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**DOSE ESTIMATION FROM DAILY
AND WEEKLY DOSIMETRY DATA
FINAL DRAFT**

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Abstract

Statistical analyses of data from epidemiologic studies of workers exposed to radiation have been based on recorded annual radiation doses. It is usually assumed that the annual dose values are known exactly, although it is generally recognized that the data contain uncertainty due to measurement error and bias. In our previous work [20], a probability distribution was used to describe an individual's dose during a specific period of time and statistical methods were developed for estimating it from weekly film dosimetry data. This study showed that there was a systematic underestimation of doses for Oak Ridge National Laboratory (ORNL) workers. This could result in biased estimates of dose-response coefficients and their standard errors. The result of this evaluation raised serious questions about the validity of the historical personnel dosimetry data that are being used in low-dose studies of nuclear industry workers.

Here we develop new methods for using additional information from daily pocket-meter data and combining it with film dosimetry data to improve the distribution estimates. Together, the methods take into account the "measurement error" that is produced by the film and pocket-meter dosimetry systems, the biases introduced by policies that lead to recording left-censored doses as zeros, and other measurement and recording practices. The combined methodology is applied to a sample of dose histories obtained from hard copy dosimetry records at ORNL for the years 1945 to 1955. First, the rigorous addition of pocket-meter information shows that the negative bias is generally more severe than was reported in [20], however the amount of bias also varies greatly between person-years. Second, the addition of pocket-meter information reduces uncertainty for some, while increasing it for others. Together, these results suggest that detailed pocket-meter and film dosimetry information is required to obtain unbiased and reliable dosimetry data for use in epidemiologic studies of workers at ORNL.

1. Introduction

In December 1941 at the University of Chicago, the first uranium-graphite pile achieved criticality and plans were soon under way to construct larger uranium-graphite piles at Oak Ridge, Tennessee, and at Hanford, Washington [2, 23]. The purpose of the then named Clinton Laboratories pilot plant at Oak Ridge was to train crews to operate the even larger production facilities at Hanford and to demonstrate the safe production and chemical separation of the fissionable ^{239}Pu isotope from uranium irradiated in the so-called X-10 pile or Graphite Reactor, at the Clinton Laboratories [13]. The Clinton Laboratories were renamed Clinton National Laboratory in 1947 and Oak Ridge National Laboratory (ORNL) in 1948.

Construction started on the ORNL Graphite Reactor in January 1943, and criticality was achieved in November 1943. The first batch of uranium irradiated slugs from the reactor entered chemical separation at the pilot plant in December 1943. By the end of December, several milligrams of plutonium were separated and shipped for experimentation at the University of Chicago, and by March 1944, gram quantities of plutonium were being made available for experimentation at Los Alamos. After the production facilities became operational at Hanford in September 1944, the ORNL Graphite Reactor was used primarily for fundamental nuclear research and production of medically important radioisotopes.

In the beginning at Chicago and later at Oak Ridge, pocket ionization chambers (or pocket meters) were considered the primary device for monitoring personnel exposures, with a film dosimeter being only a valuable adjunct [12]. With expanding experience at Oak Ridge and with the startup of the production facilities at Hanford in 1944, this practice was reversed and the film dosimeter provided the official dose of record, while the pocket meter became the day-to-day means of monitoring personnel exposures in the workplace [28]. At ORNL, however, the daily pocket-meter readings were also maintained as a part of an individual's dose records [12].

An individual's radiation dose of record at ORNL for external penetrating radiation, principally gamma rays, is based on pocket meters from 1943 to July 1944, film badges from then to 1975, and thermoluminescent dosimeters since 1975 [29]. The pocket meters were evaluated daily (minimum detectable limit of 0.02 mSv), and the film badges were evaluated weekly from July 1944 to

July 1956, when quarterly monitoring was initiated (minimum detectable limit of 0.30 mSv). This is the period to which the methods developed in this report are applied. Several reports have already been published about missing dose at ORNL during the weekly evaluations of film badges [14, 15, 17, 31, 20]. The general issue of uncertainty in individual dose estimates in epidemiologic studies of nuclear industry workers also has been discussed in [3, 10, 24, 25].

The report [20] describes methodology to estimate missing dose for individuals from recorded weekly film-badge readings. It finds the greatest missing dose for individuals that have many "below detectable limit" weekly film-badge doses that have corresponding positive pocket-meter doses. The inclusion of pocket-meter data in [20] was used primarily to provide information on uncertainty of dose when a film-badge reading was zero. Now we extend this methodology by developing a detailed model of the pocket-meter dose measurement and recording system to provide a rigorous mechanism for combining pocket-meter data with film-badge data. The product for each individual is a dose estimate in the form of a probability distribution based on combined information from film-badge and pocket-meter data.

This project is motivated by the need for adjustment for dose bias and uncertainty in epidemiologic dose-response analyses. The first step is an adjustment for bias and quantification of uncertainty in dose estimates, which is the subject of [20] and also the subject of this paper. A recent study of Oak Ridge workers [6] used a preliminary dose adjustment procedure and found an upward bias in dose-response coefficients and likelihood ratio test statistics. This study was based on a crude adjustment for missing dose and did not consider measurement and other dosimetry errors. The objective of this report is to provide a methodology for estimating the true dose of an individual during a year, given the recorded daily and weekly exposure histories for that individual in that year.

The dose estimate proposed for each individual is a nonparametric probability distribution. This is the most general description of uncertainty and can be reduced to other descriptions of uncertainty. A nonparametric probability distribution estimate, consisting of many (say 100) density points, can be reduced to a more concise description such as the five points of a boxplot (see Sect. 5), or to a few parameters of an assumed distribution (such as the mean and variance of a normal or a lognormal distribution). Each reduction is a loss of some information and a gain in simplicity. These can be computed for an individual or for

any cohort of individuals. Such generality allows the dose estimates to be useful for many purposes, including adjustment for dose uncertainty in epidemiologic dose-response analyses by methods already known or yet to be developed.

Sect. 2 gives an overview of the methodology that concentrates on how its two major components, the Bayes method and the convolution method, are used to go from daily and weekly data to a yearly dose estimate. Sect. 3 describes the Bayes methodology and its construction for the ORNL data from the period 1945-1955. One instance of the Bayes method is constructed for the pocket-meter data and another instance for the film-badge data. Sect. 4 describes the convolution methodology that takes the Bayes method estimates for single measurement periods and combines them to produce estimates of cumulative dose over several periods for an individual.

2. Methodology Overview

This methodology considers three basic quantities:

- v a recorded pocket-meter dose,
- z a recorded film-badge dose, and
- x the true total dose to the body.

The first two quantities are observed and we wish to estimate the third unobserved quantity. Of course, underlying the recorded dose to the pocket meter there is an unobserved true dose to the pocket meter. The same holds for the film badge. In this report we assume that these three unobserved true doses are the same.

Clearly, the three unobserved true doses are different simply because the measuring devices are put on different parts of the body and can be shielded by the body. These are relevant issues that relate to estimating dose to different parts of the body or to specific organs. These questions can be addressed by building more Bayesian "blocks" of the same methodology (*likelihood functions*). We stop at building the likelihoods for the true dose to the film badge and the true dose to the pocket meter and complete the process by assuming that they are the same as the true dose to the body. The likelihoods for the measurement instruments (pocket meter and film badge) should be built first, as we do in this report, before likelihoods for dose to specific organs can be considered. Building each likelihood requires careful consideration of the physics of each process.

The "functional" approach to measurement errors is used because we consider the unobserved x to have a fixed value [8]. Nevertheless, x is treated as a random variable to express the uncertainty associated with our knowledge of its true fixed value. For example, there can be only one true value for x , but, in the absence of knowledge of what that value is, we attach a probability $P(x)$ to every possible value of x , where $\sum_x P(x) = 1$. We shall refer to the function $P(x)$ as the *probability distribution* of the random variable x . We use the same notation x for both the random variable and its realization, and we hope the distinction is clear from the context. The interpretation of probability here is degree of belief in the truth of the proposition that the true dose is x . This interpretation provides a mathematical representation of the degree of uncertainty about deterministic quantities: a small bit of probability placed at each of a large number of values of x reflects a high degree of uncertainty, whereas a probability of 1 placed at a single value reflects complete certainty.

We emphasize that $P(x)$ refers to the distribution of probabilities that concerns **one individual in one exposure period**. This is important to note because in other literature "dose distributions" often refer to the distribution of doses for a cohort of individuals during a specified period of time.

A point estimate (single "best" value, by some criterion) can be obtained from this distribution, but we shall avoid this since we regard the probability distribution itself as the estimate and think of any reduction as a loss of information. In particular, if annual doses are to be used as inputs to a model that relates health effects to radiation dose, it is necessary to obtain point estimates and to quantify the uncertainty in these values.

There are two major components in our methodology. Instances of these components are arranged in a sequence to produce a yearly cumulative dose estimate from a sequence of pocket-meter and film-badge data. The first major component is a **Bayesian method** for computing a dose distribution estimate for a single measurement period. This method effectively replaces one or more measurements for a period (one, in the case of a film badge, and two, in the case of a pair of pocket meters) by an estimate of $P(x)$ for the same period. This method is described in Sect. 3. The second major component is a **convolution method** that "adds" dose distribution estimates from consecutive periods to produce a dose distribution for the combined period. This method is described in Sect. 4.

These two components are used as follows to combine daily pocket-meter and weekly film-badge dose measurements to produce an annual dose estimate for an individual:

1. The pocket-meter instance of the **Bayesian method** uses the data for a given day to produce $P(x)$ for that day. This process is repeated for each available day of the week.
2. The available daily $P(x)$ s for a week are combined with **convolutions** into a cumulative $P(x)$ for the week.
3. The weekly $P(x)$ from the pocket-meter data and the recorded film-badge reading (z) are combined using the film-badge instance of the **Bayesian method** to obtain an estimate of $P(x)$ for the week. These steps are repeated for all available weeks of the year.
4. The available weekly $P(x)$ s are combined with **convolutions** into a cumulative $P(x)$ for the year.

