AN APPROACH TO EVALUATING BIAS AND UNCERTAINTY IN ESTIMATES OF EXTERNAL DOSE OBTAINED FROM PERSONAL DOSIMETERS

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***Abstract*—This paper describes an approach to quantifying errors in recorded estimates of external radiation dose obtained from personal dosimeters and applies the approach to dose estimates of workers at the Hanford site. Because a major objective of this evaluation is to provide the information needed for adjusting epidemiologic dose-response analyses of worker data for errors in dose estimates, the paper addresses the extent that errors for different workers are correlated, focuses on recorded doses as estimates of organ doses, and gives consideration to both annual and cumulative doses. The evaluation emphasizes errors resulting from the fact that dosimeters are limited in their ability to respond accurately to all radiation energies to which workers are exposed or to radiation coming from all directions. For each of several sources of error, systematic bias factors are estimated for two energy ranges (100–300 keV and 300–1,000 keV), two geometries (anterior-posterior and rotational), and four calendar year periods. These are then combined using information provided by health physicists on energies and geometries in Hanford exposure environments. Except for the period before 1958, deep dose, the objective of modern dosimetry systems, was found to be fairly accurately estimated. Lung dose was found to be overestimated by about 10%, and bone marrow dose was found to be overestimated by about 50%. However, many aspects of this evaluation relied heavily on subjective judgments, and, thus, these factors are subject to considerable uncertainty. Estimates of uncertainty in the bias factors and uncertainty reflecting random error are provided.**
Health Phys. 70(3):336–345; 1996

Key words: dose, organ; dosimetry; nuclear workers; dosimetry, external

INTRODUCTION

ESTIMATES of external radiation dose, obtained from personal dosimeters, are used in epidemiologic studies of nuclear workers (Cardis et al. 1995; Gilbert 1991a; IARC 1994), including a mortality study of Hanford workers (Gilbert et al. 1993). A major objective of these studies is to provide a direct assessment of the carcinogenic risk of exposure to ionizing radiation at low doses and dose rates. Accomplishing this objective includes estimating risks per unit of dose and comparing these estimates with those that serve as the basis for radiation protection standards, which have been obtained by extrapolation from data on persons exposed at high doses and dose rates such as the Japanese atomic bomb survivors.

In this paper, an approach for quantifying errors in estimates of external dose is developed and applied to workers at the Hanford site. Although results from this paper may be useful for a variety of purposes, the assessment is aimed primarily at providing the information needed for adjusting epidemiologic analyses of worker data for errors in dose estimates. This affects the evaluation in several ways. First, the paper addresses the extent that errors in dose estimates for individual workers are correlated; this is accomplished by categorizing errors as random errors (where the errors primarily reflect variability among workers and are independent for measurements from different workers) and systematic errors or bias (where there is uncertainty in the magnitude of the bias). Random and systematic errors would be treated differently in statistical analyses that adjust for dose measurement error. Second, because risk estimates from high dose studies have been expressed in terms of absorbed dose to various organs, in evaluating bias, the paper focuses on bias in recorded doses as estimates of organ doses, although deep dose (energy absorbed at a depth of one cm in tissue), the objective of current dosimetry systems, is also considered. Finally, although the paper focuses on errors in annual doses, consideration is given to developing reasonable assumptions for evaluating errors in the cumulative doses that have been used in epidemiologic analyses. It is beyond the scope of this paper to describe how this information might be used in epidemiologic analyses, but interested readers are referred to Prentice (1982), Pierce et al. (1990), Armstrong (1990), Gilbert (1991b), Clayton (1992), and Thomas et al. (1993).

The evaluation focuses on errors resulting from the fact that dosimeters, especially those used in early periods of plant operation, were limited in their ability to respond accurately to all radiation energies to which workers were exposed or to radiation coming from all directions. Hanford workers were exposed under a wide

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Manuscript received 6 March 1995; revised manuscript received 27 June 1995, accepted 7 September 1995.
0017-9078/96/$3.00/0

range of conditions (energies and geometries), and errors from many sources depend on these conditions. Because the specific energy and geometry associated with any given recorded exposure is not known, and because there is uncertainty even in the "average" exposure conditions that existed in various time periods, energy and geometry dependence may be the most important source of both random and systematic error in Hanford dose estimates.

This paper does not address sources of error that primarily affect dose estimates of workers with limited potential for radiation exposure, including laboratory-measurement error and error resulting from problems related to the use of minimum detectable levels (Inskip et al. 1987). It is workers with large cumulative doses who are most influential in dose-response analyses, and Gilbert and Fix (1995) have shown that, for the Hanford data, such analyses are fairly insensitive to assumptions about biases in very low doses.

This paper is an abbreviated version of a technical report (Fix et al. 1994) that provides additional detail, particularly with regard to technical aspects of dosimetry.

METHODS

General approach for quantifying and combining bias and uncertainty

The approach developed in this paper can be considered as an elaboration of the methods used to quantify bias and uncertainty in estimated doses for personnel exposed to radiation as a result of atmospheric testing of nuclear weapons between 1945 and 1962 (NAS/NRC 1989). These methods were developed by the National Research Council (NRC) Committee on Film Badge Dosimetry in Atmospheric Tests (hereafter referred to as "the NRC committee") and involved quantifying both bias and uncertainty from each of several specified sources and then combining them to obtain an overall assessment.

