quarterly in an identification badge to a worker who does not work with radiation sources. Each year such a worker would have an absorbed dose of 4 × 300 μGy = 1.2 mGy (120 mrad) added to his record, even though he received no occupational exposure to radiation. While this practice is in line with traditional, "conservative" (i.e. tending to overestimate doses to workers when there is any doubt) health physics, it may produce a significant amount of fictitious dose in a population with many badged, yet unexposed people. Estimates of risk per unit dose resulting from an epidemiologic study of such a population would be biased downwards, that is, any health effects actually caused by radiation exposure in the population would be attributed to too much dose.

Recording MDD results as zero or "minimal" (Case 1, above), on the other hand, creates a negative bias in the data, causing an underestimation of individual and collective doses. As an example of this practice, consider a worker who wears the dosimeter described above and actually receives 200 μGy per quarter, but whose dose is recorded as 0 μGy because it is below the MDD of 300 μGy. Each year this worker receives 4 × 200 μGy = 0.8 mGy of actual radiation exposure, but his record shows zero.

The International Commission on Radiological Protection (ICRP) has recommended that doses less than or equal to a small "recording level" (such as an MDD) be treated as zero "for the purposes of radiation protection" (ICRP77, paragraph 150). Many organizations providing dosimetry to their workers for the purposes of radiation protection may have followed policies similar to the ICRP recommendation over the years. However, policies suitable for radiation protection may result in monitoring data that are not suitable for use in epidemiologic studies without some modification. In this case, any health effects in the population that really were caused by radiation would be attributed to too little dose, resulting in an inflated risk per unit dose.

An alternative to setting MDD results to zero or "minimal" is to set them equal to a small positive number (Case 3, above). A defensible method of arriving at such a small positive number is to fit the distribution of doses above the MDD to a lognormal function, and using the assumption that doses below the MDD would have had a similar distribution had they been measured, compute the average dose from zero to the MDD from the lognormal fit, and use this value for all records originally having values of MDD, "minimal," or zero. This is the method described below.

The author does not recommend that any change be made in records kept for radiation protection or compliance purposes; the method suggested here should be applied when such records are used for epidemiology, probability of causation calculations, or employee relations purposes.

If data have already been cumulated to annual dose totals for individuals by summing the results of all dosimeters worn during the year, then more elaborate procedures are needed for adjustment of individual doses.

IMPACT OF THE NUMBER OF DOSIMETERS ISSUED ON SUMMARY STATISTICS

It has been observed that annual occupational doses to individuals from external irradiation usually are distributed lognormally (Wal64; Ga65; Br76; Sp76; UN77). Deviations from the lognormal distribution are seen above 15 mGy (1.5 rad) and are attributed to the effect of occupational dose limits (UN77; Ku81). Comparisons of summary statistics such as average doses between populations and within the same population over time are of limited value unless some information about the nature of how doses are distributed in the population is available (UN77). This is because the number of persons receiving doses less than or equal to the MDD is dependent on the criteria used for issuing dosimeters, and because a large proportion of such persons will lower the average dose in a worker population.

For example, making the dosimeter a part of an identification badge may result in a large proportion of MDD results, while adherence to a criterion such as providing dosimeters only for "those apt to be exposed to more than 25% of the applicable limit" (US85) will surely result in many fewer such records.

The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) has developed more meaningful comparison statistics that are fairly insensitive to the numbers of "administrative" dosimeters issued (UN77, Annex E and Appendix I). Kraus has pointed out mathematical errors and inconsistencies of definitions in the UNSCEAR-1977 report, but with Kraus's corrections the UNSCEAR methods are valid (Kr80).

Using a simple hypothesis and an extension of the UNSCEAR techniques, a quantitative estimate of the "missed" collective dose can be made. The "missed" collective dose is that which is lost from total collective dose by assuming that all doses less than or equal to the MDD are zero (Case 1, above). If, on the other hand, all results of MDD are recorded as numerically equal to the MDD (Case 2, above), such values can be set to zero or "minimal"; the process described below applied; and the resultant lower, more realistic notional doses that are at least correct on the average substituted for values of MDD. Since the UNSCEAR statistics are calculated in the same way as the "missed" collective dose, all are considered in the material that follows.

THE LOGNORMAL DISTRIBUTION

The lognormal distribution is characterized by two parameters, μ, the natural logarithm of the median dose, and σ, the natural logarithm of the geometric standard deviation (GSD) (Ai57). The GSD may be thought of as the ratio of the 84.13th percentile dose to the 50th percentile dose, or the ratio of the 50th percentile dose to the 15.87th percentile dose. The parameters μ and σ may be extracted from the data using a graphical technique (UN77), or by using log-probit analysis such as the PROBIT procedure in the SAS statistical package (SAS85), which employs the methods of Finney (Fi71).