For example, consider a person-year that contains six pairs of pocket-meter readings and one film-badge reading for each of 50 weeks. In this case, the pocket-meter instance of the Bayesian method is used 12 times each week for a total of 600 times. The film-badge Bayesian method is used 50 times. A convolution is performed five times each week for the weekly cumulative dose and also to combine weeks into a year. The result is a total of 299 convolutions, a formidable computational task that takes on the order of two minutes on a desktop computer.

3. Bayesian Method for a Single ^{pocket meter} Measurement Period

In Bayesian estimation, quantities of interest, observed and unobserved, are endowed with a joint prior probability distribution that represents (approximately) the state of knowledge about them prior to (or external to) observation or measurement. Then the actual values of the observed measurements are put in, as conditioning information, and the laws of probability are used to find the conditional distribution of the unobserved values *given* the observed ones. See for example [1] for further background on Bayesian estimation or [18, 19] for an application in dosimetry.

In Sect. 2, we define x as the unobserved true dose. Now let y be a generic recorded measurement of that dose (a pocket meter or a film badge). The recorded dose y is also treated as a random variable. Prior to its observation, for a known x , there is uncertainty about its value. This allows the assumed relationship between x and y to take the form of a conditional probability distribution $P(y|x)$, the probability of y given x . This is an "if x , then y " relationship, but with uncertainty built in, uncertainty that exists *prior* to the observation of y .

The language of probability is used to arrive at a statement about x given y . The conditional probability distribution $P(x|y)$ is called the *posterior* distribution and is given by the Bayes' Theorem (see [1], for example)

$$P(x|y) = c(y)P(x)P(y|x), \quad (1)$$

where $c(y)$ is a normalizing constant which ensures that $\sum_x P(x|y) = 1$ and $P(x)$ describes the uncertainty about x prior to (or external to) the measurement y .

The key component for implementing this approach is $P(y|x)$. In effect, $P(y|x)$ is the answer to the question: "If the true dose is x , what is the probability that the recorded dose is y ?" This is determined by careful consideration of the physical properties of the measuring device and recording practices.

Note that $P(y|x)$ is constructed by specifying a distribution on y for each possible (fixed) value of x . After specifying $P(y|x)$ for all possible y and x , it is used as a function of x for each observed y . This is the "likelihood" of x for the observed y and is denoted by $L(x|y)$. This is illustrated in Fig. 1 with a likelihood for a single pocket meter. Vertical slices of the likelihood surface are $P(y|x)$, and horizontal slices are $L(x|y)$. We comment on the pocket-meter specific features of the likelihood surface in Sect. 3.1.3. (eq. 13) 14

The prior distribution $P(x)$ is less critical when measurements are available, but can have a strong impact when measurements are not available. In most situations, it is possible to formulate a description of $P(x)$ that is acceptably objective. In the case of no prior knowledge about x , an uninformative prior can be used so that the likelihood completely determines the posterior probabilities.

Next, consider some specific characteristics of the pocket-meter measurement system. Usually, there are two pocket-meter measurements for the same one-day period. The three quantities of interest are:

x , the unobserved true dose to both pocket meters,

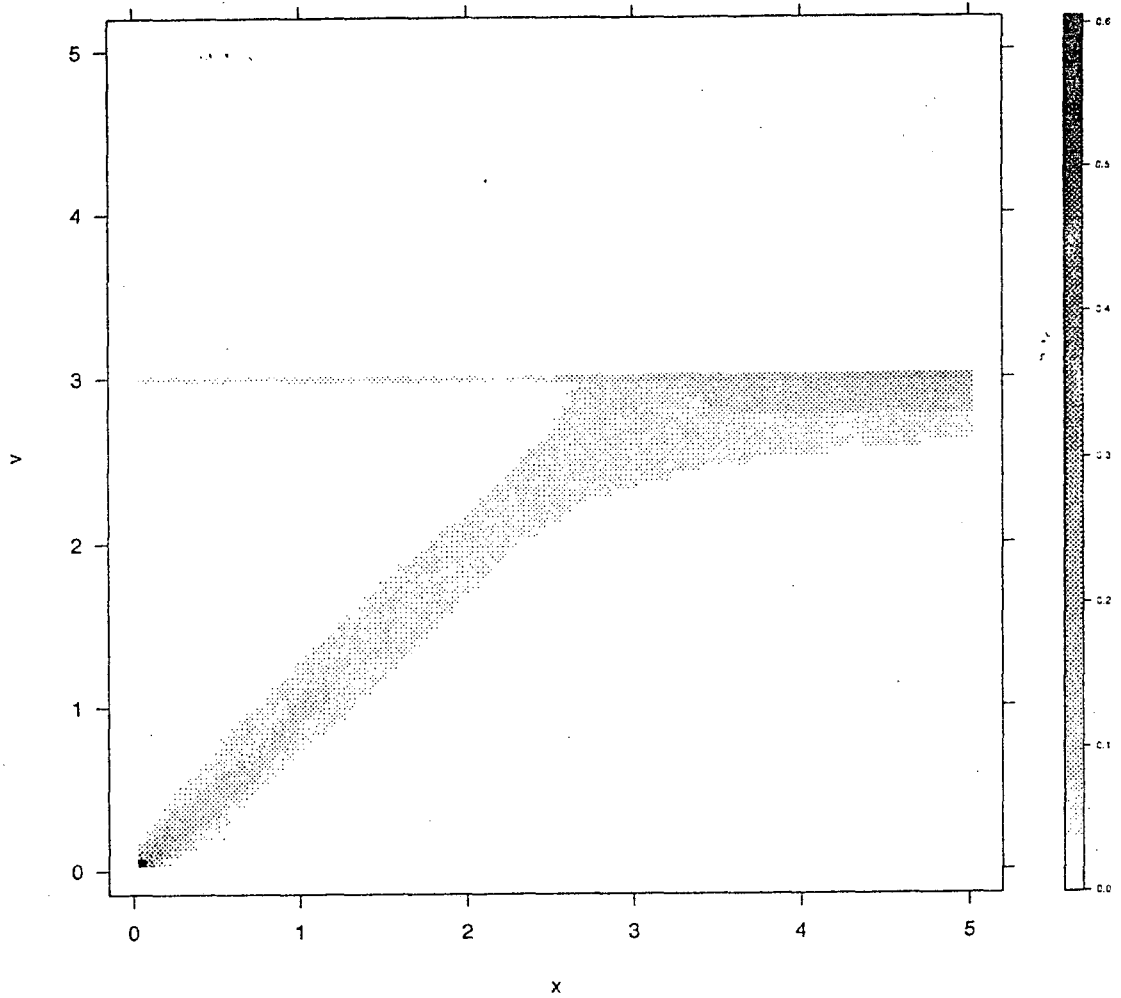


Figure 1: Likelihood surface for a single pocket meter.

v_1 , the recorded dose of the first pocket meter, and

v_2 , the recorded dose of the second pocket meter.

The designation of which pocket meter is first is arbitrary. Also, define $v = [v_1, v_2]^T$.

We assume that given the true dose, the two pocket meters are independent and thus interchangeable

$$P(v|x) = P(v_1|x)P(v_2|x),$$

where $P(v_1|x) = P(v_2|x)$. That is, the bivariate distribution $P(v|x)$ is simply a product of two identical univariate distributions. There are factors that may imply some dependence. For example, the same technician and equipment are likely to read both pocket meters in a pair. Although it is possible to model this dependence, we choose the simplicity of independence.

Note that Bayes's Theorem can incorporate the pocket meters sequentially and produces the same result for either order of pocket meters. In terms of the likelihood functions

$$\begin{aligned} P(x|v) &= c(v)P(x)L(x|v) && (2) \\ &= c(v_1)c(v_2)P(x)L(x|v_1)L(x|v_2) \\ &= c(v_2)[c(v_1)P(x)L(x|v_1)]L(x|v_2) \\ &= c(v_2)P(x|v_1)L(x|v_2), \end{aligned}$$

where $c(v) = c(v_1)c(v_2)$ and $P(x|v_1) = c(v_1)P(x)L(x|v_1)$. Similarly,

$$P(x|v) = c(v_1)P(x|v_2)L(x|v_1),$$

so that the posterior of one pocket meter becomes the prior for the other.

The film-badge system has one measurement z for each period that usually represents the dose over a week, or since the last film badge if it was read more recently. Its treatment follows the outline of the generic measurement y , [see Eq. (1)], except that the prior distribution is obtained by combining (via convolution) the daily pocket-meter results representing the same period.

Generally, the influence of prior distributions is negligible in cases with at least a moderate number of daily pocket-meter readings but becomes noticeable when few or no measurements exist. A key factor regarding the influence of priors turns out to be whether the absence of data for a given period means that the person did not work or that no measurement was recorded. As more detailed data are considered, numerous gaps and inconsistencies become apparent. Decisions on how these are handled strongly affect the influence of priors. We discuss this influence specifically for the 1945 to 1955 ORNL cohort in Sect. 5.

3.1. Constructing the Pocket-Meter Likelihood Function for the 1945 to 1955 ORNL Cohort

Pocket meters were typically worn in pairs, and both readings were recorded each day. Generally, only the lower reading was considered valid. The justification for this practice seems to be that pocket meters sometimes discharged under rough handling such as when dropped, thus making the reading artificially high. Of course, this practice (taking the minimum of two) produced an underestimate of dose, but this was thought to be less severe than a potential overestimate resulting from taking the average of the two.

The primary purpose of the pocket meter was as a monitoring device, to provide a signal when a daily dose was high enough to warrant reading the film badge before it would otherwise be read. The data were not intended for computing cumulative dose estimates for epidemiological studies, as it is now being used. It was generally believed that film badge data are superior for this purpose. However, especially in cases when the film-badge record is zero, proper use of the pocket meter data can provide more sensitive measurements of low doses. When these low doses are accumulated over a long period of time, they could significantly alter the doses calculated from film-badge data only.

3.1.1. Historical Information Sources about the Pocket-Meter System

An ORNL report [4] lists the characteristics, application, calibration, and routine maintenance of pocket meters in use at that time. Pocket meters are reported accurate to $\pm 15\%$ at 40 keV to 1 MeV of X or gamma radiation.