The NRC committee's assessment and ours are based on the assumption that errors from individual sources follow independent lognormal distributions. For each error source i, the systematic error is quantified by determining a bias factor B_i, where B_i is defined as the ratio of the recorded dose to the "true" or desired measure of dose. The overall bias from all sources is the product, B, of the B_i from all sources, and B is the factor by which one would divide the recorded dose to obtain an unbiased estimate of the true or desired measure of dose. The determination of the factors B_i is made based on evaluation of relevant data and on expert judgment.

Because the B_i are not known with certainty, and because dose estimates for individual subjects involve random as well as systematic error, 95% uncertainty factors K_i, based on the assumption that uncertainties follow independent lognormal distributions, are also provided. In the NRC assessment, these factors were determined so that the probability was judged to be 95% that the intervals obtained by respectively dividing and multiplying by them would include the true value. The lognormal distribution was chosen largely for convenience, but given the subjective nature of the evaluation of uncertainty from most sources, there was no strong reason to prefer alternative distributions. Because the uncertainty factors were evaluated subjectively, it may be more appropriate to use Bayesian terminology and refer to these intervals as credibility intervals rather than confidence intervals. We also estimate 95% uncertainty factors with similar interpretations, but attempt to separate "random" and "systematic" components of uncertainty as discussed in the section that follows. Data that would allow rigorous determination of uncertainties were not available, and thus the uncertainty factors reflect subjective judgments of the authors. Overall uncertainty factors for all error sources are obtained through lognormal propagation of errors (NAS/NRC 1989; Aitchison and Brown 1969).

Random vs. systematic errors

In order to use the results of this evaluation in epidemiologic dose-response analyses, it is necessary not only to quantify errors in dose estimates for individual workers, but also to indicate the extent to which these errors are correlated for different workers. For this purpose, it is useful to separate errors into two categories as follows: *random errors,* where errors are considered as "random" or independent for measurements from different workers, and *systematic errors,* where error consists of a systematic bias that is the same for a specified group of workers but where there may be uncertainty in the magnitude of the bias. One might also consider random errors as reflecting variability in errors among workers, and systematic errors as reflecting uncertainty in the underlying parameters of the model describing bias. Although this is an over-simplification (to the extent that errors fall in between these two extremes), most errors can reasonably be placed in one of these categories, and it should be feasible to incorporate separate treatment of random and systematic errors into epidemiologic analyses (Gilbert 1991b). For many error sources evaluated in this paper, the error is best characterized as systematic error or bias, and it is primarily this component that has been quantified. However, sources of random error are also noted, and an approach for quantifying random error resulting from variation in energy levels and geometry is developed.

To state more rigorously the above concept, suppose there is a population of N workers with estimated doses Z_k and true doses X_k ($k = 1, \ldots, N$). Let $x_k = \log X_k$, $z_k = \log Z_k$, and let i index sources of error. A possible statistical model for these doses is

$$z_k = x_k + \Sigma_i(b_i + u_{ik}), \qquad (1)$$

where i indexes sources of error that are assumed to be independent, the b_i are constants reflecting bias (about which there may be uncertainty), the u_{ik} are random variables such that the mean for all workers is zero and such that u_{ik} and $u_{ik'}$ are independent for $k \neq k'$. If it is assumed that the b_i and u_{ik} are approximately normally distributed and independent for different error sources, then the estimated doses Z_k follow approximate lognormal distributions. These distributions are characterized by bias factors $B_i = \exp(b_i)$, 95% uncertainty factors K_{iS}, which quantify the uncertainty in the B_i, and K_{iR}, which quantify the random errors u_{ik}. In general, the K_{iS} quantify the uncertainty regarding how well the estimated bias factors B_i are known, while the K_{iR} quantify the variability in errors among workers.

Sources of error

The first source of error identified by the NRC committee was laboratory error including all errors introduced in film calibration, chemical processing, reading of optical densities, etc. A second source was identified as radiological error. This source was subdivided into spectrum (the failure of the dosimeter to respond accurately to all radiation energies to which personnel were exposed), wearing (the failure of a dosimeter worn on the torso to respond accurately to exposure coming from all directions), and backscatter (the overestimation that occurs when calibration is conducted in air rather than on phantom). The third source was environmental error including all errors associated with the consequences of light, moisture, high temperatures, etc., associated with the field environment. A fourth source of error was that resulting from converting recorded measurements to estimates of deep dose.

These same sources of error are considered in this paper. However, because of the nature of certain experimental data, the source referred to as "spectrum" by the NRC committee has been combined with conversion of recorded measurements to deep dose, and this source is referred to as "energy response." Also, the term "angular response" is substituted for the source designated as "wearing" by the NRC committee. In addition, we evaluated recorded measurements not only as estimates of deep dose, but also as estimates of red bone marrow and lung dose. Particular emphasis is given to radiological errors. These errors tend to depend strongly on energy and geometry and are especially important in studies of workers, where there is substantial variation in exposure conditions.

