ORNL/TM-1999/282

DOSE ESTIMATION FROM DAILY AND WEEKLY DOSIMETRY DATA

May 2000

G. Ostrouchov
E. L. Frome
G. D. Kerr

ORNL/TM-1999/282

DOSE ESTIMATION FROM DAILY AND WEEKLY DOSIMETRY DATA

George Ostrouchov
Edward L. Frome
Computer Science and Mathematics Division

George D. Kerr
Life Sciences Division

Date Published: May 2000

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831-6285
managed by
UT-Battelle, LLC
for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

Contents

List of Figures

Acknowledgements

The research described in this report was supported by grant R01 OH12956 from the National Institute for Occupational Safety and Health of the Centers for Disease Control and Prevention. The authors thank the Office of Radiation Protection at the Oak Ridge National Laboratory for providing the data used in this study, and the Center for Epidemiologic Research at Oak Ridge Institute for Science and Education for help with data entry and verification.

This work was conducted from October 1996 through September 1998. It was submitted to the National Institute for Occupational Safety and Health in September 1998 for review. Formal publication as an ORNL report occurred in May 2000.

Abstract

Statistical analyses of data from epidemiologic studies of workers exposed to radiation have been based on recorded annual radiation doses (yearly dose of record). It is usually assumed that the 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 with weekly data, 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 the yearly dose of record systematically underestimates doses for Oak Ridge National Laboratory (ORNL) workers. This could result in biased estimates of dose-response coefficients and their standard errors. The results of this evaluation raise serious questions about the suitability of the yearly dose of record for direct use in low-dose studies of nuclear industry workers.

Here, we extend our previous work to use full information in Pocket meter data and develop the Data Synthesis for Individual Dose Estimation (DSIDE) methodology. Although the DSIDE methodology in this study is developed in the context of daily and weekly data to produce a cumulative yearly dose estimate, in principle it is completely general and can be extended to other time period and measurement combinations. The new methodology takes 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 DSIDE method 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 daily pocket-meter information shows that the negative bias is generally more severe than was reported in our work based on weekly film data only, however, the amount of bias also varies greatly between person-years. Second, the addition of pocket-meter information reduces uncertainty for some person-years, 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, the first uranium-graphite pile achieved criticality at the University of Chicago 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 Clinton Laboratories pilot plant at Oak Ridge was to train crews to operate the even larger production facilities at Hanford. The project would also 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 early December 1943. By the end of December, several milligrams of plutonium were separated and shipped for experimentation at the University of Chicago. 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.

During these early years 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.* The pocket meter became the day-to-day means of monitoring personnel exposures in the workplace [28]. At ORNL, the daily pocket-meter readings continued to be recorded and 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 thermoluminscent 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 broader issue of uncertainty in individual dose estimates in epidemiologic studies of nuclear industry workers also has been discussed in [3, 10, 24, 25].

Our previous work [20] describes methodology to estimate missing dose for individuals from recorded weekly film-badge readings. The greatest missing dose is found for individuals that have many "below detectable limit" weekly film-badge doses with corresponding positive pocket-meter doses. The inclusion of pocket-meter data in [20] was used primarily to provide information on the 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. The model provides 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 an adjustment for dose bias and uncertainty in epidemiologic dose-response analyses. Here and in our previous work [20] we take the first step by developing methodology to adjust for bias and to quantify uncertainty in dose estimates. 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 density points (e.g. 100), 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.

Section 2 gives an overview of the Data Synthesis for Individual Dose Estimation (DSIDE) methodology, demonstrating how its two major components, the Bayesian method and the convolution method, are used to go from daily and weekly data to a yearly dose distribution estimate. Section 3 describes the Bayesian methodology and its construction for the ORNL data from the period 1945-1955. One instance of the Bayesian method is constructed for the pocket-meter data and another instance for the film-badge data. Section 4 describes the convolution methodology that takes the Bayesian method estimates for single measurement periods and combines them to produce estimates of cumulative dose over several periods for an individual.

2 Overview: Data Synthesis for Individual Dose Estimation

We develop the DSIDE methodology in a dose estimation application that 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 is true 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 (or even be deliberately taken off, as noted in Sec. 5.3). 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. These 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, without the 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. The interpretation of probability here is the degree of belief in the supposition that the true dose is x. This interpretation provides a mathematical representation for the degree of uncertainty associated with deterministic quantities: a small bit of probability placed on each of a large number of values of x reflects a high degree of uncertainty; whereas, a probability of one placed on a single value reflects complete certainty.

We emphasize that $P(x)$ refers to the distribution of probabilities for *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 basic components in the DSIDE methodology. Instances of these two components are arranged in a sequence to produce a yearly cumulative dose estimate from a sequence of daily pocket-meter and weekly film-badge data. The first major component is a *Bayesian method* for computing a dose distribution estimate for a single measurement period that combines data with other information for the same 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 Section 3. The second major component is a *convolution method* that "adds" dose distribution estimates from consecutive periods to produce a cumulative dose distribution. This method is described in Section 4. Together, these two components achieve a synthesis of different measurements over various time periods to produce a dose distribution estimate over a combined time period.

The two basic components of DSIDE 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* combines the data for a given day with prior information to produce $P(x)$ dose distribution for that day. This process is repeated for each available day of the week.

2. The available daily $P(x)$ dose distributions in a week are combined with *convolutions* into a cumulative dose distribution $P(x)$ 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 a final estimate of $P(x)$ for the week. These steps are repeated for all available weeks of the year.

4. The available weekly $P(x)$ 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 to obtain the weekly cumulative dose (5×50) and also to combine weeks into a year ($49\times$). The result is a total of 299 convolutions, a formidable computational task that takes on the order of two minutes on a desktop computer.

Although the DSIDE methodology in this study is developed in the context of daily and weekly data to produce a yearly dose estimate, in principle it is completely general and can apply to other time period and measurement combinations. Application of DSIDE in a different context may require the development of different likelihood functions and a different sequence of its two basic components.

3 Bayesian Method for a Single Measurement Period

In Bayesian estimation, quantities of interest, both 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 Section 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 measurement). 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 a 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)

$$P(x|y) = c(y)P(x)P(y|x), \tag{1}$$

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, $P(y|x)$ 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 the likelihood for a single pocket meter. Vertical slices of the likelihood surface are $P(y|x)$, and horizontal slices are $L(x|y)$. The likelihood surface scale in Fig. 1 depends on the discretization used; therefore, only relative values matter. We comment on the pocket-meter specific features of the likelihood surface in Section 3.1.3.

The prior distribution, $P(x)$, is less critical when measurements are available, but can have a strong