Because of the deviation from lognormality of most annual dose distributions mentioned above, UNSCEAR recommends that the parameters μ and σ be extracted using data only up to 15 mGy (1.5 rad).

For doses distributed lognormally, the average dose among all workers is

$$\bar{D} = e^{\mu+\sigma^2/2}, \tag{1}$$

while the median dose is

$$\tilde{D} = e^{\mu}. \tag{2}$$

Note that $\bar{D}$ from eqn (1) will, in general, be greater than the average dose calculated by summing all dosimeter results, due to the observed departure from lognormality above 15 mGy.

The fraction of workers who received doses in the range 0–D is

$$P_w(0\text{–}D) = Pr(z < [\ln(D) - \mu]/\sigma) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{[\ln(D)-\mu]/\sigma} e^{-t^2/2}\, dt, \tag{3}$$

where the expression on the right is the probability that the standard normal variate z is less than $[\ln(D) - \mu]/\sigma$.

For a population of N workers, the collective dose among persons who received doses between 0 and D is

$$S(0\text{–}D) = N \frac{1}{\sqrt{2\pi}} e^{\mu+\sigma^2/2} \int_{-\infty}^{[\ln(D)-\mu-\sigma^2]/\sigma} e^{-t^2/2}\, dt, \tag{4}$$

while the total collective dose, $S(0\text{–}\infty)$ is

$$S(0\text{–}\infty) = N \frac{1}{\sqrt{2\pi}} e^{\mu+\sigma^2/2} \int_{-\infty}^{\infty} e^{-t^2/2}\, dt = N\, e^{\mu+\sigma^2/2} = N\bar{D}. \tag{5}$$

The fraction $P_S(0\text{–}D)$ of the collective dose $S(0\text{–}\infty)$ among workers receiving doses in the range 0–D is simply the ratio of eqns (4) and (5):

$$P_S(0\text{–}D) = S(0\text{–}D)/S(0\text{–}\infty) = Pr(z < [\ln(D) - \mu - \sigma^2]/\sigma) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{[\ln(D)-\mu-\sigma^2]/\sigma} e^{-t^2/2}\, dt. \tag{6}$$

Besides the annual collective dose and the average individual dose, UNSCEAR (UN77) recommended calculating $P_w(0-D)$ and $P_S(0-D)$ for D = 5, 15, and 50 mGy (0.5, 1.5, and 5 rad). UNSCEAR argued for presentation of occupational monitoring data in standardized form to facilitate intercomparisons of data and to avoid complex and unclear compilations of data. In 1982, UNSCEAR (UN82) modified its 1977 recommendations to include only calculation of the annual average dose $\bar{D}$; the annual collective dose $S(0-\infty)$; and the ratio of the annual collective dose delivered at individual doses exceeding 15 mGy (1.5 rad) per year to the total annual collective dose, $S(15 \text{ mGy}-\infty)/S(0-\infty)$. SAS computer codes that calculate and plot both the 1977, the 1982, and other statistics for large amounts of dosimetry data have been developed at the University of North Carolina at Chapel Hill for the U.S. Department of Energy Health and Mortality Studies (St84).

Since all parameters and statistics described above can be calculated from detailed knowledge of the dosimetry records, log-probit analyses would seem to be unnecessary (UN82). However, one value of interest in an epidemiologic study or in employee relations studies, namely, an estimate of the amount of individual and collective dose "missed" due to the dosimeter threshold of detection, cannot be calculated without log-probit analysis.

Two distinct forms of analysis must be used depending on whether dosimeter results are available for each worker for each monitoring period, or whether only annual totals of dosimeter results are available for each worker. The two forms are discussed separately below.

ANALYSIS USING DOSIMETER RESULTS FOR EACH MONITORING PERIOD

Suppose dosimeter results at and above the MDD are found to be distributed lognormally with parameters μ_d and σ_d, where the subscript d denotes a distribution of *d*osimeter results (as opposed to annual or lifetime totals of dosimeter results) for all workers. Then, assuming that dosimeter results at or below the MDD are distributed lognormally with the same parameters as results above the MDD, it is possible to calculate the collective dose that was "missed" when such results were recorded as zero or omitted from totals. This is the calculation of

$$S_d(0\text{–MDD}) = N_d \bar{D}_d P_S(0\text{–MDD}), \quad (7)$$

where $S_d(0\text{–MDD})$ is the collective dose of all dosimeters with MDD results, N_d is the total number of dosimeters used in the analysis, $\bar{D}_d = \exp(\mu_d + \sigma_d^2/2)$, and $P_S(0\text{–MDD})$ is the fraction of the collective dose calculated from eqn (6) that would have been recorded by those dosimeters had the MDD been zero.