Laboratory errors are discussed only briefly, although further work to quantify these errors is planned. For single dosimeter readings, which were the primary concern of the NRC committee, the most important laboratory error, especially for estimating small doses, was that resulting from variation in individual dosimeter responses about a calibration curve. Because such errors should be independent for different readings for the same worker, it is unlikely that this is an important source of error for larger cumulative dose estimates that are usually the sum of dozens of individual dosimeter results. It is these larger doses that are most influential in epidemiologic dose-response analyses.

Environmental errors are also given only limited attention. In the NRC evaluation, this error source was of importance primarily for dose estimates of participants in nuclear tests conducted on islands in the Pacific ocean.

Dependence of bias and uncertainty on the dosimetry system or calendar year period

Dosimetry practices at Hanford changed over time as technology evolved, and the personnel dosimeter programs in effect during various time periods have been described in detail by Wilson et al. (1990). The initial dosimeter used at Hanford starting in 1944 was a film badge dosimeter developed at the University of Chicago (Wilson 1987), and, at this time, dosimeters were exchanged weekly or bi-weekly. Major upgrades in the dosimeter program occurred in 1957–58 and in 1972. In 1957, an improved multi-element film badge dosimeter was introduced that allowed significant improvement in the measurement of low energy photons that would previously have been missed, and, in 1958, the frequency of dosimeter exchange was changed to monthly. In 1972, thermoluminescent dosimeters replaced film badges, a change that was particularly important in measuring dose from exposure to neutrons. An additional change was that, in 1984, "on phantom" calibration of dosimeters replaced "in air" calibration. Because of the different capabilities of dosimeters used in different time periods, separate evaluations are presented for the periods 1944–1956, 1957–1971, and 1972–1983, 1984–1993.

Dependence of bias and uncertainty on energy and geometry

Bias resulting from several of the sources evaluated depends strongly on the energy of the radiation and the direction from which it was received (geometry). Because of the variety of research and production activities that have been conducted at the Hanford site, workers have been exposed in diverse radiation environments involving a much greater range of energies and geometries than was the case for nuclear test participants evaluated by the NRC committee (1989). The Hanford complex includes uranium fuel fabrication facilities, reactors for the production of plutonium, facilities for the separation and finishing of plutonium, and extensive research and development facilities. Additional detail on Hanford exposure environments is provided by Fix et al. (1994) and by Wilson et al. (1990).

Although the type and general energy range of radiation for each of the various Hanford work environments is known, measurement of the exact energy spectra for each type of radiation (i.e., beta, photon, and neutron) in the relatively complex and diverse fields in Hanford facilities has generally not been done, and thus precise characterization of energies in various environments is not available. General information on the geometry of exposure in various environments is also available, but, again, it is not possible to characterize geometries precisely. For this reason, there would be uncertainty regarding energy levels and geometries even if it were possible to identify the facility and type of work associated with each exposure. In fact, for any specific exposure, the facility and type of work being performed is not generally known, and this limitation adds substantially to the error associated with energy levels and geometry.

The dependence on energy and geometry has been handled in two ways. First, the evaluation in this paper is restricted to workers exposed primarily to higher energy (≥ 100 keV) photons. This form of exposure is judged to contribute the vast majority of recorded dose for Hanford workers with dose from neutron radiation and lower energy x rays making a significant contribution only for the relatively few workers involved in plutonium separation activities (Wilson et al. 1990). A method for identifying these workers has been developed so that these workers can be excluded from some epidemiologic analyses if desired (Gilbert and Fix 1995).

Second, for sources that depend strongly on energy and/or geometry, a separate evaluation was made for two energy ranges and two geometries. The energy ranges were 100 to 300 keV, and 300 to 1,000 keV. The two selected geometries were anterior-posterior, where radiation is directed from the front to the back of the body, and rotational, where uniform irradiation occurs from the front, back, and sides. Bias and uncertainty factors for each source were determined and combined for each energy-geometry combination. An advantage of this approach is that in some cases the relative bias for different energy-geometry combination is in different directions for different sources, and thus "cancels out" to some extent when sources are combined, reducing the dependence of the bias factors on energy and geometry.

Based on any assumed distribution of the four energy-geometry combinations evaluated in this report, an overall bias factor can be obtained as a weighted geometric mean of the four energy-geometry specific bias factors. Because energy and geometry vary among workers, and because even the "average" energy-geometry distribution is uncertain, the obtained overall bias factor is subject to both the uncertainty in its average value and that reflecting variation among workers. Health physicists with experience in Hanford's historical dosimetry program are the main resource for information on distributions of energy levels and geometries in Hanford radiation environments, and at the end of the Results section, we use specific information provided by four such health physicists to estimate overall bias and its associated uncertainties.

For application in epidemiologic analyses, it would be necessary to combine the systematic uncertainty resulting from energy and geometry dependence with systematic uncertainties from other sources. Provided these latter factors do not depend strongly on energy and/or geometry, this is straightforward. As will be seen later, some uncertainties are larger for the rotational than for the anterior-posterior geometry; as an approximation, this situation can be handled by using an intermediate uncertainty, or by conducting epidemiological analyses based on more than one choice of uncertainty factor.

Bias and uncertainty in cumulative dose

The NRC committee report emphasized the errors in dose estimates obtained from readings of single dosimeters. Computerized dose estimates for Hanford workers are available only on an annual basis, although the annual dose was usually obtained as the sum of several individual results. Uncertainty factors given in this paper are intended to apply to estimates of annual dose.