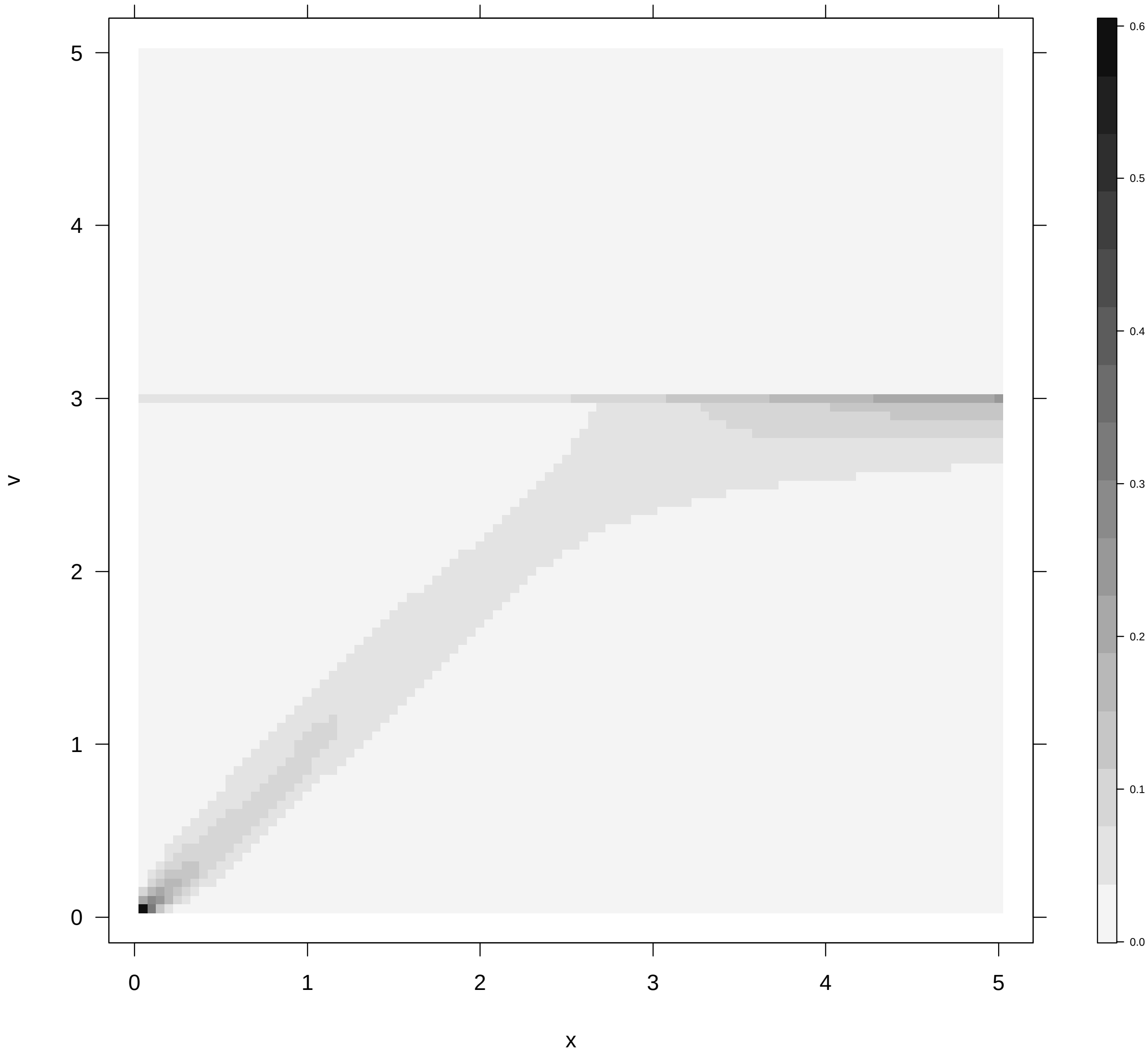


Fig. 1. Likelihood surface for a single pocket meter. Units for x and v are mSv.

impact when measurements are not available. In most situations, it is possible to formulate a description of $P(x)$ that is acceptably objective. If there is 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,

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, we 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

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

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 reading if it is more recent. 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 is 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 for handling these inconsistencies can strongly affect the influence of priors. We discuss this influence specifically for the 1945 to 1955 ORNL cohort in Section 5.

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

At ORNL, pocket meters were typically worn in pairs and both readings were recorded each day. Generally, only the lower reading was considered valid [5]. The justification for this practice seems to be that pocket meters sometimes discharged under rough handling (e.g. 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 the consequences of a potential overestimate resulting from taking the average of the two.

The primary purpose of the pocket meter was as a monitoring device, and 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. It was generally believed that film badge data were 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 can 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 versus 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 versus using a single pocket meter. The study 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 also reports data on proportion of "bad" pocket meters:

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

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

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

$$\begin{aligned} v_1 &= x_r + e_1 \qquad (3) \\ v_2 &= x_r + e_2, \end{aligned}$$

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 the p_i 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 values of d in terms of the p_i are

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

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

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

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

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

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

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 described in Section 5 along with data on pocket-meter pair differences reported in [5]. Error distribution results for seven sets of pocket-meter pairs are reported in Table 2. 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

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

e mSv	**All[a] Pairs**	**Low[b] Pairs**	**Exclude[c] Zeros**	**Both[d] Nonzero**	**S > 20[e]**	**S > 40[f]**	**Op Group[g]**
-.50	.00298	.00193	.00543	.00429	.00837	.01205	.00551
-.45	.00298	.00193	.00543	.00429	.00837	.01205	.00551
-.40	.00298	.00232	.00543	.00429	.00837	.01205	.00551
-.35	.00298	.00232	.00543	.00429	.00837	.01205	.00551
-.30	.00298	.00232	.00543	.00429	.00837	.01205	.00551
-.25	.00298	.00232	.00543	.00429	.00837	.01205	.00551
-.20	.00298	.00232	.00543	.00429	.00837	.01205	.00551
-.15	.00298	.00232	.00543	.00429	.00837	.01205	.00551
-.10	.02494	.02445	.07459	.00429	.00837	.01205	.00551
-.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

[a]Includes all good pocket-meter pairs.
[b]Includes pocket-meter pairs for weeks with a film-badge reading of zero and a minimum of four good pairs.
[c]Includes all good pocket-meter pairs with at least one nonzero reading.
[d]Excludes any pocket-meter pair with a zero reading.
[e]Includes good pairs with sum of at least 0.20 mSv.
[f]Includes good pairs with sum of at least 0.40 mSv.
[g]Consists of the Difference data for "operating group" in [5].

range increase.

3.1.3 Constructing the Likelihood Function

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 *expressed dose* to the pocket meter be the reading that would be recorded if there were no rounding or censoring and denote it by $\tilde{v}_1$. "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,

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

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 Section 3.1.1 is consistent with the pocket-meter pair results of Section 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

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

Next, we incorporate a probability that a pocket meter is damaged so that it discharges and reads 3.00 mSv. From historical information in Section 3.1.1, we have that the probability of a damaged pocket meter is about 0.006. Let $\tilde{\tilde{v}}_1$ be the reading that would be obtained if there is a 0.006 probability 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 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 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 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 detection limit of about 0.30 mSv was 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 many details that went into constructing the film-badge likelihood are described in our previous research [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:

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

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

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 to accumulate the daily pocket-meter $P(x)$ (posterior) distributions into a weekly cumulative $P(x)$. This becomes the prior distribution for the film-badge Bayesian 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 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.orau.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