A statistical study [5] of a two-pocket-meter system vs a one-pocket-meter system was produced in 1949. Its purpose was to assess the economy of wearing two pocket meters and taking the lower reading as the dose of record vs using a single pocket meter. The study [5] assumes that the error in a pocket-meter reading can only be positive. Although we agree that all pocket-meter readings were nonnegative and that the error distribution is positively skewed, negative errors are possible [i.e., the error is the difference between the recorded dose estimate and the true dose, see Eq. (4)]. For example, if a pocket meter starts with a higher than nominal charge, the error can be negative. The study reports data on proportion of "bad" pocket meters:

[Bad pocket meters are defined as] lost meters, meters with caps

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missing, damaged meters, or readings of 300 mr or over. ... In the operating sample there were 9081 pairs [which contained] 53 pairs with one of the entries [bad]. In no pair were both entries [bad]. ... In the non-operating sample, there were 9702 pairs [which contained] 55 pairs with one entry [bad], and 29 pairs with both entries [bad]. ... However 28 of the 29 pairs with both entries [bad] were due to an [unusual] accident ...

The nonoperating group was made up of staff in occupations not ordinarily exposed to radiation. The bad pocket-meter rates were 0.00584 and 0.00578 in the operating and the nonoperating groups, respectively. We exclude the bad pocket meters caused by the accident.

3.1.2. Estimating Error Distribution from Pocket-Meter Pairs

Because pocket meters were worn in pairs, they provide some information about the error distribution of a single pocket-meter measurement. We cannot recover the error distribution location, but we can get some indication of the distribution spread.

We define the pair of pocket-meter measurements of a true dose x_r as

$$\begin{aligned} v_1 &= x_r + e_1 \\ v_2 &= x_r + e_2, \end{aligned} \quad \left. \begin{array}{l} \\ \\ \end{array} \right\} \begin{array}{l} (3) \\ \text{rec} - \text{true} \end{array}$$

where e_1 and e_2 are the two measurement and recording errors, and x_r is the true dose for both measurements. For simplicity, we assume that the true dose, x_r , and the errors e_1 and e_2 occur in increments of 0.05 mSv. Let

$$d = |v_1 - v_2| = |e_1 - e_2|.$$

Let p_i be the probability that $e_1 = 0.05i$, where i is an integer. If e_1 and e_2 are independent and identically distributed, then $P(e_1 = 0.05i_1, e_2 = 0.05i_2) = p_{i_1} p_{i_2}$. It is reasonable to assume that the errors cannot exceed $0.05M$ for some $M > 0$. That is, we assume that p_i is zero for $|i| > M$.

We illustrate this with $M = 1$. Table 1 shows the possible values for e_1 and e_2 with corresponding values of d . The probabilities of observing the three possible

Table 1: Relationship between e_1 , e_2 , and d for $M = 1$

e_1	d			
0.05	0.10	0.05	0.00	
0.00	0.05	0.00	0.05	
-0.05	0.00	0.05	0.10	
	-0.05	0.00	0.05	e_2

values of d in terms of the p_i are

$$\begin{aligned} P(d = 0.00) &= p_{-1}^2 + p_0^2 + p_1^2 \\ P(d = 0.05) &= 2p_{-1}p_0 + 2p_0p_1 \\ P(d = 0.10) &= 2p_{-1}p_1. \end{aligned}$$

Let n_j be the frequency of observing $d = 0.05j$, $j = 0, 1, 2$. Then the likelihood of observing n_0 , n_1 , and n_2 under the above probability model is

$$L(p_{-1}, p_0, p_1 | n_0, n_1, n_2) = [p_{-1}^2 + p_0^2 + p_1^2]^{n_0} [2p_{-1}p_0 + 2p_0p_1]^{n_1} [2p_{-1}p_1]^{n_2}.$$

The log-likelihood is then

$$l(p_{-1}, p_0, p_1 | n_0, n_1, n_2) = c + n_0 \log[p_{-1}^2 + p_0^2 + p_1^2] + n_1 \log[2p_{-1}p_0 + 2p_0p_1] + n_2 \log[2p_{-1}p_1],$$

where c is a constant. The parameters have constraints

$$p_{-1} + p_0 + p_1 = 1, \quad \text{and } p_j > 0, \quad j = -1, 0, 1.$$

Also, note that p_{-1} and p_1 are interchangeable; that is, interchanging them does not change the likelihood. For a unique estimate, we must impose further constraints. Because pocket-meter leakage results in positive errors, it is reasonable to impose a restriction that the error distribution is positively skewed, that is $p_{-1} \leq p_1$. We also impose the constraint that the error distribution is unimodal with the mode at zero.

In general, for $M > 0$, the log-likelihood is

$$l(p_j, j = -M, \dots, M | n_i, i = 0, \dots, 2M) = c + \sum_{i=0}^{2M} n_i \log \left(\sum_{j=-M}^{M-i} p_j p_{j+i} \right),$$

where $\sum_{j=-M}^M p_j = 1$, $p_j > 0$ for $j = -M, \dots, M$, and $p_{-j} \leq p_j$ for $j = 1, \dots, M$.

Maximizing the likelihood is a constrained nonlinear optimization problem in $2M + 1$ variables. We use NAG [26] optimization software to obtain estimates for $M = 10$. The nonlinear manifold turns out to be difficult to maximize as it appears to have local maxima. We report the best solutions obtained from 30 randomized starting points. In every case, two or three solutions were reported but the best solution was always the most frequent.

We use data computerized from hard copy records, as described in Sect. 5 and also data on pocket-meter pair differences reported in [5]. Error distribution results for the following seven sets of pocket-meter pairs are reported in Table 2. -pk

All Pairs includes all good pocket-meter pairs.

Low Pairs includes pocket-meter pairs for weeks with a film-badge reading of zero and a minimum of four good pairs.

Exclude Zeros includes all good pocket-meter pairs with at least one nonzero reading.

Both Nonzero excludes any pocket-meter pair with a zero reading.

S > 20 includes good pairs with sum of at least 0.20 mSv.

S > 40 includes good pairs with sum of at least 0.40 mSv.

Op Group consists of the Difference data for "operating group" in [5].

In all instances we exclude pairs when one or both readings are 3.00 mSv.

Several observations can be made about this table. First, recall that neither the location nor the skewness direction can be estimated from the difference data. The mode location is constrained to zero and the skewness is constrained to be nonnegative. When all data are considered, the errors are slightly positively skewed with a 96% range of about -0.10 to 0.30 mSv. When low pairs are considered, the skewness decreases and the range slightly decreases. When higher pairs are considered, both the skewness and the range increase.

Table 2: Error distributions for various pocket-meter pair subsets

e mSv	All Pairs	Low Pairs	Exclude Zeros	Both Nonzero	S > 20	S > 40	Op Group
-0.50	.00298	.00193	.00543	.00429	.00837	.01205	.00551
-0.45	.00298	.00193	.00543	.00429	.00837	.01205	.00551
-0.40	.00298	.00232	.00543	.00429	.00837	.01205	.00551
-0.35	.00298	.00232	.00543	.00429	.00837	.01205	.00551
-0.30	.00298	.00232	.00543	.00429	.00837	.01205	.00551
-0.25	.00298	.00232	.00543	.00429	.00837	.01205	.00551
-0.20	.00298	.00232	.00543	.00429	.00837	.01205	.00551
-0.15	.00298	.00232	.00543	.00429	.00837	.01205	.00551
-0.10	.02494	.02445	.07459	.00429	.00837	.01205	.00551
-0.05	.02494	.02445	.07459	.00429	.00837	.01205	.00551
0	.74872	.81222	.46864	.55694	.46696	.44472	.62472
.05	.05474	.03474	.11055	.14519	.15126	.13566	.11045
.10	.05474	.03474	.11055	.14519	.15126	.13566	.11045
.15	.02337	.01701	.04256	.03672	.03670	.04555	.02852
.20	.02337	.01701	.04256	.03672	.03670	.04555	.02852
.25	.00471	.00456	.00543	.00961	.01995	.01205	.01012
.30	.00471	.00456	.00543	.00961	.01995	.01205	.01012
.35	.00298	.00232	.00543	.00429	.00837	.01205	.00551
.40	.00298	.00232	.00543	.00429	.00837	.01205	.00551
.45	.00298	.00193	.00543	.00429	.00837	.01205	.00551
.50	.00298	.00193	.00543	.00429	.00837	.01205	.00551

True → zero
 → zero < 0 →

3.1.3. Constructing the Likelihood

The likelihood $L(x|v)$ is available from the complete specification of $P(v|x) = P(v_1|x)P(v_2|x)$ for all possible values of x and v . We construct $P(v_1|x)$ and use the same form for $P(v_2|x)$.