Analyses of data from the Hanford mortality study have been based on cumulative dose, which in many cases was received over many years and was estimated as the sum of estimates from many dosimeters. The relationship of uncertainties in cumulative dose estimates, annual dose estimates, and single dosimeter dose estimates depends on the extent to which different measurements for the same worker are correlated. To the extent that workers remain in the same jobs in the same locations, random error from sources that depend on energy levels and geometry can be expected to remain fairly constant over time for a given worker, and thus will be highly correlated for different calendar years. In this case, the random uncertainty in the cumulative dose will be similar to that in the annual dose. To the extent that work environments change and that workers change jobs and habits, these random uncertainties will not be perfectly correlated over time. In this case, some "canceling out" occurs, and the relative uncertainty in cumulative dose is less than the uncertainty in annual doses. Errors that exhibit little correlation for different measurements for the same worker (for example, laboratory uncertainties) are not likely to be very important for cumulative doses received over many years.

As noted above, different dosimetry systems were in use for the periods 1944–56, 1957–71, and 1972–89, and bias and uncertainty factors thus depend on the calendar year period. The application of different bias factors for different time periods is straightforward, but accounting for differential systematic uncertainties is more difficult. A possible approximation would be to use the uncertainty factor associated with the period in which most of the exposure occurred. In adjusting epidemiologic analyses, it may be feasible to assign different uncertainties for contributions from different periods and make various assumptions about the correlation across time periods. Systematic uncertainties in different dosimetry systems are unlikely to be perfectly correlated, and, for this reason, the overall systematic uncertainty in cumulative doses that include contributions from more than one of these periods may be less than that for the individual periods.

RESULTS

The sources of error described above were evaluated for each of the three specific Hanford dosimetry systems [i.e., Hanford two-element film dosimeter, 1944–56; Hanford multi-element film dosimeter, 1957–71; and Hanford multi-element thermoluminescent dosimeter (TLD), 1972–1993]. Results are summarized in Table 1. The technical basis for quantifying the bias from each source is described in detail by Fix et al. (1994), and is briefly summarized below. The systematic uncertainty factors shown in Table 1, which are for specific energy-

Table 1. Summary of bias (B) and systematic uncertainty factors (K_S) by error source.[a]

Error source	Bias (systematic uncertainty factor)		
	1944–89		
Laboratory	1.0 (1.0)		
Energy response	1944–56	1957–71	1972–89
Anterior-posterior			
100–300 keV	1.60 (1.3)	0.64 (1.2)	0.87 (1.1)
300–1,000 KeV	1.00 (1.3)	1.00 (1.2)	1.00 (1.1)
Rotational			
100–300 keV	3.00 (1.4)	1.20 (1.3)	1.64 (1.2)
300–1,000 keV	1.46 (1.4)	1.46 (1.3)	1.46 (1.2)
Angular response	*1944–89*		
Anterior-posterior	1.0 (1.0)		
	1944–56	1957–71	1972–89
Rotational			
100–300 keV	0.71 (1.4)	0.65 (1.3)	0.63 (1.4)
300–1,000 keV	0.68 (1.4)	0.73 (1.3)	0.76 (1.4)
Backscatter	*1944–83*	*1984–89*	
	1.1 (1.2)	1.0 (1.1)	
Environmental	1944–89		
	1.0 (1.1)		
Conversion to organ dose	Red bone marrow	Lung	
Anterior-posterior			
100–300 keV	2.0 (1.2)	1.2 (1.2)	
300–1,000 KeV	1.63 (1.2)	1.13 (1.2)	
Rotational			
100–300 keV	1.0 (1.2)	0.89 (1.2)	
300–1,000 keV	1.0 (1.2)	0.93 (1.2)	

[a] Entries are bias factors (B), with systematic uncertainty factors (K_S) given in parentheses. The bias factors are defined as the ratio of the recorded dose to the "true" or desired measure of dose. By multiplying and dividing by the 95% uncertainty factors K_S, 95% credibility intervals may be obtained.

geometry combinations, were based on the judgment of the authors, and were usually judged to be largest for earlier calendar years when documentation was not as complete as for recent dosimetry systems. The most important random error is judged to be that due to variation by energy and geometry and is discussed at the end of this section. Other random errors, applying to specific sources, are noted in the material below, and in most cases were judged to be relatively unimportant.

Laboratory error

No significant bias is expected from laboratory sources, and it was not judged necessary to allow for systematic error from this source. Because laboratory errors are not highly correlated across time, it is unlikely that this is an important source of random error for workers with larger doses that have been accumulated over many years.

Radiological errors

To supplement historical data in evaluation of two of the radiological errors energy and angular response, a laboratory study was conducted in 1993. This study, which is described in detail by Fix et al. (1994), was conducted primarily because it was not possible to locate adequate historical data for evaluating bias from body wearing position although it was known that angular response data were measured and published (Little 1968). In addition to measuring angular response, the radiation sources used in this experiment were also used to evaluate bias resulting from energy response. Although historical data on this latter source of bias were available, it was of interest to confirm earlier results and to use the same energy sources that were used to measure angular response.