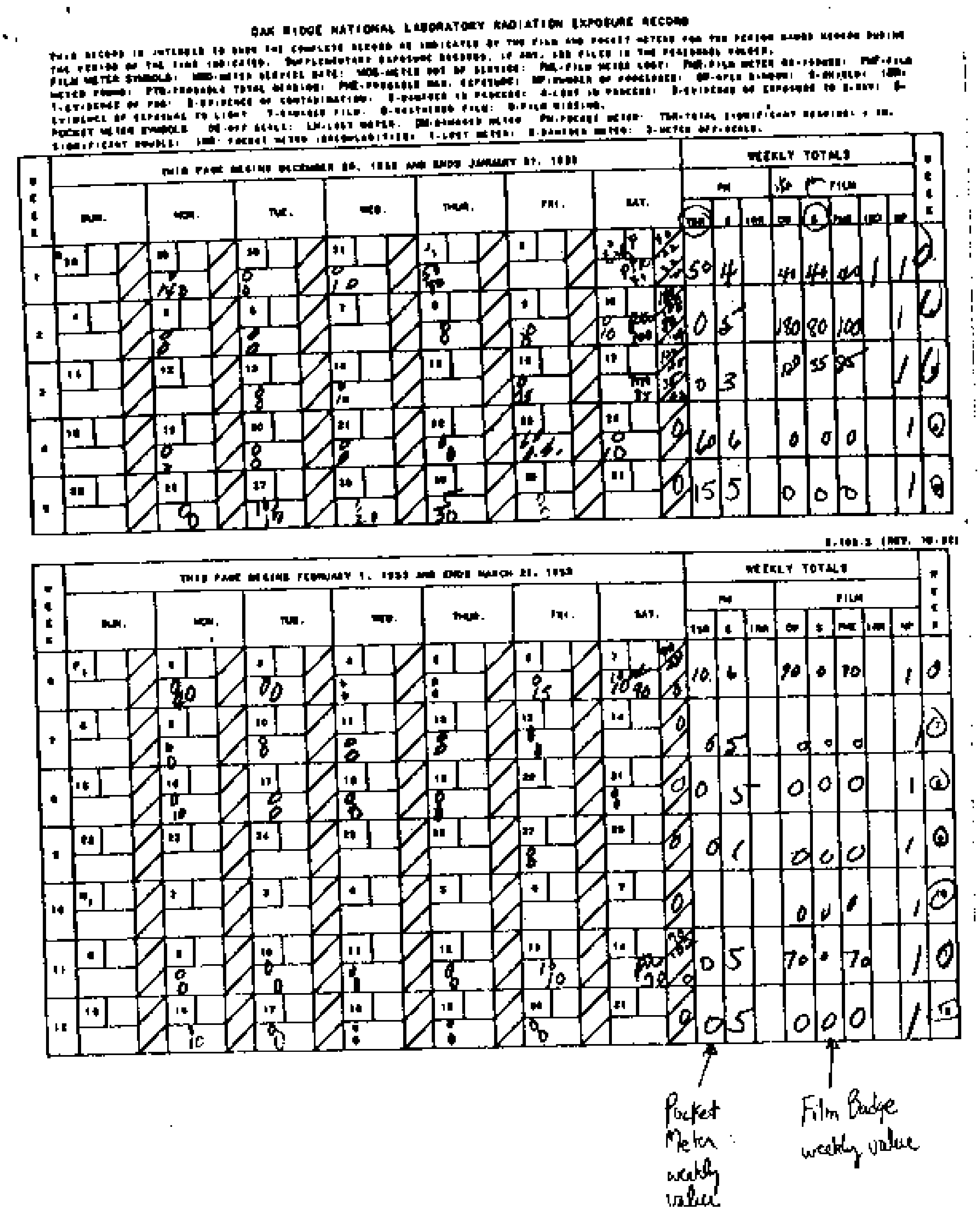


Fig. 2. First page of a sample hard-copy record. The record is in the form of a file folder and its four sides contain one person-year of detailed dosimetry data.

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 assumptions 1 and 5, and indirectly assumptions 2, 3, and 4 by treating them as assumption 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 Figs. 3 and 4:

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.

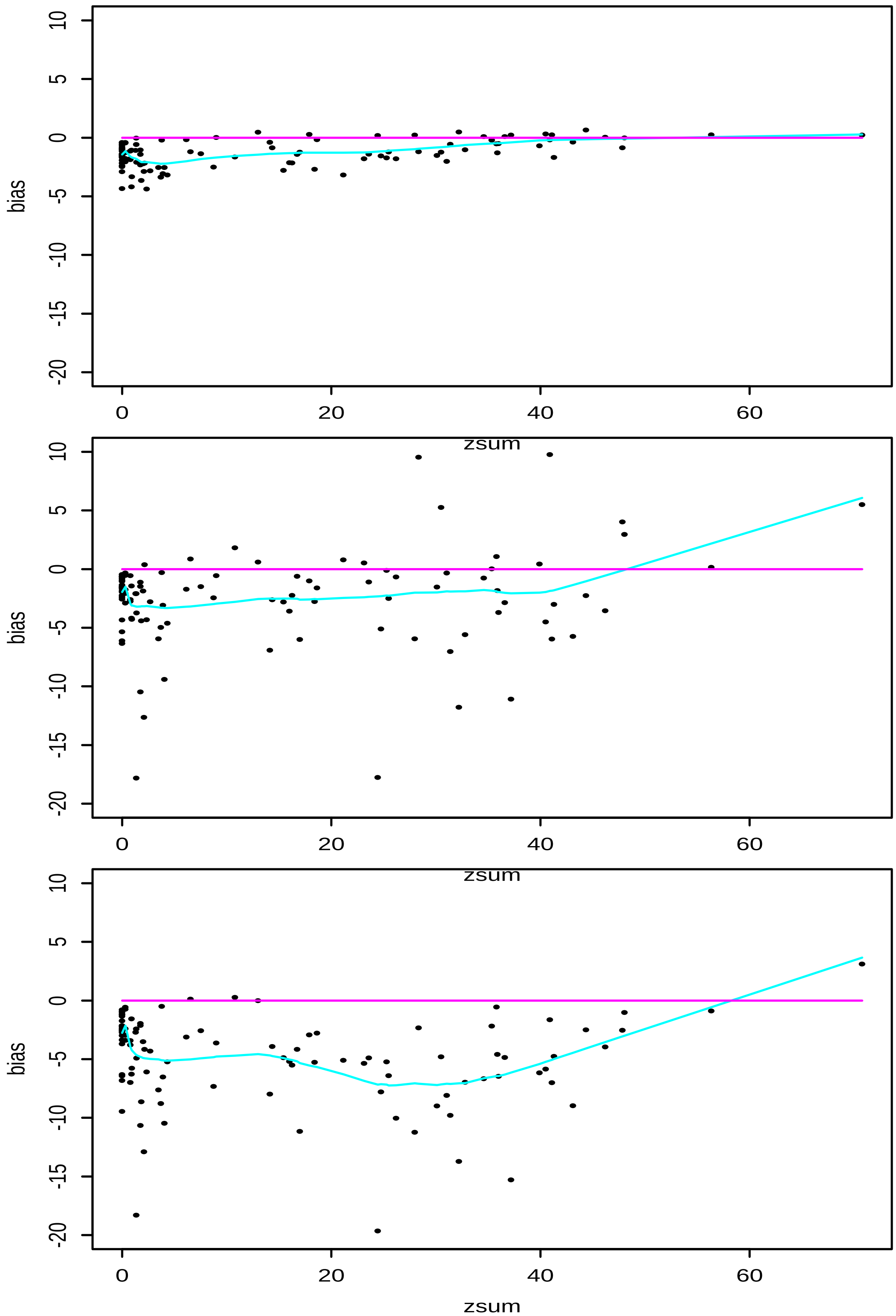


Fig. 3. Bias versus dose of record (zsum) for three scenarios: *Film Only*, *All Data*, **and** *Data Plus*, **respectively. All units are milisieverts.**