Let \tilde{v}_1 be the *expressed dose* to the pocket meter, that is, the reading that would be recorded if there were no rounding or censoring. "Rounding" means that readings are given in multiples of 0.05 mSv. "Censoring" for pocket meters means that doses above 3.00 mSv, the upper detection limit, were recorded as 3.00 mSv. The lower detection limit was 0.02 mSv, which can be ignored because of rounding. The variability in \tilde{v}_1 for fixed x is intended to represent instrument error and reading error. We assume that \tilde{v}_1 has a lognormal distribution such that $\log(\tilde{v}_1)$ has mean $\log(x)$ and standard deviation $\alpha(x)$, both of which depend

on x . Thus,

$$P(\tilde{v}_1|x) = \frac{1}{\sqrt{2\pi}\tilde{v}_1\alpha(x)} \exp\left\{-\frac{1}{2\alpha(x)^2} [\log(\tilde{v}_1) - \log(x)]^2\right\} \quad x > 0, \quad \tilde{v} > 0.$$

Information about the dependence of α on x is obtained from two sources: historical studies that report on pocket-meter errors and estimates from paired pocket-meter data. The reported error of $\pm 15\%$ from historical sources discussed in Sect. 3.1.1 is consistent with the pocket-meter pair results of Sect. 3.1.2, except at low pocket-meter values. The error distribution is only slightly narrower when high pocket-meter readings are excluded. For this reason we further assume that the error is fixed at 0.15 mSv (below) 1 mSv. To construct $\alpha(x)$, we interpret this as a three standard deviation interval. Under the lognormal assumption, the probability that this upper limit is exceeded is only 0.0013. This produces the following standard deviation function for log dose

$$\alpha(x) = \begin{cases} 0.04658731 - 0.1905704 * \log(x) & x < 1.00 \\ 0.04658731 & x \geq 1.00 \end{cases} \quad (4)$$

Next, we incorporate a probability that a pocket meter is damaged so that it discharges and reads 3.00 mSv. From historical information in Sect. 3.1.1, we have that the probability of a damaged pocket meter is about 0.006. Let \tilde{v}_1 be the reading that would be obtained if there is a probability 0.006 that a pocket meter is dropped and its reading is changed to 3.00 mSv. Then

$$P(\tilde{\tilde{v}}_1|x) = \begin{cases} 0.994P(\tilde{v}_1|x) & \tilde{v}_1 \neq 3.00 \text{ mSv} \\ 0.006 + 0.994P(\tilde{v}_1 = 3.00|x) & \tilde{v}_1 = 3.00 \text{ mSv} \end{cases}$$

Next, we can add the right censoring point of 3.00 mSv (the upper detection limit of the pocket meter) to get

$$P(\tilde{\tilde{\tilde{v}}}_1|x) = \begin{cases} 0.994P(\tilde{v}_1|x) & \tilde{v}_1 < 3.00\text{mSv} \\ 0.006 + 0.994P(\tilde{v}_1 \geq 3.00|x) & \tilde{v}_1 = 3.00\text{mSv} \\ 0 & \tilde{v}_1 > 3.00\text{mSv} \end{cases}$$

Finally, adding the rounding conventions similar to those reported in [20] provides the form of $P(v_1|x)$ for any v_1 and x . Figure 1 gives the resulting likelihood surface for a single pocket meter. Note the ridge at $v = 3.00$, indicating the drop

increased reading

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probability. The ridge increases with x as censoring goes into effect.

3.2. Constructing the Film-Badge Likelihood Function for the 1945 to 1955 ORNL Cohort

The lower limit of detection of the most sensitive film used at ORNL was 0.10 to 0.30 mSv. A lower detection limit of 0.10 mSv was possible if an experienced technician evaluated the exposed films with special care [21]. During film-badge exchange, when hundreds to thousands of films were read in large batches by technicians with widely varying experiences, a lower limit of detection of about 0.30 mSv was about as good as could be expected [22]. In practice, a film-badge reading of zero means the radiation dose to the worker was less than 0.30 mSv unless a smaller value is given.

The design of the film badge and its use at ORNL changed considerably over the years. In November 1951, for example, the photo film badge was introduced and all ORNL employees were required to wear a film badge on the job [12]. Before November 1951, only those ORNL employees who entered a radiation area were required to wear a film badge. Two or more filters were used in all ORNL film badges to aid in interpreting the radiation dose and in resolving the difficulty caused by the fact that the unshielded films were more sensitive to X rays between 50 and 100 keV than to X or gamma rays above 200 keV [22]. The film-badge readings quoted throughout this report are estimates of the equivalent dose from external penetrating radiation at a depth of approximately 1 cm within the total body or a major portion of the total body.

The many details that went into constructing the film-badge likelihood are described in [20]. The main ideas are similar to the pocket-meter likelihood construction including a lognormal error assumption. Some of the differences include left-censoring at 0.30 mSv instead of the right-censoring at 3.00 mSv used with the pocket meters and no provision for damaged film badges as this was very rare.

4. Combining Measurement Periods with Convolutions

It is well known (see p. 123 of [16], for example) that the distribution of a sum $x = x_1 + x_2$, where x_1 and x_2 are independent and $x, x_1, x_2 \in X$, is given by the

convolution

$$f_x(x) = \int_X f_{x_1}(x - x_2) f_{x_2}(x_2) dx_2.$$

The Fourier transform and its inverse are particularly useful for computing f_x from f_{x_1} and f_{x_2} (see p. 120 of [7], for example). The Fourier transform of the sum is the product of the Fourier transforms of the components multiplied by 2π :

$$\begin{aligned} h_x(\omega) &= \frac{1}{2\pi} \int_X f_x(x) e^{-i\omega x} dx \\ &= \frac{1}{2\pi} \int_X \int_X f_{x_1}(x - x_2) f_{x_2}(x_2) e^{-i\omega x} dx_2 dx \\ &= \frac{1}{2\pi} \int_X \int_X f_{x_1}(x - x_2) e^{-i\omega(x-x_2)} f_{x_2}(x_2) e^{-i\omega x_2} dx_2 dx \\ &= \frac{1}{2\pi} \int_X f_{x_1}(x_1) e^{-i\omega x_1} dx_1 \int_X f_{x_2}(x_2) e^{-i\omega x_2} dx_2 \\ &= 2\pi h_{x_1}(\omega) h_{x_2}(\omega). \end{aligned} \tag{5}$$

The inverse Fourier transform is used to recover the density as in

$$f_x(x) = \frac{1}{2\pi} \int_{\Omega} h_x(\omega) e^{i\omega x} d\omega.$$

Replacing the preceding integrals with finite sums, we obtain similar results for discrete probability distributions and the discrete Fourier transform (DFT). Because our probability distributions are discretized on a finite number of points, we use the DFT for combining dose distributions. Many software packages are available for the DFT. We use DFT functions from [26].

The DFT is used accumulate the daily pocket-meter $P(x)$ (posterior) distributions into a weekly cumulative $P(x)$. This becomes the prior distribution for the film-badge Bayes method. The resulting (posterior) distributions $P(x)$ of the film-badge Bayes method are then accumulated with the DFT into a cumulative $P(x)$ distribution for the year.

5. Results and Conclusions Regarding the ORNL 1945 to 1955 Cohort

The data currently being used in epidemiologic studies of ORNL workers [3, 11, 29, 30, 32] consist of a yearly total of the weekly film-badge readings for each worker. This yearly total was obtained from hard copy records (see Fig. 2) by

SAN RIDGE NATIONAL LABORATORY RADIATION EXPOSURE RECORD

YOUR RECORD IS INTENDED TO BE USED FOR DOSE-RESPONSE RESEARCH OR INDICATORS OF THE RISK OF EFFECTS FROM THE RADIATION EXPOSURE DURING THE PERIOD OF THE YEAR YOU CHOOSE. THE RADIATION EXPOSURE RECORD IS NOT TO BE USED FOR: 1. PUBLIC RELEASE. 2. STATISTICAL ANALYSIS. 3. RESEARCH ON THE EFFECTS OF RADIATION EXPOSURE. 4. RESEARCH ON THE EFFECTS OF RADIATION EXPOSURE. 5. RESEARCH ON THE EFFECTS OF RADIATION EXPOSURE. 6. RESEARCH ON THE EFFECTS OF RADIATION EXPOSURE. 7. RESEARCH ON THE EFFECTS OF RADIATION EXPOSURE. 8. RESEARCH ON THE EFFECTS OF RADIATION EXPOSURE. 9. RESEARCH ON THE EFFECTS OF RADIATION EXPOSURE. 10. RESEARCH ON THE EFFECTS OF RADIATION EXPOSURE. 11. RESEARCH ON THE EFFECTS OF RADIATION EXPOSURE. 12. RESEARCH ON THE EFFECTS OF RADIATION EXPOSURE. 13. RESEARCH ON THE EFFECTS OF RADIATION EXPOSURE. 14. RESEARCH ON THE EFFECTS OF RADIATION EXPOSURE. 15. RESEARCH ON THE EFFECTS OF RADIATION EXPOSURE. 16. RESEARCH ON THE EFFECTS OF RADIATION EXPOSURE. 17. 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THIS PAGE BEGINS DECEMBER 31, 1982 AND ENDS JANUARY 31, 1983

DAY	MON	TUE	WED	THUR	FRI	SAT	WEEKLY TOTALS													
							RADIATION DOSE (mR)							FILM BADGE DOSE (mR)						
							DOSE	DOSE	DOSE	DOSE	DOSE	DOSE	DOSE	DOSE	DOSE	DOSE	DOSE	DOSE		
1	12	13	14	15	16	17	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
2	18	19	20	21	22	23	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
3	24	25	26	27	28	29	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
4	30	31	1	2	3	4	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
5	6	7	8	9	10	11	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15

THIS PAGE BEGINS FEBRUARY 1, 1983 AND ENDS MARCH 31, 1983

DAY	MON	TUE	WED	THUR	FRI	SAT	WEEKLY TOTALS													
							RADIATION DOSE (mR)							FILM BADGE DOSE (mR)						
							DOSE	DOSE	DOSE	DOSE	DOSE	DOSE	DOSE	DOSE	DOSE	DOSE	DOSE	DOSE		
1	1	2	3	4	5	6	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
2	7	8	9	10	11	12	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
3	13	14	15	16	17	18	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
4	19	20	21	22	23	24	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
5	25	26	27	28	29	30	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
6	31	1	2	3	4	5	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
7	11	12	13	14	15	16	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
8	17	18	19	20	21	22	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
9	23	24	25	26	27	28	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
10	29	30	31	1	2	3	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15

↑
 Pocket Meter weekly value
 ↑
 Film Badge weekly value

Figure 2: First page of a sample hard-copy record. The record is in the form of a file folder and its four sides contain one person-year of detailed dosimetry data.

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adding up the weekly film-badge doses and is referred to as the *dose of record*. Hard copy records for the ORNL 1945 to 1955 cohort consist of roughly 30,000 person-years of detailed daily and weekly data. Each person-year is on a single hard copy record. A sample of 211 person-years was computerized [27] (see <http://www.ornl.gov/ehsd/cerdoc1.htm>). This includes 90 person-year records randomly sampled from all records and 121 person-year records from a stratified sample of higher exposures. An additional 18 records were rejected because they differed by more than 10% from the dose of record, and 11 records were blank.

The data set used in [27, 20] consists of weekly information from the 211 person-years. In this report we use a more detailed data set from the same 211 person-years that includes daily information. We only report on 93 of the 211 person-years. These are the person-years that contain at least 20 film-badge readings or 100 pocket-meter readings.