For this laboratory study, Hanford multi-element film and thermoluminescent dosimeters were exposed to filtered x-ray beams of M150 (effective energy of 70 keV), H150 (effective energy of 120 keV and representing energies in the 100–300 keV range), and gamma radiation from ^{137}Cs (mono-energetic energy of 662 keV and representing energies in the 300–1,000 keV range). These sources of exposure typify the dosimeter response under actual field conditions. Even though the evaluation in this paper is restricted to photon energies of 100 keV or larger, the lower energy x-ray source (M150) was included to better measure the significant dependence in dosimeter response that occurs as photon energies become progressively lower. The original two-element film dosimeter, used from 1944–56, was not included in these measurements because the response of one component of the multi-element dosimeter could be used to approximate the response of this dosimeter.

Energy response. Both film dosimeters and TLDs may respond inaccurately at certain photon energies, leading to bias in estimated doses. The design of Hanford dosimeter holders and the use of metallic filters were intended to minimize the effect of photon energy on the response, but, especially with the earliest dosimeter, bias was still present. Table 1 shows the estimated factors for bias and systematic uncertainty.

The estimation of bias from this source was based on the laboratory experiments described above and on historical data (Wilson et al. 1990), which indicate the ratio of recorded dose to exposure in R[†] as a function of photon energy. Published factors for converting exposure in R to deep dose (ICRP 1987; ICRU 1988) are available and these are shown in Table 2; these were used in combination with the historical data to determine the bias in recorded dose as an estimate of deep dose for the two geometries and several photon energy levels. Both the current laboratory data and historical data gave similar values, and historical values did not vary greatly within the range 100–300 keV or within the range 300–1,000 keV.

Historical data on the relationship between recorded dose and exposure in R were available only for the anterior-posterior geometry. To obtain the needed information for the rotational geometry, it would have been necessary to conduct laboratory experiments investigat-

[†] The Roentgen (R) is defined as a unit of *exposure* to photon (i.e., gamma or x rays) radiation. An exposure of 1 R is approximately equivalent to an absorbed dose of 1 rad or a deep dose (equivalent) of 1 rem in tissue for higher energy photon radiation. Also see material in the subsection entitled "Conversion to organ doses."

Table 2. Ratios of various measures of dose for the anterior-posterior (AP) and rotational (R) geometries by photon energy.

Photon energy (keV)	Ratio of exposure to deep dose equivalent[a]		Ratio of deep dose equivalent to red bone marrow dose[b]		Ratio of deep dose equivalent to lung dose equivalent[c]	
	AP	R	AP	R	AP	R
100	0.70	1.30	2.19	1.01	1.26	0.88
200	0.82	1.43	1.88	0.96	1.20	0.89
400	0.91	1.44	—	—	—	—
500	—	—	1.68	1.00	1.14	0.92
600	0.96	1.43	—	—	—	—
800	0.99	1.41	—	—	—	—
1000	1.00	1.39	1.52	1.00	1.11	0.94

[a] Determined from Tables 2, 3a, and 6 of ICRP Report 51 (1987).
[b] Determined from Tables C.1 and 6 of ICRP Report 51 (1987).
[c] Determined from Tables C.1 and 6 of ICRP Report 51 (1987).

ing the relationship between recorded and deep dose at several angles, and this was not feasible. Thus, for the rotational geometry, it was necessary to assume that the relationship between recorded dose and exposure in R was the same as that for the anterior-posterior geometry. Additional systematic uncertainty is allowed for bias arising from energy response with the rotational geometry.

Angular response. Dosimetry systems, including those used at Hanford, are usually calibrated for the anterior-posterior geometry, that is, under the assumption that the dosimeter is worn on the front of the torso, and that exposure is directed from the front to the back. If exposure comes from other directions, and also if dosimeters are not worn in the correct position, the estimated dose may be biased.

For the vast majority of Hanford personnel the bias from angular response would be intermediate between that resulting with the anterior-posterior geometry (no bias) and that resulting with the rotational geometry. The anterior-posterior geometry is most applicable to work with discrete sources of radiation, maintenance of equipment, etc., where the worker generally faces the source of exposure. The rotational geometry is most applicable to worker exposure within the large Hanford reactor, reprocessing, and waste handling facilities where there are elevated levels of ambient exposure in many areas.

As noted above, historical data on bias from this source could not be located, and thus a laboratory study was conducted. Specifically, measurements of the angular response of Hanford multi-element film and thermoluminescent dosimeters were conducted using an anthropomorphic phantom to best simulate the response for actual worker exposures. Exposure angles of 0°, ±45°, ±90°, ±135°, and 180° were used. To estimate the effect of the rotational geometry on dosimeter response, an evenly weighted average of dosimeter results for all exposure angles was calculated. These results, which are shown in Table 1, indicate that deep dose was underestimated by 25–35% with the rotational geometry.

Backscatter. Hanford dosimeters were calibrated "in-air" until 1984 when "on-phantom" calibration was introduced. The "in-air" practice had the effect of overestimating the calibration factor because dosimeter response from secondary photon scatter from a phantom was eliminated. Measurements conducted with the TLD in preparation for implementing the "on-phantom" calibration procedure in 1984 indicated previous "in-air" exposure geometry had overestimated deep dose by about 10%. The effect was judged to be nearly constant across energy levels, and to be similar for film badges and TLDs since all Hanford dosimeters had nearly identical filters on both the front and back side.