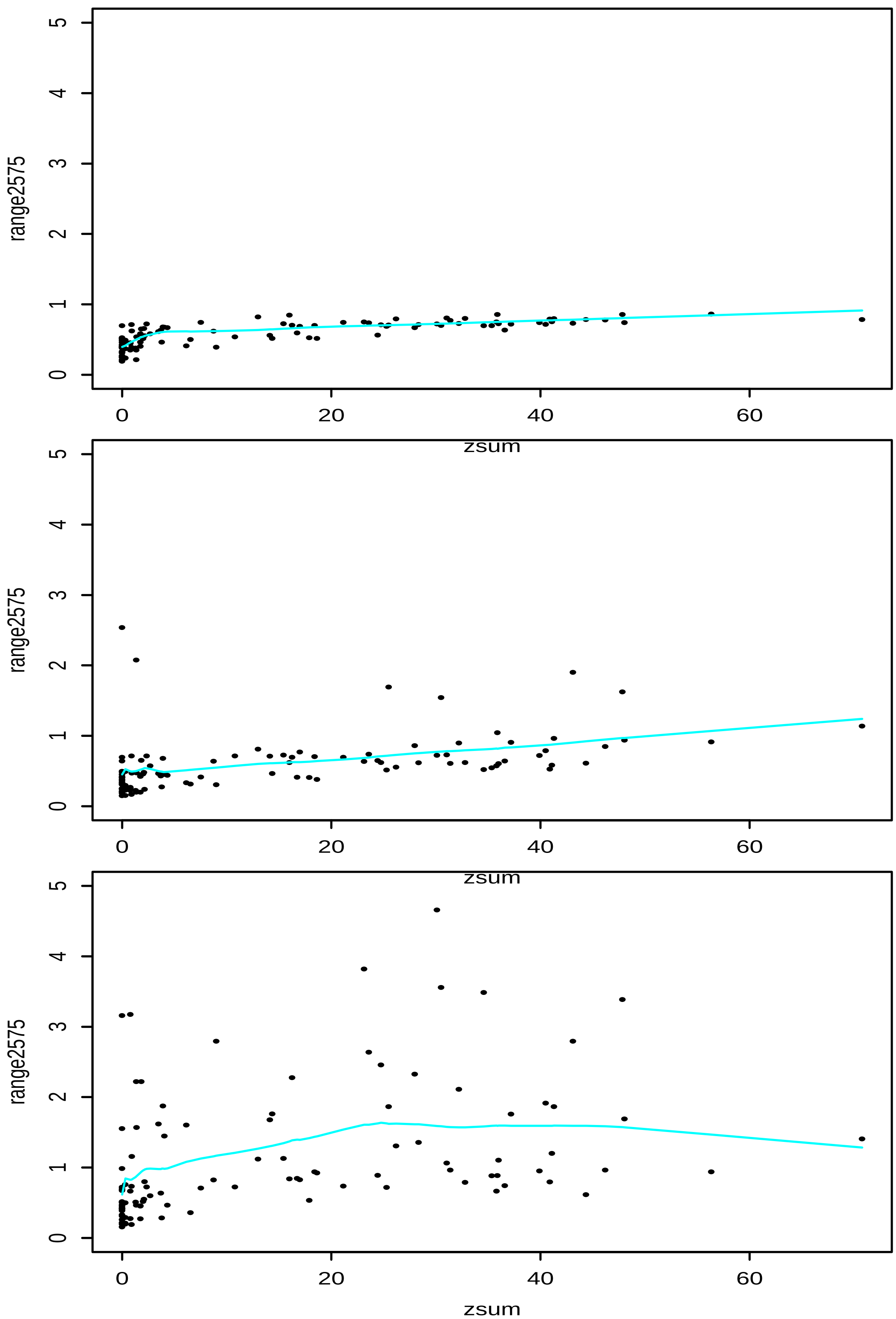


Fig. 4. Uncertainty as interquartile range versus dose of record (zsum) for three scenarios: *Film Only*, *All Data*, **and** *Data Plus*, **respectively. All units are milisieverts.**

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. Some conclusions about bias are as follows:

- 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 versus 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.

A comparison of the dose of record to the estimated true dose is also shown with a series of boxplots. Figs. 5 and 6 report the *Film Only* scenario, Figs. 7 and 8 report the *All Data* scenario, and Figs. 9 and 10

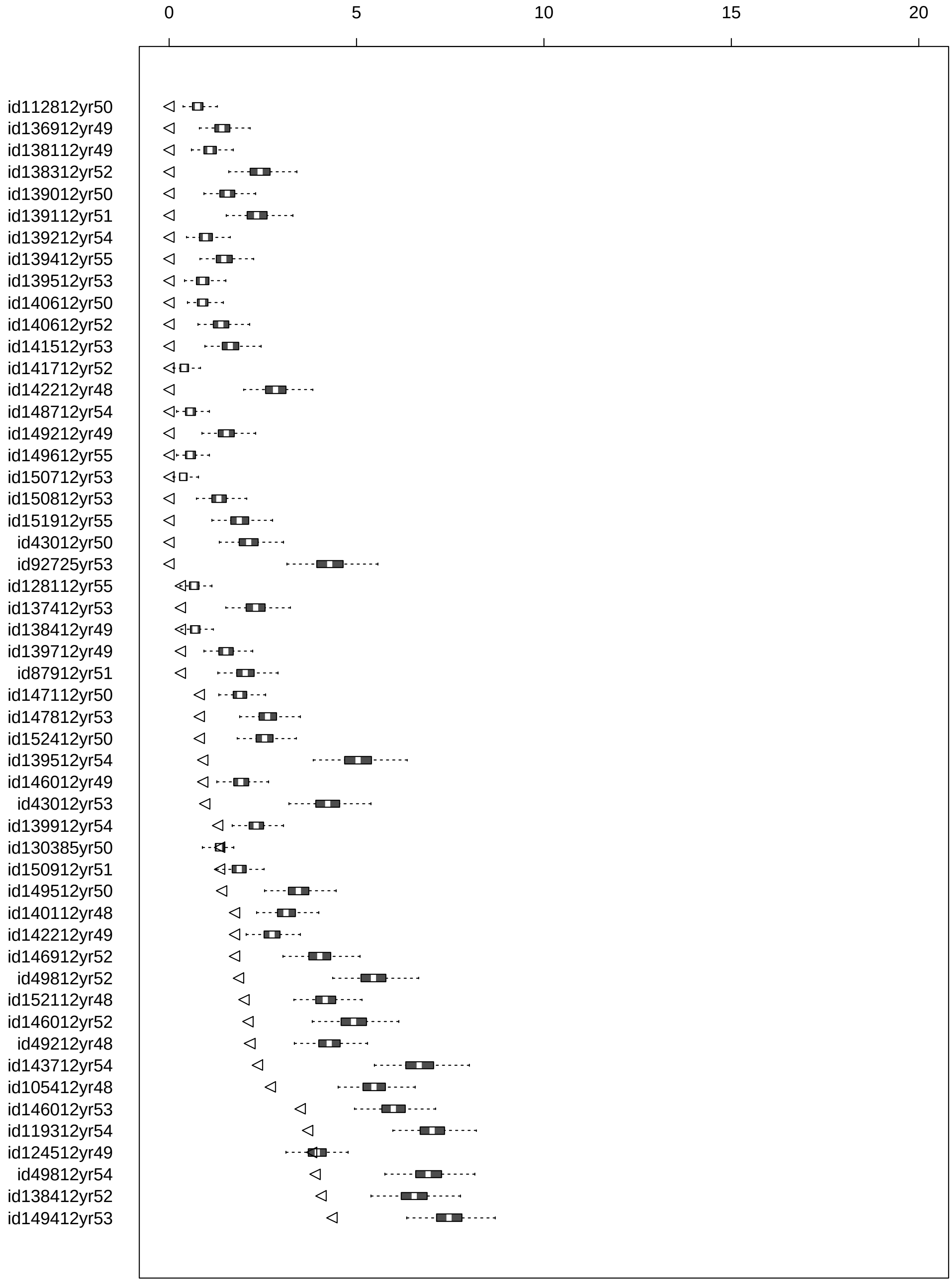
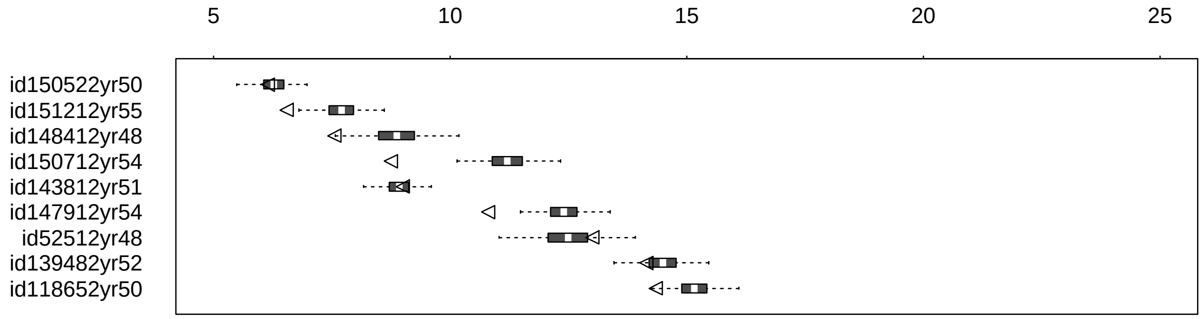
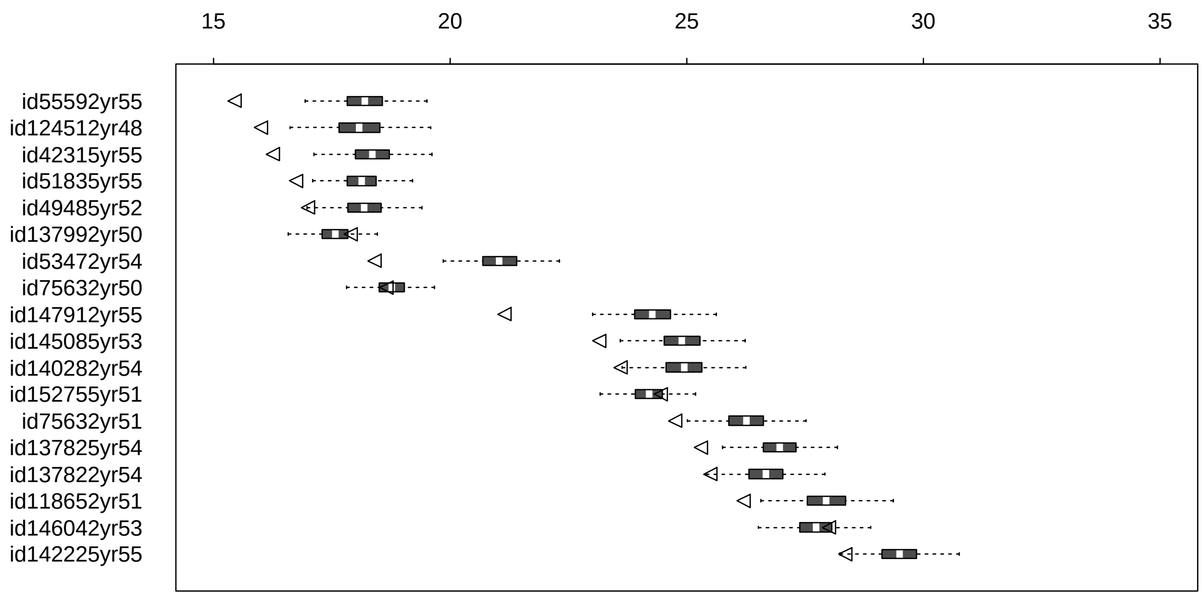