The mean or expectation value of the dose "missed" for each dosimeter having an MDD result is

$$\bar{D}_{d,\,\text{missed}} = S_d(0\text{–MDD})/N_d P_d(0\text{–MDD}) = \bar{D}_d P_S(0\text{–MDD})/P_d(0\text{–MDD}), \quad (8)$$

where $P_d(0\text{–MDD})$ is the fraction of all dosimeters having results at or below the MDD calculated from eqn (3). The value $\bar{D}_{d,\,\text{missed}}$ can be assigned as a notional dose (Re82) to replace each occurrence of an MDD result. An individual i who has z_i "zero" dosimeter readings in a year would have received a "missed dose" of, on the average,

$$\bar{D}_{i,\,\text{missed}} = \frac{z_i}{N_d} S_d(0\text{–MDD}). \quad (9)$$

To eliminate a negative bias in an external dosimetry data set for use in an epidemiologic study in which MDD results were set to zero, notional doses such as shown in eqn (9) can be added to individual's annual totals. If $P_S(0\text{–MDD})$ is significantly above zero, then such a correction would reduce estimates of risk per unit dose.

To eliminate a positive bias in an external dosimetry data set for use in an epidemiologic study in which MDD results were set equal to the MDD, notional doses such as shown in eqn (8) can be substituted for each of the z_i occurrences of MDD in an individual's records before computing an individual's annual totals. If $\bar{D}_{d,\,\text{missed}}$ is significantly less than the MDD, then such a correction would increase estimates of risk per unit dose.

ANALYSIS USING ANNUAL TOTALS FOR WORKERS

If only annual dose records are available for workers, an estimate of the "missed" collective dose can not be made with the same degree of confidence as when individual dosimeter readings are available; and without knowledge of the number of dosimeters issued to each person, little can be said about "missed" doses for individuals. However, if dosimeters were issued quarterly, careful analyses of all data can yield estimates of average "missed" doses for individuals that are fairly accurate.

To understand the problem, imagine that j dosimeters per year are issued to persons working the entire year. In the following example, j is taken to be 4, that is, monitoring was done on a quarterly basis. There are two cases to be considered.

In Case 1, annual totals for workers are computed from records in which any occurrence of an MDD result is recorded as 0. The left half of Table 1 shows all of the logically possible numbers of MDD results (recorded as zeros) a person might have had as a function of the number of

Table 1. *This table illustrates the difficulty in estimating the number of MDD results that occurred among all persons during a year when only annual dose totals are available. Table entries are the logically possible number of occurrences of MDD results* ($0 \le D_{d_i} \le MDD$) *for an individual during a year as a function of dose and number of dosimeters issued to the individual in a given year, separated into Case* 1 (*MDD results recorded as* 0) *and Case* 2 (*MDD results recorded as MDD*). *Here, MDD* = 0.3 mGy, Δ = 0.1 mGy (*so a dosimeter result of* 0.4 mGy *is real*), *and* j = 4 *dosimeters per year* (*quarterly monitoring*). *An entry of* 0, 1, 2, *for example, means that having the dose in column* 1 *recorded is consistent with the worker's having had* 0 *or* 1 *or* 2 *MDD results in the year. Individuals beginning radiation work late in the year or stopping radiation work at some point in the year complicate the inference of "missed" collective dose. Only when one dosimeter is issued per year is it possible to enumerate exactly the occurrences of MDD results*

Recorded Annual Dose (mGy)	<----Case 1----> (MDD results recorded as 0) No. dosimeters issued to an individual during year				<----Case 2----> (MDD results recorded as MDD) No. dosimeters issued to an individual during year			
	1	2	3	4	1	2	3	4
0	1	2	3	4	*	*	*	*
0.1	*	*	*	*	*	*	*	*
0.2	*	*	*	*	*	*	*	*
0.3	*	*	*	*	1	*	*	*
0.4	0	1	2	3	0	*	*	*
0.5	0	1	2	3	0	*	*	*
0.6	0	1	2	3	0	2	*	*
0.7	0	1	2	3	0	1	*	*
0.8	0	0,1	1,2	2,3	0	0,1	*	*
0.9	0	0,1	1,2	2,3	0	0,1	3	*
1.0	0	0,1	1,2	2,3	0	0,1	2	*
1.1	0	0,1	1,2	2,3	0	0,1	1,2	*
1.2	0	0,1	0,1,2	1,2,3	0	0,1	0,1,2	4
1.3	0	0,1	0,1,2	1,2,3	0	0,1	0,1,2	3
1.4	0	0,1	0,1,2	1,2,3	0	0,1	0,1,2	2,3
1.5	0	0,1	0,1,2	1,2,3	0	0,1	0,1,2	1,2,3
1.6	0	0,1	0,1,2	0,1,2,3	0	0,1	0,1,2	0,1,2,3
(All entries are the same from here on.)								