Environmental errors

This category includes all errors related to the field environment such as the consequences of exposure of dosimeters to moisture, light, high temperatures, chemicals, handling, etc. Bias from this source would be expected to be relatively insignificant because of efforts made to control such effects, or to compensate for them. The bias factor from this source was taken to be 1.0 with systematic uncertainty in the annual recorded dose estimated to be 1.1. Because environmental error is not likely to be highly correlated for different dosimeter readings for the same worker, the error in doses accumulated over many years is likely to be even smaller.

Conversion to organ doses

For the purpose of comparing risk estimates based on studies of workers with those based on studies of populations exposed at high doses, it is organ doses that are of greatest interest. Tables are available in the scientific literature (ICRP 1987; ICRU 1988) that provide factors for converting deep dose to doses to various organs. These relationships, which depend on both energy and geometry, are based on computer calculations using the ICRU 30 cm diameter sphere and the effective dose equivalent on an anthropomorphic phantom for different photon energies and exposure geometries. Table 2 shows the respective relationship between deep dose and bone marrow dose, and deep dose and lung dose, (as well as the relationship between exposure and deep dose noted earlier). Because these factors were derived by others, it is difficult to assign uncertainty factors, but we have arbitrarily assigned a systematic uncertainty factor of 1.2. In addition, random error would result from variation in body size and shape; this would be independent across workers, but would be highly correlated for different readings for the same workers.

Combined bias and uncertainty for specific energies and geometries

Bias and uncertainty factors from the individual sources discussed above were combined as described in the Methods section of this paper, and the factors for estimating deep dose, red bone marrow dose, and lung dose are shown in Table 3. Separate factors are shown for each calendar year period and for each energy-geometry combination.

For higher energy photons (300–1,000 keV), the recorded dose slightly overestimated the deep dose for both the anterior-posterior and the rotational geometries. For lower energy photons (100–300 keV), deep dose was overestimated by a factor of about two before 1958 (primarily due to the energy response of the two-element dosimeter used during this period), but was slightly underestimated in the period 1958–71. In general, for the rotational geometry, the overestimation of deep dose resulting from energy response tended to cancel out the underestimation resulting from angular dependence.

From Table 2, it is seen that deep dose slightly overestimated lung dose for the anterior-posterior geometry, and slightly underestimated lung dose for the rotational geometry. Thus, bias in the recorded dose as an estimate of lung dose followed fairly closely the pattern for bias in deep dose. Also from Table 2, it is seen that deep dose was an accurate estimate of red bone marrow dose for the rotational geometry, but overestimated red bone marrow dose substantially for the anterior-posterior geometry. Thus, recorded doses substantially overestimated bone marrow dose for the anterior-posterior geometry and slightly overestimated bone marrow dose for the rotational geometry.

Table 3. Combined bias and uncertainty from several sources[a] in recorded dose as estimates of deep dose, red bone marrow dose, and lung dose by geometry and photon energy.[b]

Geometry and photon energy	1944–56	1957–71	1972–83	1984–89
Deep dose:				
Anterior-posterior				
100–300 keV	1.76 (1.4)	0.70 (1.3)	0.96 (1.2)	0.87 (1.2)
300–1,000 KeV	1.10 (1.4)	1.10 (1.3)	1.10 (1.2)	1.00 (1.2)
Rotational				
100–300 keV	2.34 (1.8)	0.86 (1.5)	1.14 (1.3)	1.03 (1.3)
300–1,000 keV	1.09 (1.8)	1.17 (1.5)	1.22 (1.3)	1.11 (1.3)
Red bone marrow dose:				
Anterior-posterior				
100–300 keV	3.52 (1.5)	1.41 (1.3)	1.91 (1.3)	1.74 (1.3)
300–1,000 KeV	1.79 (1.5)	1.79 (1.3)	1.79 (1.3)	1.63 (1.3)
Rotational				
100–300 keV	2.34 (1.8)	0.86 (1.6)	1.14 (1.4)	1.03 (1.4)
300–1,000 keV	1.09 (1.8)	1.17 (1.6)	1.22 (1.4)	1.11 (1.4)
Lung dose:				
Anterior-posterior				
100–300 keV	2.11 (1.5)	0.84 (1.3)	1.15 (1.3)	1.04 (1.3)
300–1,000 KeV	1.24 (1.5)	1.24 (1.3)	1.24 (1.3)	1.13 (1.3)
Rotational				
100–300 keV	2.09 (1.8)	0.76 (1.6)	1.01 (1.4)	0.92 (1.4)
300–1,000 keV	1.02 (1.8)	1.09 (1.6)	1.14 (1.4)	1.03 (1.4)

[a] The sources included are those shown in Table 1.
[b] Entries are bias factors (B), with systematic uncertainty factors (K_S) given in parentheses. The bias factors are defined as the ratio of the recorded dose to the "true" or desired measure of dose. By multiplying and dividing by the 95% uncertainty factors K_S, 95% credibility intervals may be obtained.

Overall combined bias and uncertainty factors

Because the energy level and geometry associated with a specific recorded dose would not generally be known, to use the results shown in Table 3, the distribution of energy levels and geometries in the Hanford work environment needs to be considered. Based on evaluations of these distributions by Hanford health physicists, we derived overall bias factors for each calendar year period, and also derived factors quantifying both systematic and random uncertainties in these energy-geometry distributions.