Fig. 5. Boxplots of yearly dose distribution estimates and the corresponding dose of record (mSv) for the ***Film Only*** **scenario.**





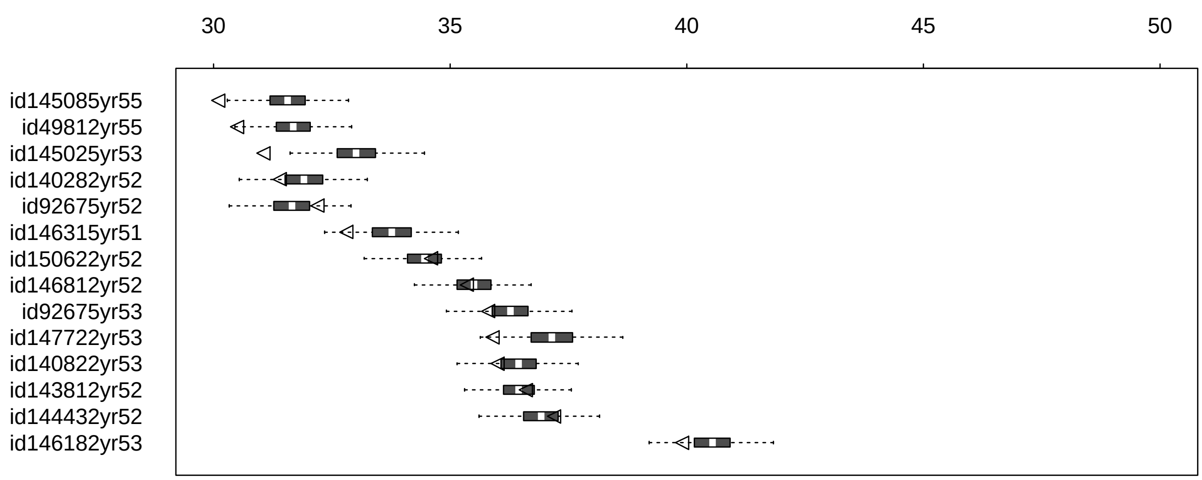


Fig. 6. Boxplots of yearly dose distribution estimates and the corresponding dose of record (mSv) for the ***Film Only*** **scenario, continued.**

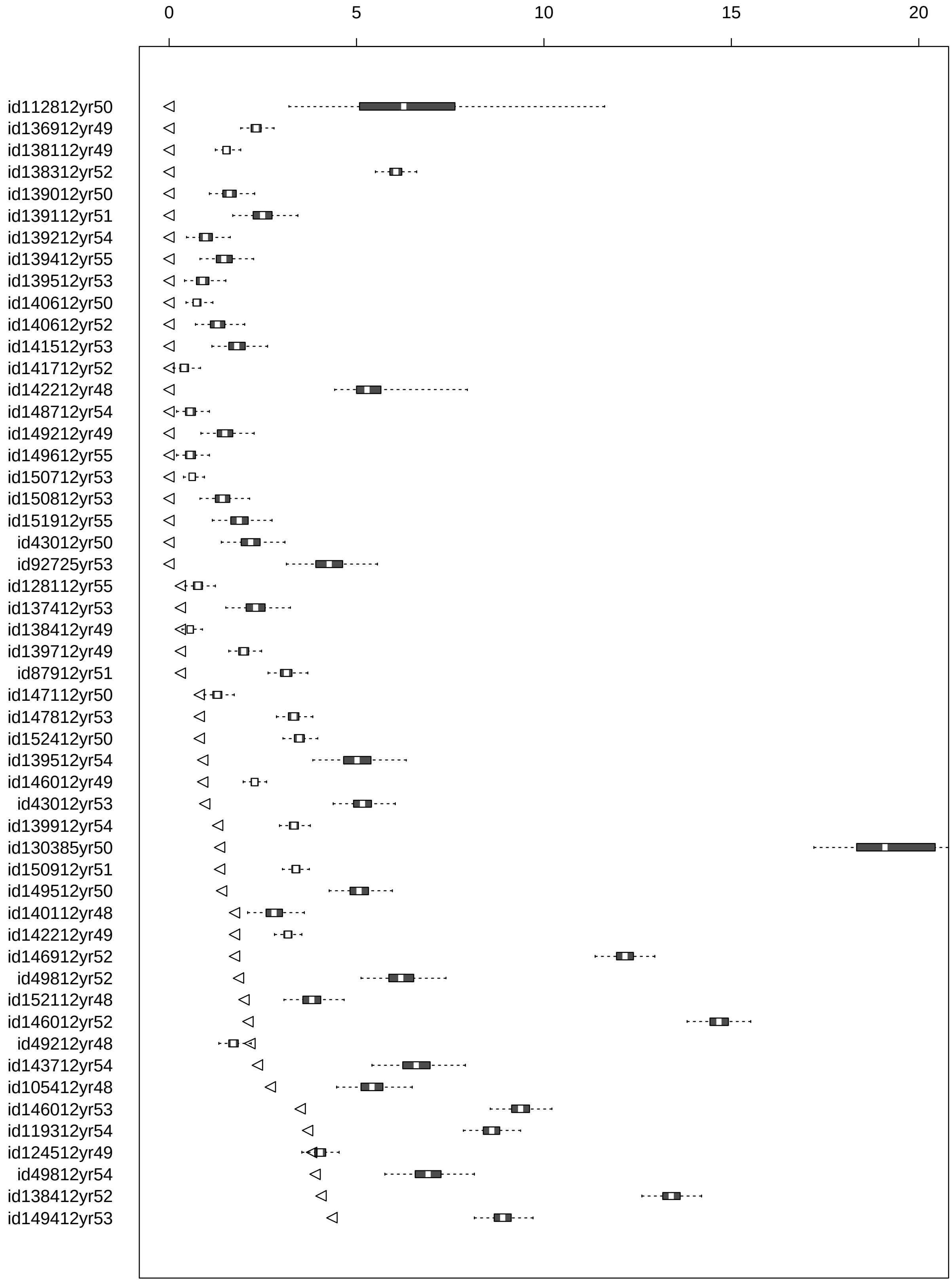


Fig. 7. Boxplots of yearly dose distribution estimates and the corresponding dose of record (mSv) for the ***All Data*** **scenario.**