Examination of the detailed data brings out several important assumptions that were apparently used in computing the dose of record. The fact that film-badge readings below 0.30 mSv were recorded as zero is well known. But there are other assumptions that are not widely known or considered when the dose of record is used. Some of these assumptions are obvious, but their impact needs to be fully considered:

1. pocket-meter readings are ignored.
2. Readings recorded as "30-" are considered zero. This is in addition to the fact that most readings below 30 mrem (.30 mSv) are recorded as zero.
3. Film damaged in processing or for other reasons is considered zero.
4. Illegible recorded dose is considered zero.
5. Periods without recorded dose are considered zero.

Each of these assumptions produces a downward bias in the dose of record. The methodology that we have developed allows us to consider some of the alternatives to these assumptions and to comment on the sensitivity of the results. Specifically, we address the bias and uncertainty introduced by 1 and 5, and indirectly 2, 3, and 4 by treating them as 5 (although the methodology allows more specific treatment of 2, 3, and 4).

The following are three basic scenarios, each of which is presented in Fig. 3 and 4:

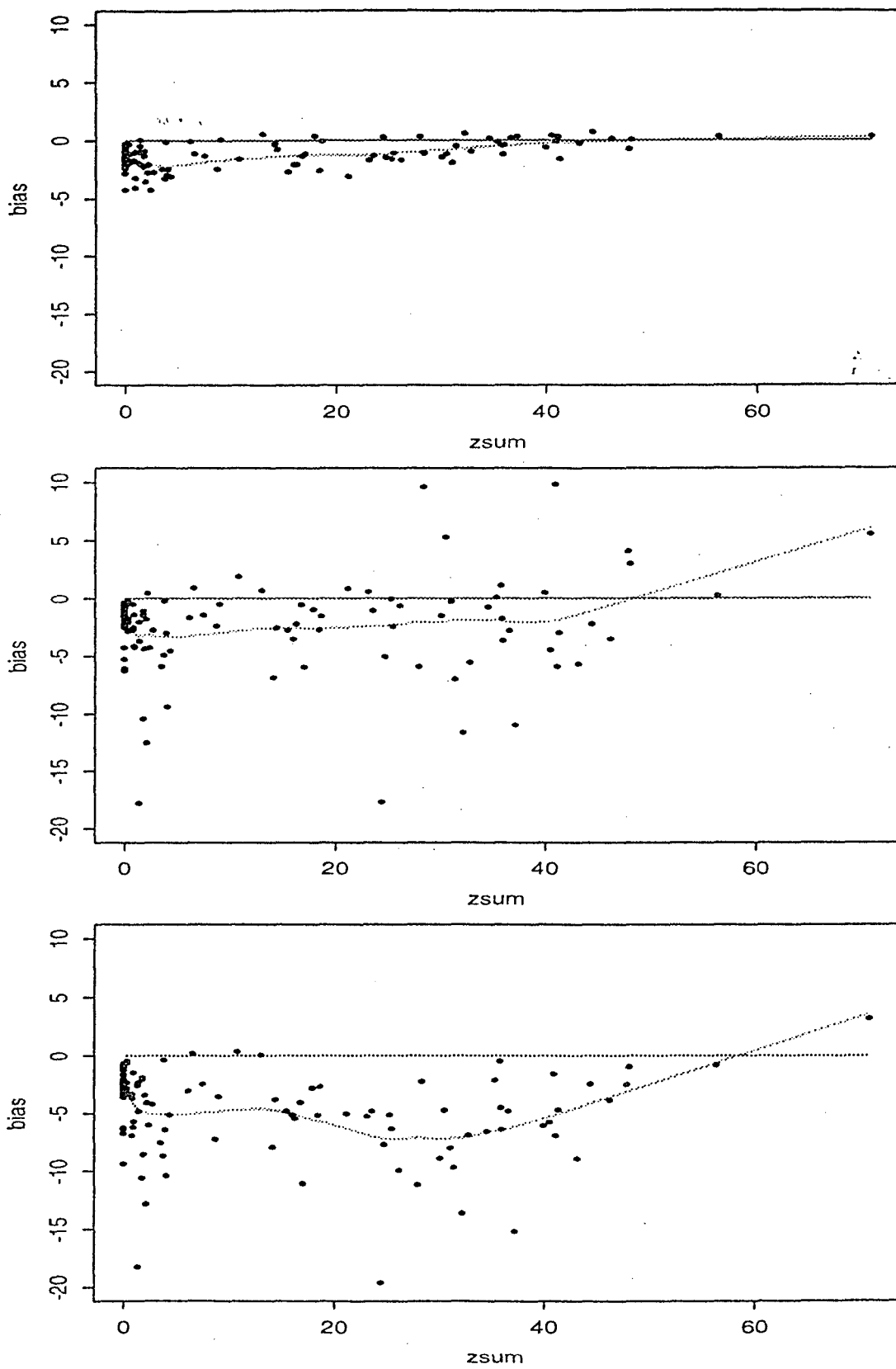


Figure 3: Bias vs dose of record (zsum) for three scenarios: **Film Only**, **All Data**, and **Data Plus**, respectively. All units are millisieverts.

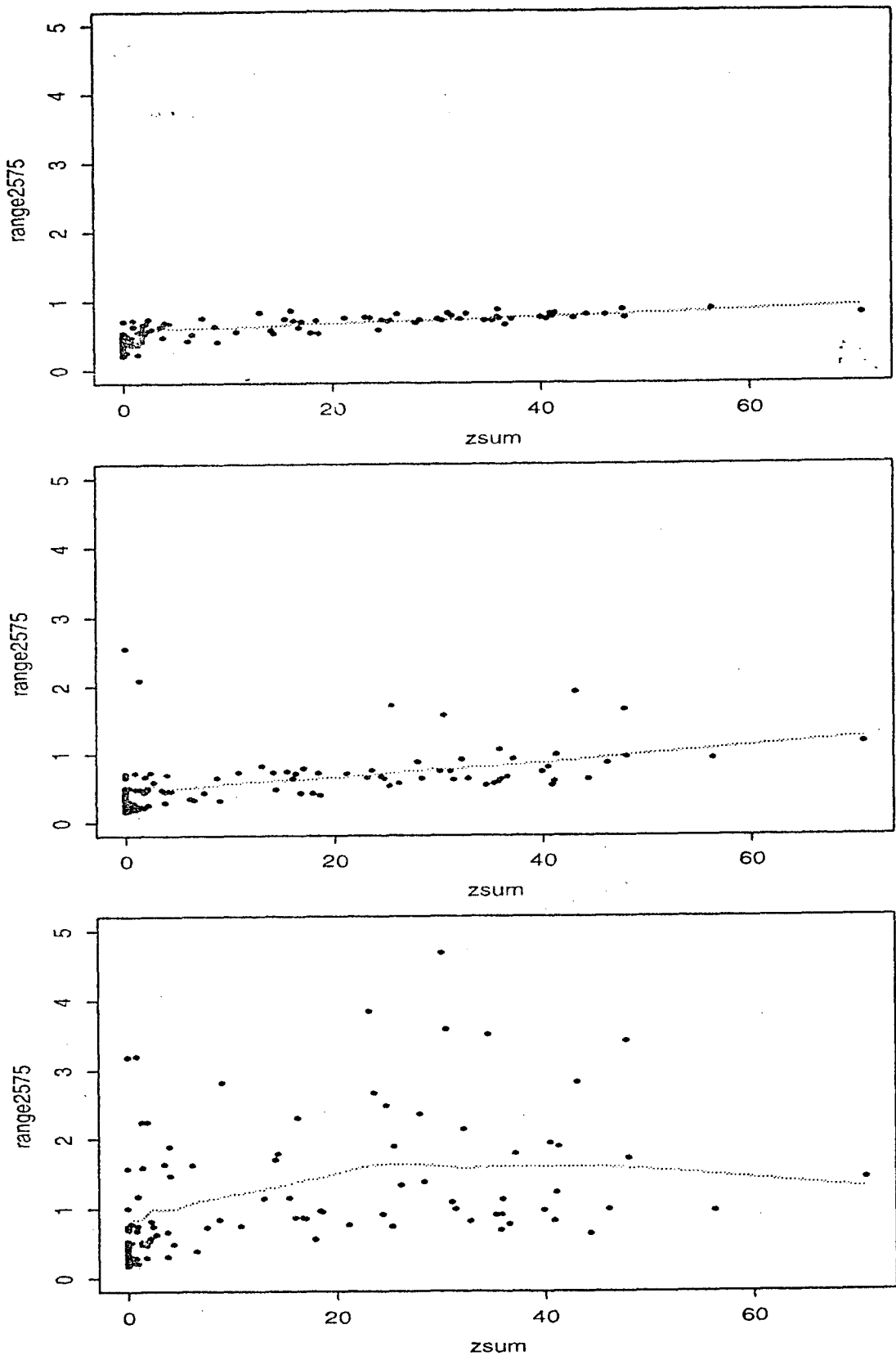


Figure 4: Uncertainty as interquartile range vs dose of record (zsum) for three scenarios: **Film Only**, **All Data**, and **Data Plus**, respectively. All units are millisieverts.

Film Only The weekly portion of the methodology with only film-badge data is used. Assume $P_b(x)$ as the prior true dose distribution for each week with a film-badge reading.

All Data The full daily-weekly methodology is used with an assumption that no pocket-meter data on a given day means no exposure. $P_p(x)$ is the prior true dose distribution for each day with at least one pocket-meter reading.

Data Plus The full daily-weekly methodology is used, and a minimum of five days per film-badge week as "on the job" is required. $P_p(x)$ is the prior true dose distribution for each day "on the job." We consider this to be the most likely scenario.

The priors $P_b(x)$ for film-badge readings and $P_p(x)$ for pocket-meter readings are nearly flat and have a negligible effect when combined with a data generated likelihood. Only the **Data Plus** scenario uses $P_p(x)$ without a data-generated likelihood to complete five days when there are fewer than five days of pocket-meter data in a week. $P_p(x)$ is a lognormal density with a median of 0.016 mSv and the 0.95 quantile at 3.00 mSv. Its effect in those cases is mainly an increase in uncertainty.