* Existence of data in these regions contradicts assumptions of model. Such data could be valid only if a change were made during the year to a dosimetry system with a lower MDD, such as TLD's or pocket ion chambers, or if there were an admixture of pocket chamber and film data.

dosimeters he had during the year (columns) and as a function of his annual dose (rows). The problem lies in estimating the number of MDD results that occurred among all persons during a year when only annual dose totals are available. Since the annual distribution consists of records of persons who were issued between one and four dosimeters during the year, an unambiguous count of the number of MDD results cannot be made.

A log-probit analysis of the distribution of *an*nual doses yields parameters μ_a and σ_a. Using these parameters, it would be a simple matter to estimate the collective dose "missed" for individuals having annual doses of 0 mGy if everyone had been issued four dosimeters during the year (top row, column 5 of Table 1). But this does not include all persons who had one or more occurrences of an MDD result, nor does it include persons who were, for whatever reason, issued fewer than four dosimeters during the year. Each person with an annual dose of 0.4 mGy or more and two or more dosimeters issued in the year may have had one or more MDD results. The difficulty in estimating the number of MDD results starting from annual totals is complicated by individuals having fewer than four dosimeters issued during the year due to the fact that they began radiation work late in the year or stopped radiation work at some point in the year. Only when each person is issued one dosimeter per year is it possible to enumerate exactly the occurrences of MDD results. This is equivalent to analyzing individual dosimeter readings, as discussed above.

However, estimates can be made of the number of MDD results if some simplifying assumptions are made. If one can assume that there are very few individuals who were issued fewer than four dosimeters per year (as in a stable working population), then column 5 shows the possible numbers of MDD results versus dose.

Monitored personnel can be divided into $j + 1$ groups, depending on the number of dosimeters each person had with MDD results. Let n_z be the number of workers in group z, where z denotes the number of MDD results (zeros). Then

$$\sum_{z=0}^{j} n_z = N, \qquad (10)$$

where N is the total number of workers. The number of workers who had all MDD results for the year is n_j ($=n_4$ in the example); under the simplifying assumption made above, this number can be obtained directly by examining the annual dose distribution and simply counting the zeros. One other value, n_{j-1} ($=n_3$ in the example), can be identified as having a lower limit. If the lowest nonzero dose that can be recorded is MDD + Δ (say, 400 μGy if MDD = 300 μGy and Δ = 100 μGy, as above), then

$$n_3 \geq (\text{number of records such that } [\text{MDD} + \Delta] \leq D_d < 2[\text{MDD} + \Delta]). \qquad (11)$$

Further, define the total number of "zero" results among all workers as

$$N_0 \equiv jn_j + (j-1)n_{j-1} + \cdots + (1)n_1 = \sum_{z=1}^{j} zn_z. \qquad (12)$$

Using $j = 4$ as in the example in Table 1,

$$N_0 = 4n_4 + 3n_3 + 2n_2 + n_1. \qquad (13)$$

Since jN is the total number of dosimeter results for the year, of which N_0 were "zero," then N_0/jN is the fraction of the results which were "zero." Thus one can set a lower bound for N_0:

$$N_0 > jn_j; \qquad (14)$$

further, one can set a higher (i.e. more restrictive) lower bound by using the lower bound for n_{j-1} from eqn (11):

$$N_0 > jn_j + (j-1)n_{j-1}; \quad \text{or,} \quad \text{for } j = 4,$$
$$N_0 > 4n_4 + 3n_3. \qquad (15)$$

The "missed" annual collective dose for group $z = j$ (all zeros) is

$$S_{z=j}(0\text{–MDD}) = jn_j\bar{D}_{d,\,\text{missed}} \approx S_a(0\text{–MDD}). \qquad (16)$$

This expression can be solved for the average dose missed per dosimeter having an MDD result, $\bar{D}_{d,\,\text{missed}}$ giving

$$\bar{D}_{d,\,\text{missed}} \approx S_a(0\text{–MDD})/jn_j. \quad (17)$$

One might expect that $\bar{D}_{d,\,\text{missed}}$ would be greater for workers who were more highly exposed ($z < j$) than for those in group $z = j$ if there were a positive correlation between doses in one monitoring period and doses in another.