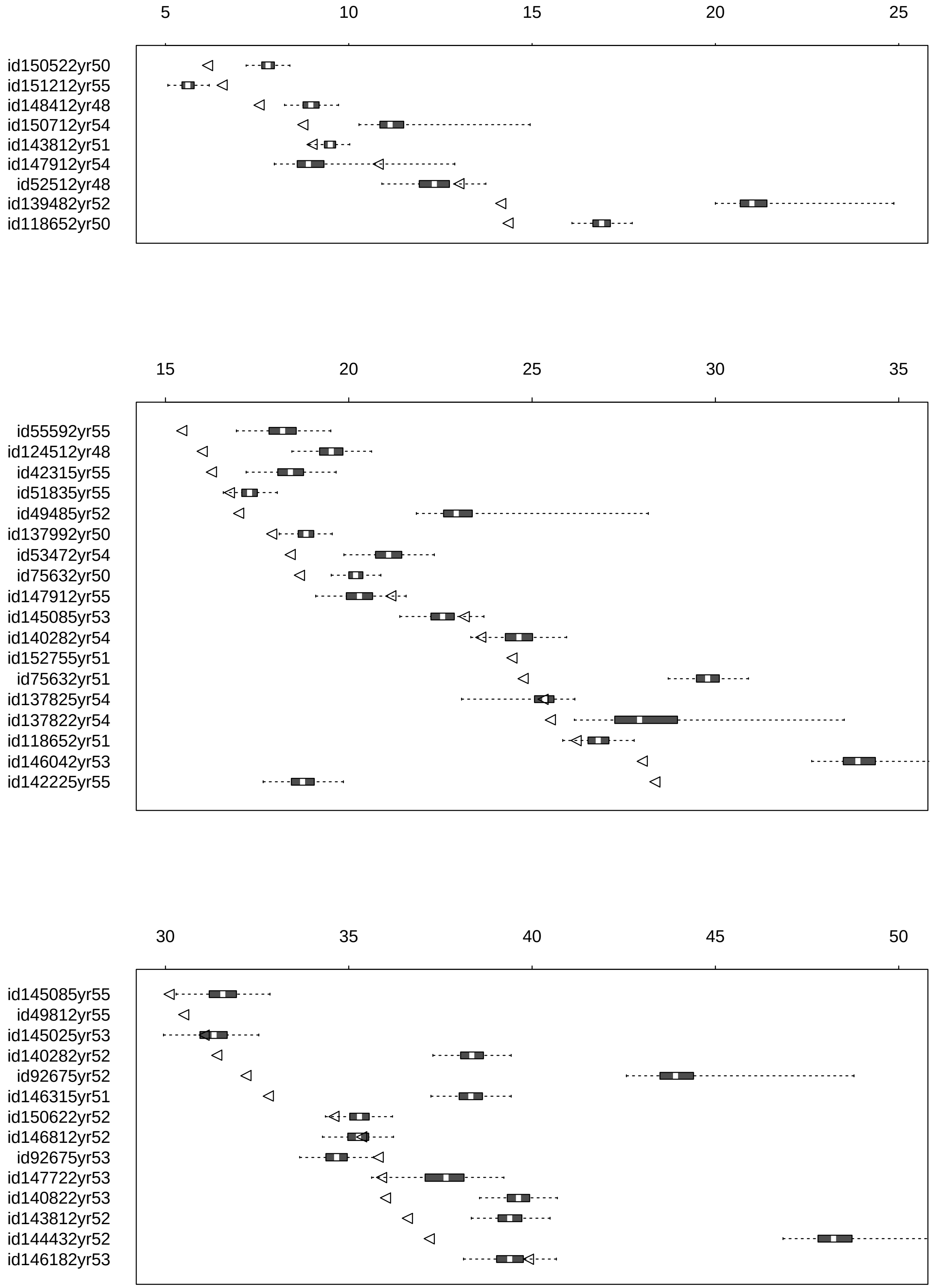


Fig. 8. Boxplots of yearly dose distribution estimates and the corresponding dose of record (mSv) for the *All Data* scenario, continued.