5.1. Bias

In Fig. 3, we report bias as the difference between the median of the true dose distribution and the dose of record. Each point represents a person-year. The zero bias line and loess line are shown on each plot. The loess line is a variable span smoother and is intended to guide the eye through the middle of the data. It is not intended as a model for the data.

- Introduction of pocket-meter data greatly increases variability of bias.
- Some pocket-meter information produces positive bias. Examination of the data reveals that these are instances of only one or two days of pocket-meter pairs with a low total combined with a high film-badge reading. Adding the uncertainty for the apparently missing days makes the bias negative again. In fact, this is our primary motivation for including the **Data Plus** scenario.

- It is clear, particularly in the **Data Plus** scenario, that bias is poorly correlated with dose of record. The pocket-meter detail is needed to correctly quantify bias.

5.2. Uncertainty

We report uncertainty as the interquartile range of the true dose distribution. This range contains the middle 50% of true dose distribution. The plots also include a loess line to guide the eye through the middle of the data. Some comments about the three scenarios in Fig. 4, which plots the dose of record vs uncertainty, follow:

- Adding the pocket-meter information reduces the uncertainty of some person-years while greatly increasing it for others. This seems plausible, as some people were likely more "consistent" in using their pocket meters and film badges than others.
- Accounting for potentially missing pocket-meter readings greatly increases the uncertainty for some person-years.
- Uncertainty is poorly correlated with dose of record when pocket-meter data are included, especially in the most likely **Data Plus** scenario.

At the outset of this study, we expected to obtain dose estimates with less uncertainty by including the pocket-meter data. Although this is true for the cases with "clean" pocket-meter data, the detailed but incomplete and sometimes conflicting data in other cases raises the uncertainty. It is also possible that the true uncertainty and bias are still understated if anecdotal reports that film badges and pocket meters were sometimes taken off to "take a closer look" are true. The concluding remarks in report [5] can be interpreted to suggest that a climate to keep reported dose down did exist. Further, one could argue that the likelihood of being "reassigned" away from usual work location and colleagues would be a factor potentially contributing to underreporting of actual dose.

A comparison of the dose of record to the estimated true dose is also shown with a series of boxplots. Figures 5 and 6 report the **Film Only** scenario, Figures 7 and 8 report the **All Data** scenario, and Figures 9 and 10 report the **Data Plus** scenario. Each boxplot represents a person-year and is labeled with an id number and year. The boxplots show the 1, 25, 50, 75, and 99 percentiles of the

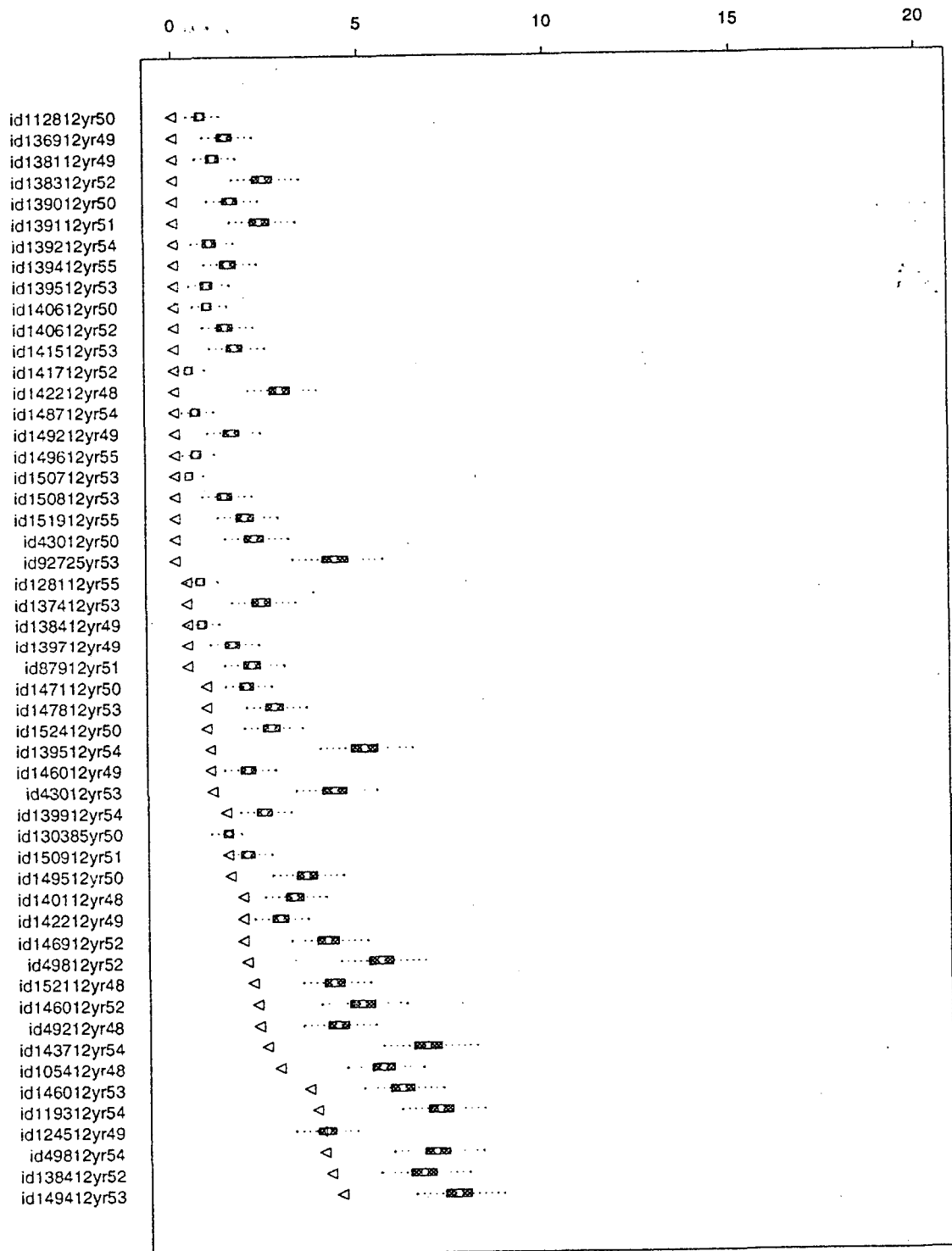


Figure 5: Boxplots of yearly dose distribution estimates and the corresponding dose of record (mSv) for the **Film Only** scenario.

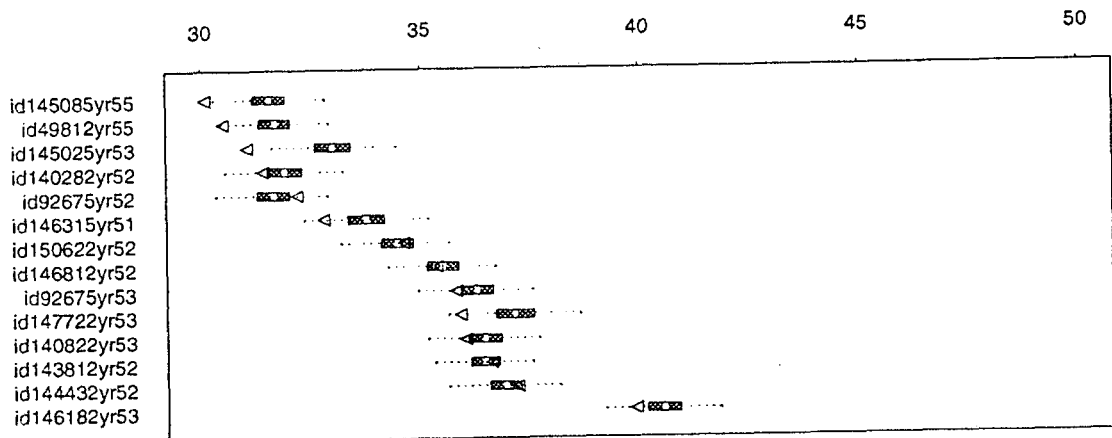
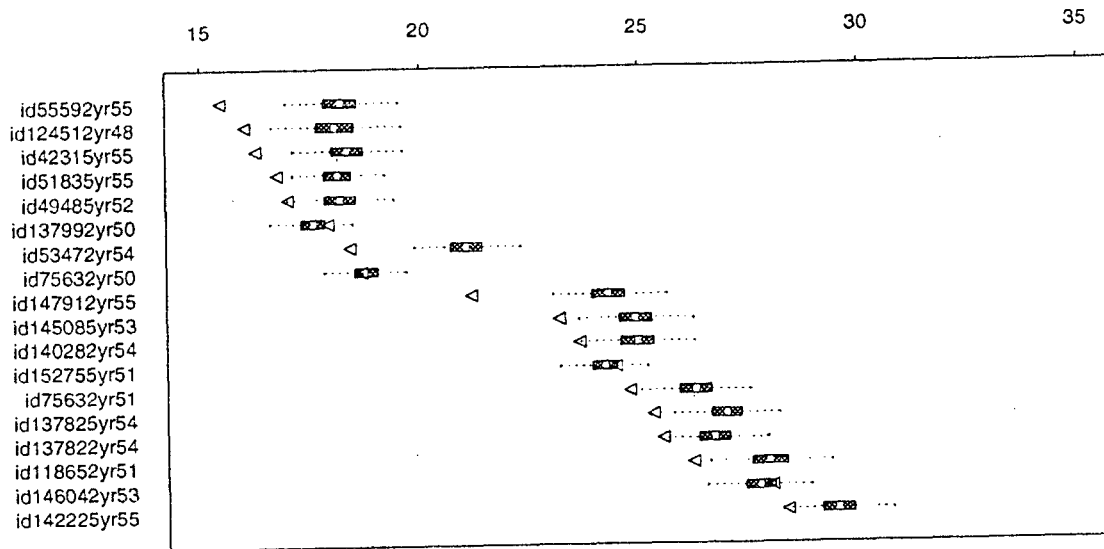
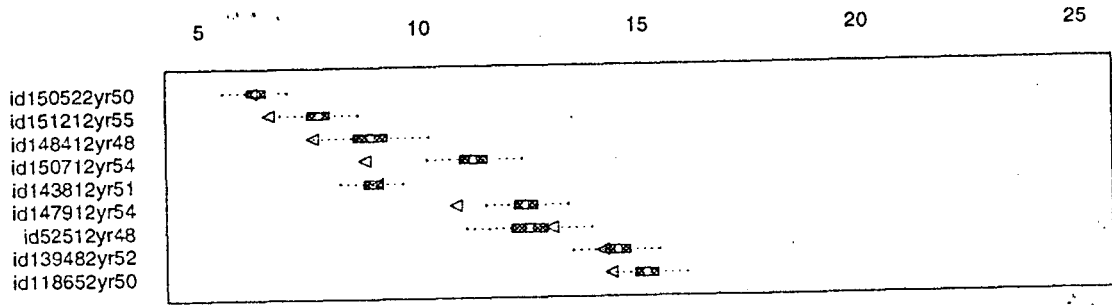


Figure 6: Boxplots of yearly dose distribution estimates and the corresponding dose of record (mSv) for the **Film Only** scenario, continued.