Determining these factors was accomplished by using expert judgment to specify "most-likely" distributions of Hanford exposures by both energy level and geometry, and alternative distributions intended to reflect extremes such that the probability that the true overall bias factor falls between these extremes was judged to be 95%. Distributions by geometry and energy level were specified separately and assumed to be independent. For each of the specified distributions, weighted geometric means of the energy-geometry specific bias factors (as shown in Table 3) were calculated. The weighted mean for the "most likely" distribution was then used as the overall estimate of bias, while means associated with the alternative distributions were used to determine an uncertainty factor describing the systematic uncertainty resulting from energy and geometry dependence. The specific application described below may help to clarify this procedure.

Four Hanford health physicists with many years of experience in Hanford's dosimetry program offered subjective estimates of the percentage of dose resulting from energies in the 300–1,000 keV range (with the remainder from energies in the 100–300 keV range). These estimates were 40%, 75%, 80%, and 90% with a mean value of 71% and a median of 77.5%; the value 75% was somewhat arbitrarily chosen as the most likely estimate with a range of 40% to 95% to reflect uncertainty in this average value. The four health physicists also offered estimates of the percentage of dose from the anterior-posterior geometry (with the remainder from a rotational geometry)[‡], and these were 50%, 50%, 70%, and 75% with a mean of 61% and a median of 60%. In this case, the value 60% was chosen as the most likely estimate

[‡] A particular mixture of P% anterior-posterior and (1−P)% rotational can be interpreted as meaning that the geometry is such that the resulting bias factor would be that obtained by taking the corresponding weighted average of the factors from the two geometries.

with a range of 45% to 80% to reflect uncertainty in this average value.

The use of this information for deriving overall bias and uncertainty factors is illustrated in detail for bone marrow dose in the period 1957–71. Table 4 shows the overall bias factors in recorded dose as an estimate of bone marrow dose that would be obtained by weighting (on a logarithmic scale) the energy-geometry specific factors according to several energy-geometry distributions including those described above under the assumption that the distributions (by energy and geometry) are independent. The energy-geometry specific factors were taken from the second column of the section of Table 3 pertaining to bone marrow dose. The estimated overall bias, based on the most likely distribution, was 1.41. The alternative distributions noted in the previous paragraph resulted in the four values 1.20, 1.41, 1.40, and 1.62. The extremes, 1.20 and 1.62, reflect uncertainties of 1.18 (2.41/1.20) and 1.15 (1.62/1.41), and a systematic uncertainty factor of 1.2 was thus selected.

The above distributions apply to the expected "average" for exposure in Hanford facilities, and the alternative distributions reflect only uncertainty in this average value. Because information on energy level and geometry is not available for individual workers, it is of interest, in addition, to develop a random uncertainty factor that expresses the variation in bias that results from variation in energy levels and geometry among workers. This can be accomplished by considering the range of bias factors shown in Table 3. Based on our discussions with Hanford health physicists, the full range from 0.86 to 1.79 was judged to be needed to include 95% of the workers. The ratio 1.79/1.41 = 1.27 while the ratio 1.41/0.86 = 1.64; an uncertainty factor of 1.6 was selected.

Using this same approach, and the same assumptions regarding the most likely and alternative distributions of energy and geometry, the overall bias for estimating deep dose, red bone marrow dose, and lung dose was calculated for the four Hanford dosimetry systems. These values and the estimated uncertainty factors are shown in Table 5. This evaluation indicates that overall, except for the period before 1958, deep dose was fairly accurately estimated, lung dose was overestimated by about 10%, and bone marrow dose was overestimated by about 50%. Overestimation was more serious prior to 1958. It is noted that the use of the lognormal distribution, which is symmetric on a multiplicative scale, to describe these uncertainties may not be fully appropriate. In general, the selected uncertainty factors reflect the direction yielding the largest factor; in the absence of symmetry, the effect of this practice is to overestimate uncertainty in the opposite direction.

DISCUSSION AND CONCLUSIONS

The main objective of the evaluation in this paper was to provide the information needed to conduct epidemiologic dose-response analyses that account for errors in dose estimates. To this end, overall bias factors, specific to calendar year period, were derived, and these can be used to adjust recorded dose as estimates of deep dose, red bone marrow dose, or lung dose.

In addition to simple bias corrections, epidemiologic analyses should take account of both uncertainty in the overall average correction factors (systematic uncertainties) and random uncertainty reflecting variability among workers. Systematic uncertainty could be taken into account by conducting computer simulations as described by Gilbert (1991b), and this would have the effect of increasing the length of confidence intervals on risk estimates. Random uncertainty would be more difficult to account for, but recent methods described by Clayton (1992), Pierce et al. (1989), and Thomas et al. (1993) might be applied. Such errors can lead to underestimation of risk estimates and can distort dose-response analyses in other ways.

The evaluation described in this paper was limited in several ways. Data that would allow rigorous objective evaluation of biases for many of the considered sources were limited or unavailable, and for this reason the uncertainty in the derived factors for converting doses is substantial. It was necessary to rely on subjective judgments both for evaluation of uncertainty factors for the various sources shown in Table 1, and for information on distributions of energies and geometries in Hanford exposure environments.