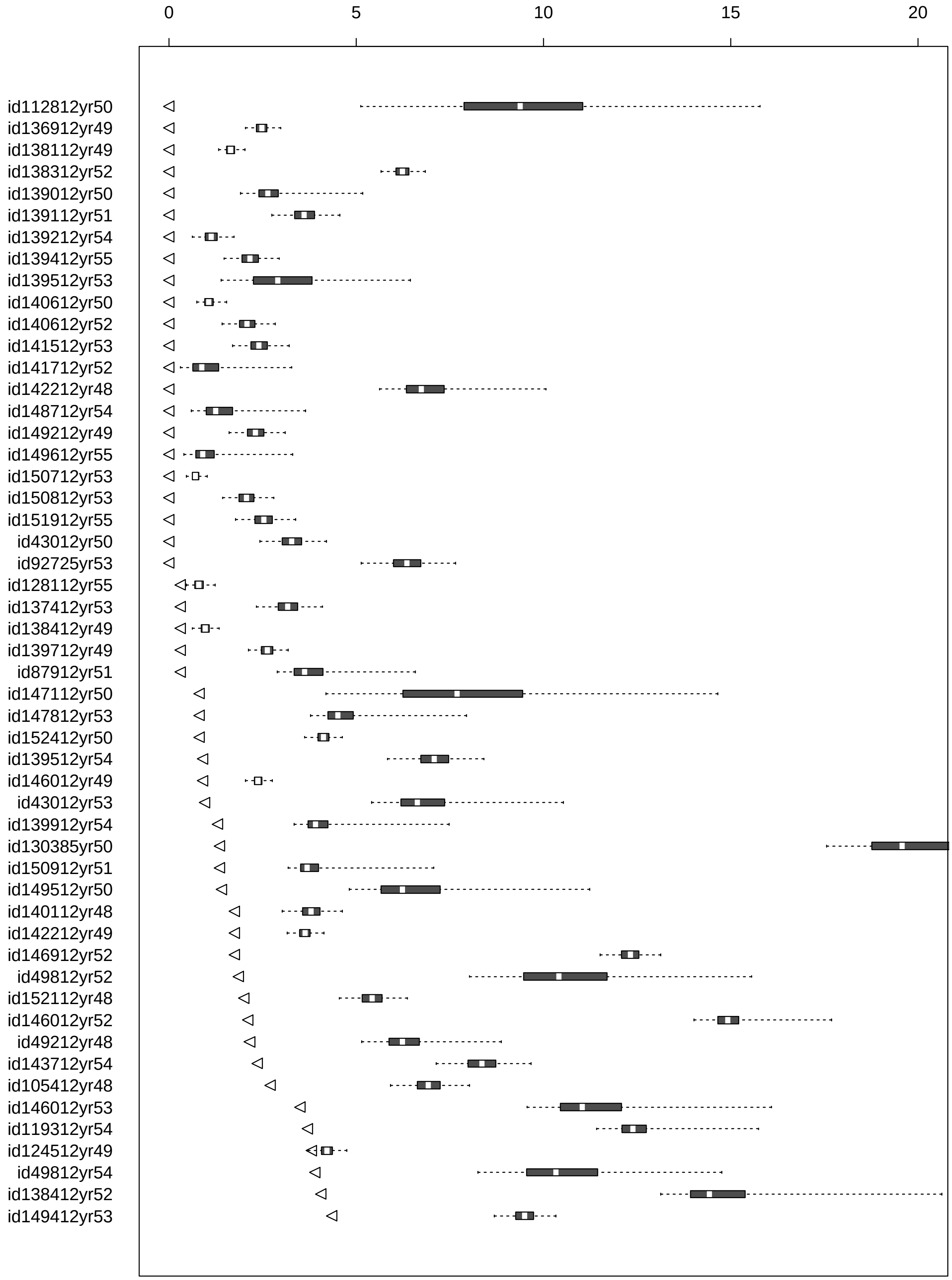
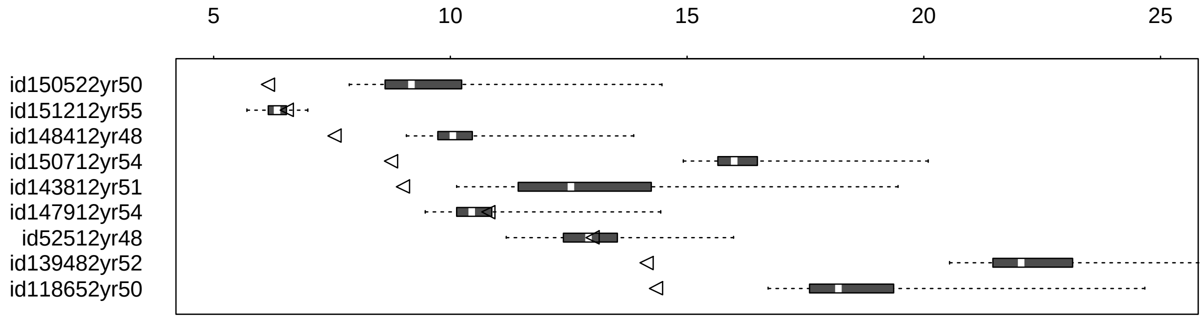
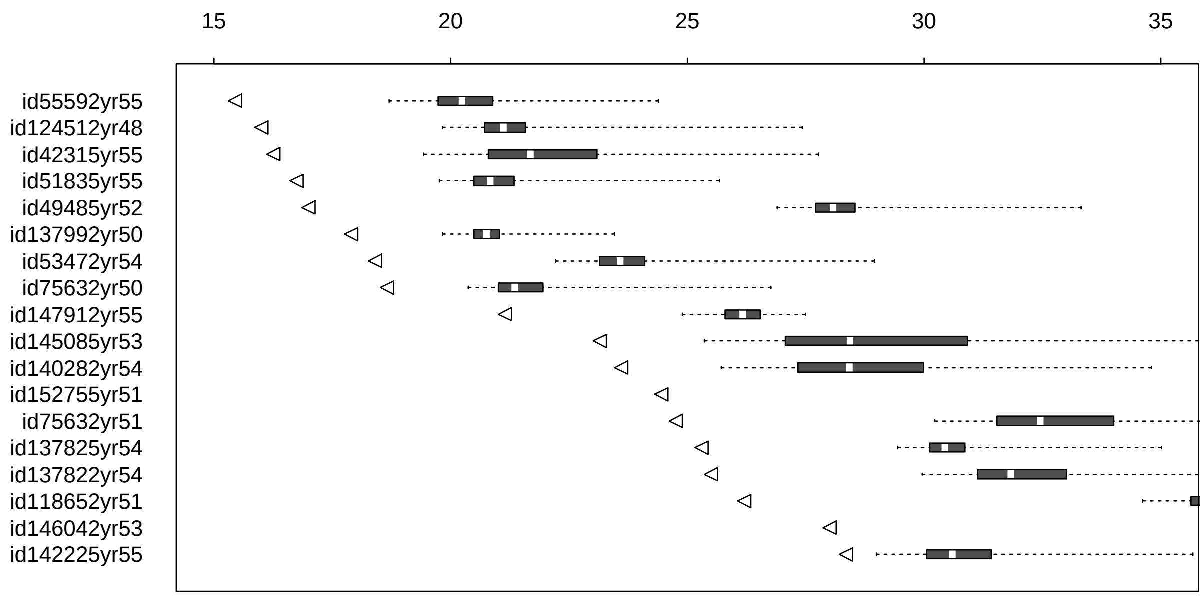


Fig. 9. Boxplots of yearly dose distribution estimates and the corresponding dose of record (mSv) for the *Data Plus* **scenario.**





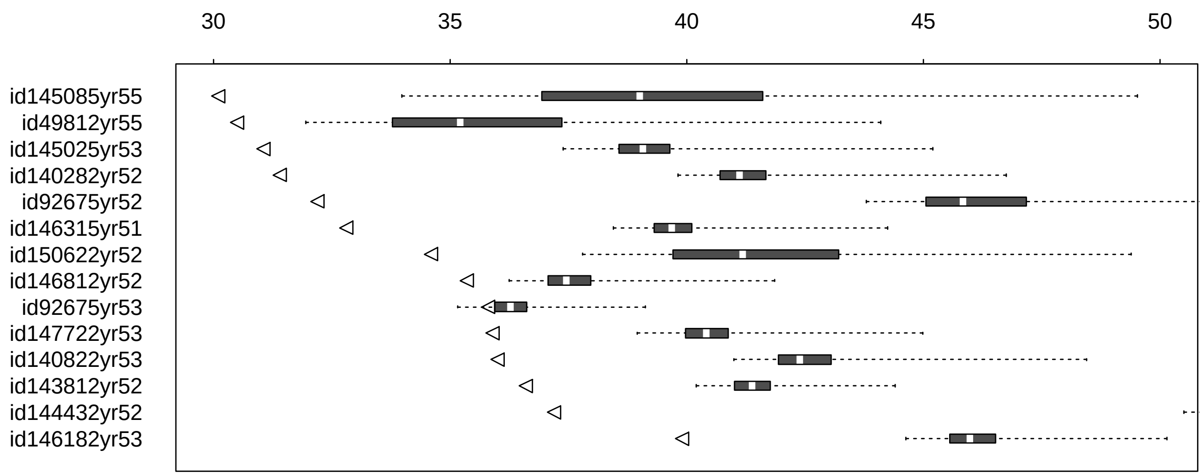


Fig. 10. Boxplots of yearly dose distribution estimates and the corresponding dose of record (mSv) for the ***Data Plus*** **scenario, continued.**

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 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:

- `id112812yr50` increase. (see Figs. 5, 7, and 9, top line).
- `id142212yr49` decrease. (see Figs. 5, 7, and 9, line 14 from bottom).
- `id149412yr53` decrease. (see Figs. 5, 7, and 9, bottom line).
- `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. (see Figs. 6, 8, and 10, top line).

5.3 Summary

It is evident from the results presented in this section that bias in the dose of record (the most likely *Data Plus* scenario) is substantial, it is negative, and its magnitude is highly variable. Since the bias magnitude has little correlation with the dose of record, the information in the daily PM data is necessary for a valid adjustment.

The dose of record is often considered to be the "gold standard" for dose risk estimation, especially if compared to studies where only "area" sensor data is available. Perhaps as a result, typical use of the data ignores any possible uncertainty that may be present, and significance tests are based on an assumption of exact data. The uncertainty results of this section show that when the more detailed daily data is considered, the uncertainty can increase as well as decrease. Usually, the increase is due to conflicting or incomplete data. Also, the uncertainty has little correlation with the dose of record, suggesting again that the information in the daily PM data is needed for a valid assessment of uncertainty.

It is also possible that the true bias and uncertainty are further understated if frequent anecdotal reports that film badges and pocket meters were sometimes taken off to "take a closer look" are true. For example, concluding remarks in report [5] suggest that a climate to keep reported dose low did exist. One could argue that the likelihood of being "reassigned" away from usual work location and usual colleagues would be a psychological factor potentially contributing to underreporting of actual dose.

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 Section 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 in hard copy form at ORNL (30,000 person years) is about 65 person years of effort. Clearly, this is a monumental task if undertaken with the same technology used 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 detailed information has a strong impact on both bias and uncertainty in individual dose estimates. 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 dose-response analyses.