The "missed" annual collective dose for all workers is

$$S_d(0\text{–MDD}) = N_0\bar{D}_{d,\,\text{missed}} > \frac{4n_4 + 3n_3}{4n_4} S_a(0\text{–MDD}), \quad (18)$$

where the inequality arises from combining eqns (15) and (17).

The estimate in eqn (18) of annual collective dose missed is affected by the fact that $4n_4$ is an overestimate of the number of dosimeters contributing to $S_a(0\text{–MDD})$, since some of the zero results would have come from persons being issued only one, two or three dosimeters during the year. The value of n_3 is also somewhat overestimated by the inclusion of persons who were issued 0, one or two dosimeters during the year, but somewhat underestimated due to the failure to include persons in group 4 with doses greater than 0.8 mGy. The net effect is difficult to judge, but eqn (18) may not overestimate $S_a(0\text{–MDD})$ by a great deal.

The approximation in eqn (18) is fairly good if $4n_4 + 3n_3 \approx N_0$. Parrish reported that about 60% of annual results at the Oak Ridge National Laboratory were zero, so that $4n_4 \approx 0.6N_0$ (Pa82). To see how well eqn (18) works, consider the examples with $j = 4$ and $N = 1000$ for $4n_4/N_0 = 0.6$ shown in Table 2. It can be seen that in case C, using the lower limit for N_0 results in an underestimation error of only 10%, and in other cases, 0–5%.

When j, the number of dosimeters issued per year, increases to 12, 52, or even 250, the analysis using annual totals is unlikely to be useful, due to the fact that it becomes less and less likely that anyone would have all zeros.

When MDD results are recorded as equal to the MDD (Case 2, above), and only annual totals are available, the methodology outlined above is not very useful. This can be seen by examining the right half of Table 1, where all of the logically possible numbers of zero results are distributed over doses ranging from 0.3 mGy to 1.6 mGy and above. Unless there were very large peaks in the distribution of annual doses at integral multiples of the MDD, estimating the number of MDD results is not feasible. In that case, and with the removal of those MDD results from the distribution and setting them to zero, there is still the potential for a large bias due to MDD results hidden elsewhere in the data.

Table 2. Consideration of four hypothetical cases permits evaluation of the validity of the approximation for the total number of MDD results. $N_0 \approx 4n_4 + 3n_3$ *used in eqn* (18). *The four cases concern a distribution in which* 60% *of annual doses are zero in a population of* 1000 *that was monitored quarterly. Columns* 2–6 *show the percent of workers who had* 4, 3, 2, 1, *or* 0 *MDD results for cases* A–D. *The error ratio tabulated here is* $(4n_4 + 3n_3)/N_0$. *The fact that it is close to* 1.0 *for a variety of distributions of MDD results in workers with nonzero annual totals shows that the approximation in eqn* (18) *is fairly good*

	% with j MDD results					No. of MDD results in each group				Approx. $N_0 \approx$	Exact	Error
Case	j=4	j=3	j=2	j=1	j=0	$4n_4$	$3n_3$	$2n_2$	n_1	$4n_4+3n_3$	N_0	Ratio
A	60	10	5	5	20	2400	300	100	50	2700	2850	0.947
B	60	20	10	5	5	2400	600	200	50	3000	3250	0.923
C	60	10	10	10	10	2400	300	200	100	2700	3000	0.900
D	60	0	0	0	40	2400	0	0	0	2400	2400	1.000

DISCUSSION

If results from individual dosimeters are available for a working population, if those results are distributed lognormally from the MDD to 15 mGy or above (as is often the case), and if there is some record of the value of the MDD and how MDD results were recorded, using properties of the lognormal distribution, estimates can be made of the collective dose "missed" due to the MDD results being recorded at zero, or of the correct collective dose to be used in place of MDD results that were recorded as the MDD. Similarly, estimates can be made of individual doses. Such estimates will be useful in epidemiologic studies for evaluation of the completeness of monitoring, is the sense that they permit comparison of the tabulated doses with those "missed" due to the existence of an MDD. For largely unexposed populations, this may be a significant fraction of the collective dose.

Such estimates may also be used to generate input values to probability of causation calculations that are more defensible than values assigned, for example, by simply assuming that every occurrence of a zero should be replaced by the value of the MDD.

CONCLUSIONS

When individual dosimeter results are available for analysis, individual (eqn 9) and collective (eqn 7) notional doses can be generated by assuming that the distribution of doses below the MDD is the same as the distribution of those above. When only annual totals are available, the method results in fairly good estimates (eqn 18) only when monitoring was done no more often than quarterly.

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