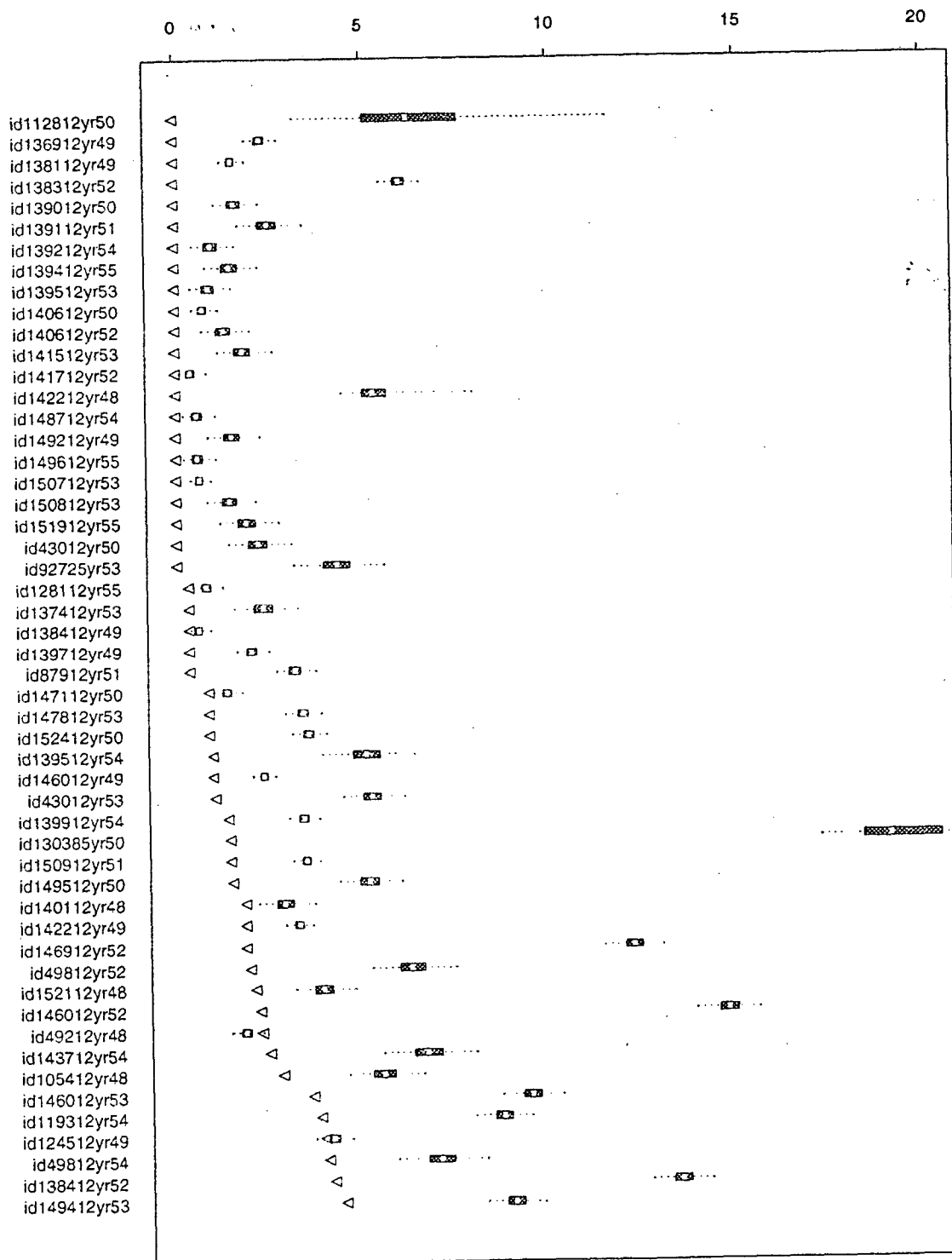


Figure 7: Boxplots of yearly dose distribution estimates and the corresponding dose of record (mSv) for the All Data scenario.

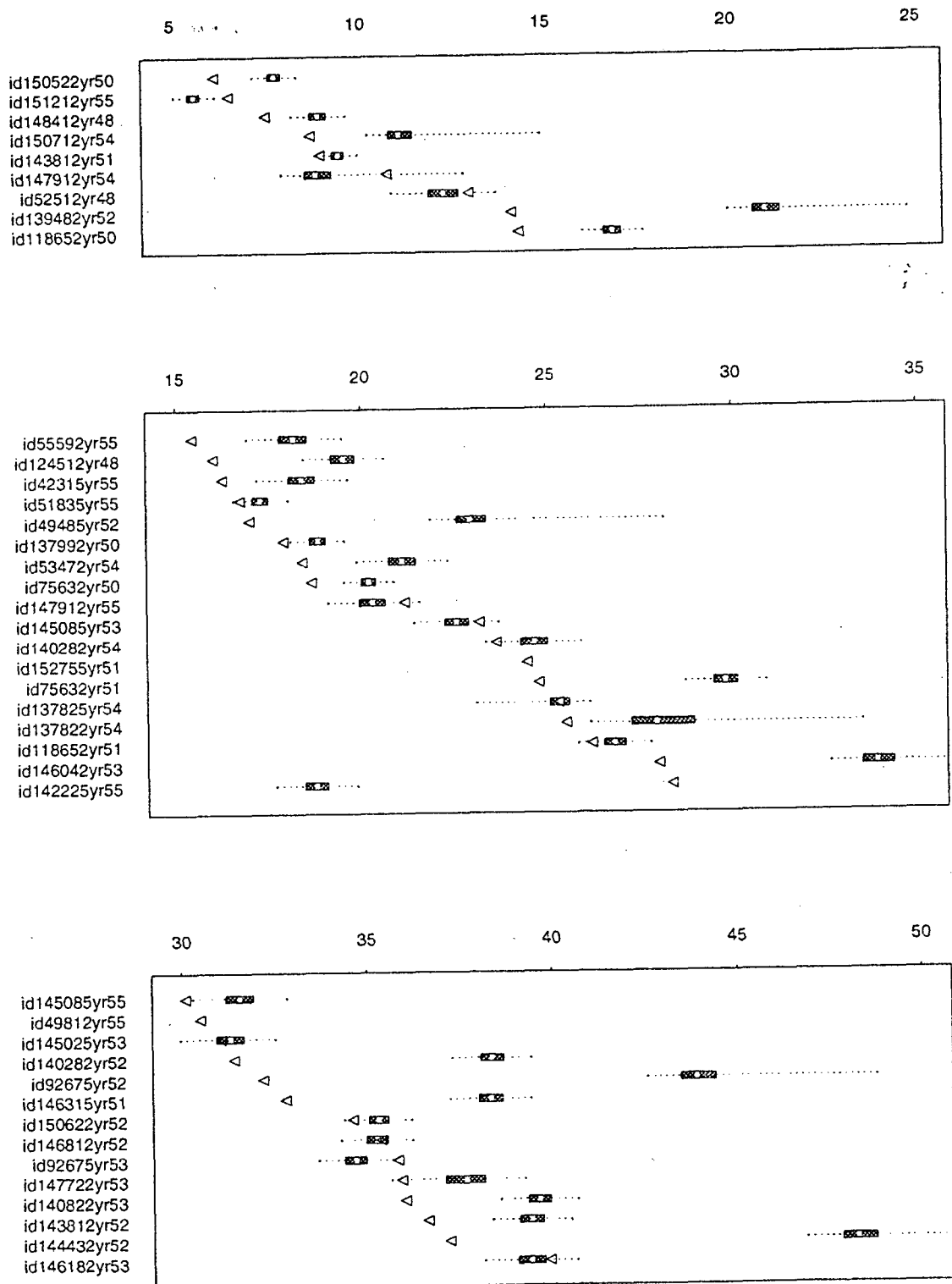


Figure 8: Boxplots of yearly dose distribution estimates and the corresponding dose of record (mSv) for the All Data scenario, continued.