References

[1] George E. P. Box and George C. Tiao. *Bayesian Inference in Statistical Analysis*. Addison-Wesley Pub. Co., 1973. Wiley Classics Library edition published 1992.

[2] A. C. Brown and C. B. MacDonald, editors. *The Secret History of the Atomic Bomb*. Dial Press/James Wade, New York, 1977.

[3] E. Cardis and J. Estéve. Uncertainties in recorded doses in the nuclear industry: identification, quantification and implications for epidemiological studies. *Radiat. Prot. Dosim.*, 36(2/4):315–319, 1991.

[4] D. M. Davis, E. D. Gupton, and J. C. Hart. Applied health physics radiation survey instrumentation. Technical Report ORNL-332 (1st Rev.), Oak Ridge National Laboratory, January 1 1954.

[5] W. F. Elkin and J. C. Hart. A statistical study of the 2-pocket meter system. Technical Report internal, Oak Ridge National Laboratory, Health Physics Division, June 28 1949. An unpublished internal report.

[6] E. L. Frome, D. L. Cragle, J. Watkins, S. Wing, C. Shy, W. Tankersley, and C. M. West. A mortality study of employees of the nuclear industry in Oak Ridge, Tennessee. *Radiat. Res.*, 148:64–80, 1997. (see also http://www.epm.ornl/ frome/ORMS).

[7] Wayne A. Fuller. *Introduction to Statistical Time Series*. John Wiley & Sons, 1976.

[8] Wayne A. Fuller. *Measurement error models*. John Wiley & Sons, Inc., New York, 1987.

[9] M. D. Garris, J. L. Blue, G. T. Candela, P. J. Grother, S. A. Janet, and C. L. Wilson. Form-based handprint recognition system (release 2.0). Technical Report NISTIR 5959, National Institute of Standards and Technology, January 1997.

[10] E. S. Gilbert. Accounting for bias and uncertainty resulting from dose measurement errors and other factors. Technical Report PNL-SA-18907, Pacific Northwest Laboratory, Richland, WA 99352, February 1990.

[11] E. S. Gilbert, S. A. Fry, L. D. Wiggs, G. L. Volez, D. L. Cragle, and G. R. Petersen. Analyses of combined mortality data on workers at the Hanford Site, Oak Ridge National Laboratory, and Rocky Flats Nuclear Weapons Plant. *Radiat. Res.*, 120:19–35, 1989.

[12] J. C. Hart. A progress report dealing with the derivation of dose data from ORNL personnel exposure records applicable to the Mancuso study. Technical Report ORNL/M-2614 (formerly, ORNL CFM 66-1-84), Oak Ridge National Laboratory, Oak Ridge, TN, 37831, January 14 1966.

[13] G. D. Kerr, R. H. Ritchie, S. V. Kaye, and J. S. Wassom. History of the Health and Safety Research Division at Oak Ridge National Laboratory. Technical Report ORNL/M-2108, Oak Ridge National Laboratory, Oak Ridge, TN, 1992.

[14] George D. Kerr. Missing dose from mortality studies of radiation effects among workers at Oak Ridge National Laboratory. *Health Phys.*, 66:206–208, 1994.

[15] G. W. Kneale, T. Sorahan, and A. M. Stewart. Evidence of biased recording of radiation doses of Hanford workers. *Am. J. Ind. Med.*, 20:799–803, 1991.

[16] Bernard W. Lindgren. *Statistical Theory*. Chapman & Hall, fourth edition, 1993.

[17] Fred C. Maienschein and R. W. Peelle. Radiation dosage estimation and health risk. *JAMA*, 267:929, 1992.

[18] G. Miller, W. C. Inkret, and H. F. Martz. Bayesian detection analysis for radiation exposure. *Radiation Protection Dosimetry*, 48(3):251–256, 1993.

[19] G. Miller, W. C. Inkret, and H. F. Martz. Bayesian detection analysis for radiation exposure, II. *Radiation Protection Dosimetry*, 58(2):115–125, 1995.

[20] Toby J. Mitchell, George Ostrouchov, Edward L. Frome, and George D. Kerr. A method for estimating occupational radiation dose to individuals, using weekly dosimetry data. *Radiation Research*, 147:195–207, 1997.

[21] K. Z. Morgan. Dosimetry requirements for protection from ionizing radiation. In *Selected Topics in Radiation Dosimetry*, pages 3–23. Vienna: International Atomic Energy Agency, IAEA Proceedings Series, 1961.

[22] K. Z. Morgan. Techniques of personnel monitoring and radiation surveying. In A. H. Snell, editor, *Nuclear Instruments and Their Uses*, volume 1, pages 391–469. John Wiley & Sons, 1962.

[23] K. D. Nichols. *The Road to Trinity: A Personal Account of How America's Nuclear Policies Were Made*. William Morrow and Company, New York, 1987.

[24] Daniel J. Strom. Estimating individual and collective doses to groups with 'less than detectable' doses: A method for use in epidemiologic studies. *Health Phys.*, 51(4):437–445, 1986.

[25] N. A. Taylor. Estimation of dose received when dosemeter results are recorded below a threshold level. *J. Radiol. Prot.*, 11(3):191–198, 1991.

[26] The Numerical Algorithms Group. *NAG Fortran Library, Mark 18.* Oxford, UK, 1997.

[27] J. P. Watkins, D. L. Cragle, E. L. Frome, C. M. West, D. J. Crawford-Brown, and W. G. Tankersley. Adjusting external doses from the ornl and y-12 facilities for the oak ridge nuclear facilities mortality study. Technical Report ORISE 94/G-34, Oak Ridge Institute for Science and Education, Oak Ridge, TN 37831-0117, 1994.

[28] R. H. Wilson, W. V. Baumgartner, J. J. Fix, and L. L. Nichols. Description and evaluation of the hanford personnel dosimeter program from 1944 to 1989. Technical Report PNL-7447, Pacific Northwest Laboratory, Richland, WA, 1990.

[29] S. Wing, C. M. Shy, J. L. Wood, S. Wolf, D. L. Cagle, and E. L. Frome. Mortality among workers at Oak Ridge National Laboratory: Evidence of radiation effects in follow-up through 1984. *JAMA*, 265:1397–1402, 1992.

[30] S. Wing, C. M. Shy, J. L. Wood, S. Wolf, and D. L. Cragle. Reply to comments by Maienschein and Peelle. *JAMA*, 267:929–930, 1992.

[31] S. Wing, C. M. West, J. L. Wood, and W. Tankersley. Recording of external radiation exposures at Oak Ridge National Laboratory: Implications for epidemiologic studies. *J. Exposure Analysis and Environmental Epidemiology*, 4(1):83–93, 1994.

[32] Steve Wing, Carl M. Shy, Joy L. Wood, Susanne Wolf, Donna L. Cragle, William Tankersley, and E. L. Frome. Job factors, radiation and cancer mortality at Oak Ridge National Laboratory: Follow-up through 1984. *Am. J. Ind. Med.*, 23:265–279, 1993.

INTERNAL DISTRIBUTION

1-2. G. Ostrouchov
3-4. E. L. Frome
5. G. D. Kerr
6. C. K. Bayne
7. B. A. Worley
8. T. Zacharia
9. Central Research Library
10. ORNL Laboratory Records**B**RC
11. ORNL Laboratory Records**B**OSTI

EXTERNAL DISTRIBUTION

12. B. G. Brooks, U.S. Department of Energy, EH-6, 19901 Germantown Road, Germantown, Maryland 20874

13. H. G. Stockwell, U.S. Department of Energy, EH-6, 19901 Germantown Road, Germantown, Maryland 20874

14. P. Wambach, U.S. Department of Energy, EH-6, 19901 Germantown Road, Germantown, Maryland 20874

15. D. F. Utterback, NIOSH, 4676 Columbia Parkway, Cincinnati, Ohio 45226