Uncertainty in the energy/geometry distributions is especially large, as evidenced by the varied responses of the health physicists who were queried. However, except for the dosimeter used before 1958, the factors for converting recorded doses to other doses of interest do

Table 4. Combined bias for estimating red bone marrow dose for the multi-element film dosimeter, 1957–71.

Distribution by energy level, percentage from 300–1,000 keV[b]	Distribution by geometry, percentage anterior-posterior[a]				
	0%	45%	60%	80%	100%
0%	0.86	1.07	1.16	1.28	1.41
40%	0.97	1.20	1.29	1.41	1.55
75%	1.08	1.32	1.41	1.54	1.69
95%	1.15	1.40	1.49	1.62	1.77
100%	1.17	1.42	1.51	1.64	1.79

[a] The remainder of exposure is assumed to come from the rotational geometry.
[b] The remainder of exposure is assumed to come from the range 100–300 KeV.

Table 5. Overall bias and uncertainties in recorded doses as estimates of deep dose, red bone marrow dose, and lung dose.

	1944–56	1957–71	1972–83	1984–89
Deep dose				
Overall bias (B)	1.27	1.02	1.12	1.01
Systematic uncertainty (K_S)				
From energy and geometry	1.2	1.1	1.05	1.05
From other sources[a]	1.4, 1.8	1.3, 1.5	1.2, 1.3	1.2, 1.3
Random uncertainty (K_R)				
From energy and geometry	1.8	1.4	1.2	1.2
Red bone marrow dose				
Overall bias (B)	1.75	1.41	1.54	1.40
Systematic uncertainty (K_S)				
From energy and geometry	1.3	1.2	1.1	1.1
From other sources[a]	1.5, 1.8	1.3, 1.6	1.3, 1.4	1.3, 1.4
Random uncertainty (K_R)				
From energy and geometry	1.9	1.6	1.4	1.4
Lung dose				
Overall bias (B)	1.33	1.07	1.17	1.06
Systematic uncertainty (K_S)				
From energy and geometry	1.2	1.1	1.05	1.05
From other sources[a]	1.5, 1.8	1.3, 1.6	1.3, 1.4	1.3, 1.4
Random uncertainty (K_R)				
From energy and geometry	1.6	1.4	1.2	1.2

[a] Taken from Table 3. The first entry is uncertainty for the anterior-posterior geometry; the second entry is uncertainty for the rotational geometry.

not depend strongly on energy (see Table 3), and thus results do not depend strongly on assumptions about energy levels. Relatively little exposure was incurred at Hanford prior to 1958 (Gilbert and Fix 1995). Geometry is more important, especially for estimating bone marrow dose, where the estimated bias is strongly dependent on the assumptions made regarding the mix of geometries. However, even in this case, the rather large uncertainty in energy levels and geometries translated into only modest systematic uncertainty in the overall correction for bias.

This evaluation has stopped short of providing detailed methods for evaluating uncertainties in cumulative doses, but general guidance has been provided. This is also true with regard to combining the factors reflecting systematic uncertainties in energy-geometry sources with factors reflecting uncertainties from other sources. It is anticipated that several alternative approaches would be considered in adjusting epidemiologic analyses.

The only source of random error given detailed consideration in this paper was that resulting from variation in energy levels and geometries among workers; it is the opinion of the authors that this is the most important source of such error. However, further work is needed to evaluate laboratory random errors, although this error is probably small for workers with larger cumulative doses. Finally, converting deep dose to lung dose or to bone marrow dose would be expected to involve additional random error because of variation in body size.

Both systematic and random uncertainties have been specified in terms of lognormal distributions, which have the property of symmetry on a multiplicative scale. Such distributions may not adequately describe all uncertainties evaluated. Although alternative distributions could be considered, given that the uncertainty distributions are at best an attempt to summarize subjective information, the use of lognormal distribution seems a reasonable choice.

In general, the uncertainty distributions in this paper, especially the combined distributions expressing all uncertainties including those due to geometry and energy, cannot be considered to provide a fully rigorous characterization of errors. However, the uncertainty factors at least give a sense of how well a particular bias factor is known, and allow one to distinguish those values that are known very precisely from those about which there is considerable uncertainty. In using results of this evaluation to adjust epidemiologic dose-response analyses, it is anticipated that a range of uncertainty factors would be considered to provide an indication of the sensitivity of results to various assumptions. The evaluation here cannot be expected to do more than provide an indication of the values that are likely to be most realistic.

Although this paper has provided quantitative information on errors in Hanford dose estimates, its main contribution may be the development of a general approach for obtaining the information needed to adjust epidemiologic analyses for errors in estimates of annual and cumulative doses obtained from personnel dosimeters. The general approach is applicable not only to workers at Hanford, but to workers at other facilities. Although the approach necessarily relies strongly on subjective judgments, it has the advantage that it is based on clearly stated assumptions regarding which sources of error were included, how each source was handled, and how uncertainties from different sources were combined.

This project was supported by contract DE-AC06-76RLO 1830 from the U.S. Department of Energy, and by grant RO1 OH03270 from the National Institute for Occupational Safety and Health of the Centers for Disease Control and Prevention. We also acknowledge useful discussions with G.W. Endres, L.W. Brackenbush, L.L. Nichols, and R.H. Wilson.

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