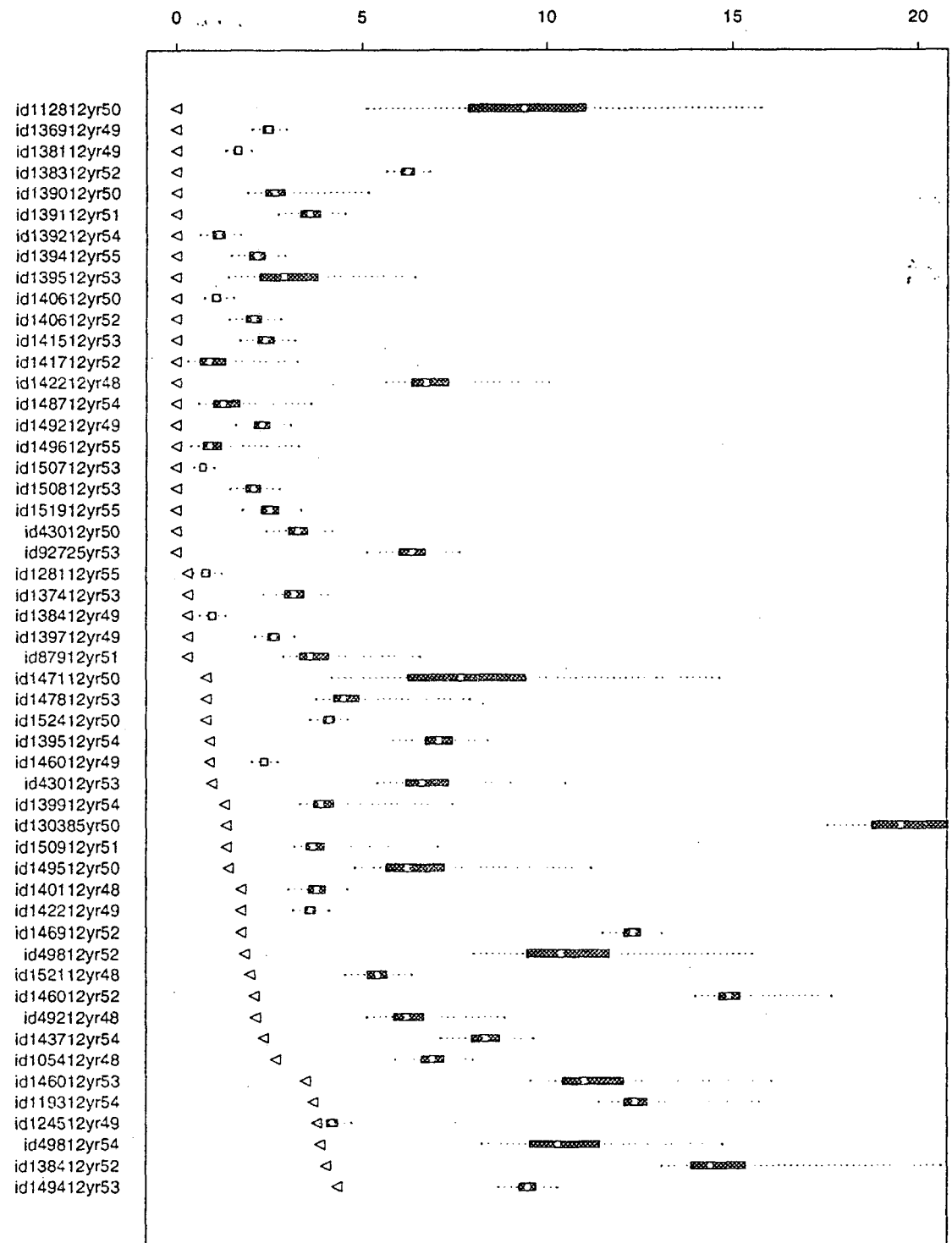


Figure 9: Boxplots of yearly dose distribution estimates and the corresponding dose of record (mSv) for the Data Plus scenario.

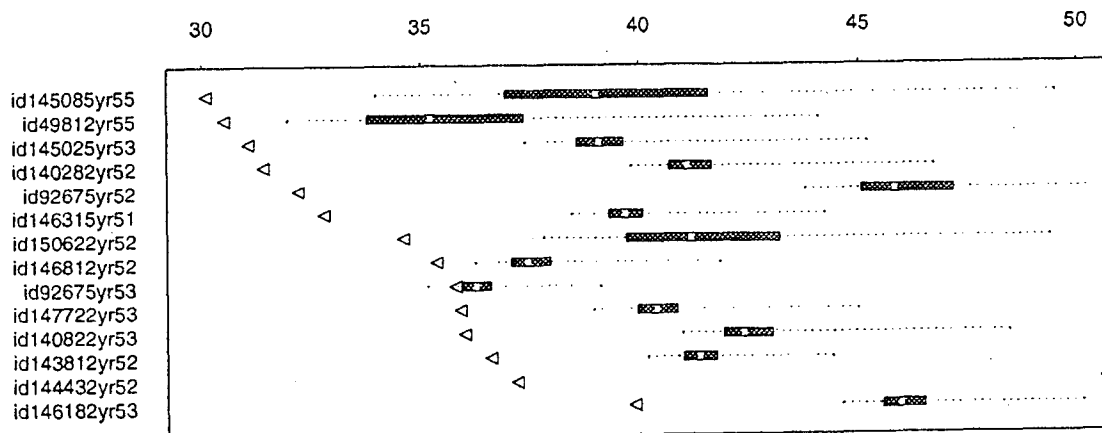
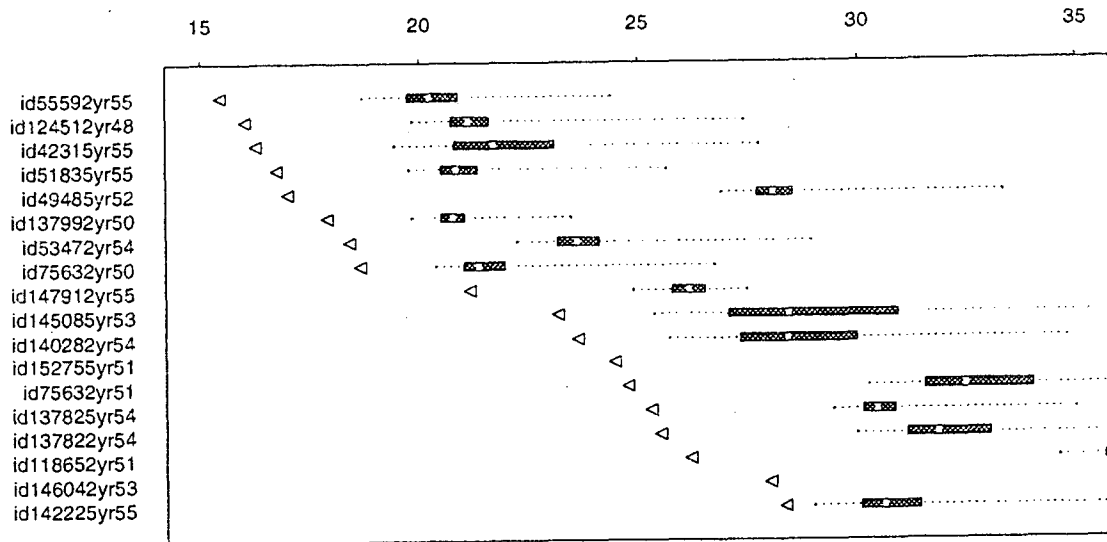
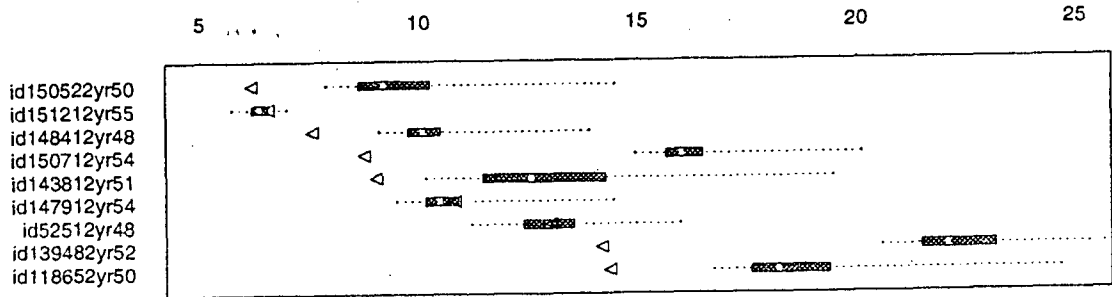


Figure 10: Boxplots of yearly dose distribution estimates and the corresponding dose of record (mSv) for the Data Plus scenario, continued.

estimated dose distribution. In addition, a triangle indicates the dose of record for each person-year. The person-years along the vertical axis are in increasing order of dose of record. Some examples of how the inclusion of pocket-meter data reduces uncertainty for some person-years while increasing it for others follow:

- id142212yr49 decrease.
- id149412yr53 decrease.
- id150522yr50 has reduced uncertainty in the **All Data** scenario, but in the **Data Plus** scenario uncertainty goes up dramatically. This pattern repeats in several of the high dose person-years. It is possible, that personnel with high doses were rotated to other work locations at times to limit their accumulated dose. However, without work location records, there is uncertainty, as is reflected in the **Data Plus** scenario.
- id112812yr50 increase.

6. Feasibility and Benefits of Computerizing Hard-Copy ORNL Data

Hard copy records for the ORNL 1945-1955 cohort consist of roughly 30,000 person-years of detailed daily and weekly data. Each person-year is on a single hard copy record that is in the form of a file folder that has four sides. Figure 2 shows the front page of a sample file folder.

The sample of 211 person-years that were computerized from hard copy records (see Sect. 5) is described in more detail in [27]. During data entry an estimate was obtained of the time required to enter one complete person-year.

- 52 weekly film-badge entries required 31 minutes, and
- 715 daily pocket-meter readings required 85 minutes.

A total of 116 minutes was required for single entry of one complete person-year using a manual key data entry system.

Double entry for error detection and correction would therefore require about 4 hours per person-year. A conservative estimate of the data entry time for all available dosimetry data (30,000 person years) that is available in hard copy form

at ORNL is about 65 person years of effort. Clearly, this is a monumental task if undertaken with the same technology as in the past.

The above estimate can be taken to suggest that it is only feasible to computerize some subset of the data to support a case-control study. However, as computing technology and optical character recognition technology is rapidly improving, we suggest that it is mainly a matter of time before the entire hard copy dosimetry data base is computerized. We think that current handprint recognition systems [9] are "good enough" to reduce the computerization effort estimate by an order of magnitude, if they are carefully adapted for the ORNL hard copy dosimetry data. The adaptation is critical for obtaining high efficiency in handprint recognition. It requires intimate knowledge of the hard copy records as well as the development of statistical relationships between hard copy form fields.

In summary, the results of our study suggest that detailed pocket-meter and film dosimetry information is required to obtain unbiased and reliable dosimetry data for use in epidemiologic studies of workers at ORNL. The primary benefit of computerizing the hard copy detail would be better external dosimetry data for use in future epidemiologic studies of the ORNL cohort. A secondary benefit would be the development of a data base that could be used to develop new statistical methods that incorporate the uncertainty and bias in the dosimetry data into the dose-response analyses.

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