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Missing annual external radiation dosimetry data among Hanford workers

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Epidemiological studies of workers employed at the Hanford Site have been underway for nearly 30 years. Although the external radiation dosimetry program at Hanford has been fairly comprehensive, some workers included in previous epidemiological analyses have periods of employment during which there are missing annual external radiation dosimetry records. In this report, employment history records and annual external dosimetry records have been used to investigate the extent of missing annual external dosimetry records for workers at the Hanford facility. A "nearby" procedure for estimating values for missing annual external dosimetry records was evaluated. Among the 33,459 workers who were employed at least 180 days and had at least one annual external dosimetry record, annual external dosimetry records were missing for 8% of the years of employment (32,323 missing annual external dosimetry records). Missing annual external dosimetry records were more common for female Hanford workers than for male workers, and for workers employed in the early years of Hanford's operation than for workers employed in later years of operation. The nearby procedure provided reliable estimates of values for missing annual external dosimetry records. Using this procedure, 18,937.5 mSv were estimated for missing annual external dosimetry records; this was 2% of the total recorded cumulative external radiation dose for these workers. Missing annual external dosimetry records should be considered as a potential source of bias and uncertainty in investigations of radiation–cancer associations among Hanford workers.

Keywords: *dosimetry, epidemiology, Hanford, radiation.*

Introduction

This paper examines the problem of missing annual external radiation dosimetry data in studies of workers employed at the Hanford nuclear facility. Since many of the workers at this facility were individually monitored for external radiation exposure, studies of these workers offer a valuable source of information about the effects of occupational exposure to radiation (Mancuso et al., 1977; Gilbert et al., 1993; Cardis et al., 1995a,b; Stewart and Kneale, 1996). Decisions about how to handle missing data are an important consideration for minimizing biases in epidemiological study results.

In previous epidemiological analyses of radiation–cancer associations among Hanford workers, people who had no annual external dosimetry data were excluded from analyses, while people who had at least one annual external dosimetry record were included (Gilbert et al., 1993; Cardis et al., 1995a,b; Stewart and Kneale, 1996). Workers could have missing annual external dosimetry records due to lost files, data entry errors, or errors in computerized linkages between dosimetry files and demographic or work history files. In addition, coverage of Hanford workforce by the external radiation dosimetry program was incomplete; over time, a greater proportion of the workforce was included in the external dosimetry program. Consequently, previous analyses included workers who were employed at Hanford during years when they were not monitored for external exposure to ionizing radiation (for example, workers who were not monitored for external radiation exposure in the early years of Hanford's operation, but were monitored in later years of operation).

In this report, information from work history records has been used to identify periods of employment during which workers have missing annual external dosimetry records. We evaluate the use of a 'nearby' procedure, originally developed for estimating missing annual external dosimetry data among workers employed at the Oak Ridge X-10 and Y-12 facilities, for calculating estimated values for missing annual external dosimetry records (Watson et al., 1994; Watkins et al., 1997).

1. Abbreviations: mSv, milliSievert; ORNL, Oak Ridge National Laboratory.

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These analyses should contribute to future epidemiological investigations of the Hanford data. Sub-cohort analyses may be considered involving those workers with the most complete annual external dosimetry data; and, estimated values for missing annual external dosimetry records may supplement the available annual external radiation dosimetry data.

Methods

This report examines information for workers who were employed at the Hanford nuclear facility. Analyses focus on those workers who will be included in upcoming epidemiological analyses of radiation–cancer associations among Hanford workers. Similar to previous analyses of workers employed at the Hanford facility, our study cohort includes workers who were employed at least 180 days at the Hanford nuclear facility, who were hired by prime operations contractors between 1944 and 1978, and who had at least one annual external dosimetry record. In addition, two workers with annual external doses greater than 250 mSv were excluded from our study cohort; and, two additional workers involved in radiation accidents that led to substantial internal and external radiation exposures were excluded (Gamertsfelder et al., 1962; Palmer et al., 1983).

Computerized Records

External radiation doses for Hanford workers were primarily due to exposure to gamma radiation; in the later years of operation, doses due to internal exposure to tritium were included in the recorded annual external dosimetry file (Buschbom and Gilbert, 1993). At Hanford, dosimeters were initially exchanged weekly or bi-weekly. Furthermore, workers employed in more than one work location may have had more than one dosimetry record for a given dosimetry period (Gilbert, 1990). In 1957, dosimeters began to be read monthly; and in 1964, some workers were put on a quarterly dosimeter exchange schedule. In 1972, thermoluminescent dosimeters were introduced, and dosimeters began to be exchanged on a yearly schedule (Gilbert, 1990). A computerized file describing the available annual external dosimetry records for the calendar years 1944 through 1989 was used in these analyses.

This annual external dosimetry file was linked with a computerized file containing work history information from both operations and construction contractors. The work history file describes workers' dates of employment, including dates at which there were changes in employment status and dates at which there were changes in job title. The work history file was edited in order to resolve logical errors in dates of employment, and in order to ensure that dates of hiring and termination were associated with all job changes. A file was created that described the number of days that a worker was employed by operations or construction contractors during each calendar year (1944–1988), and the longest held occupation during each calendar year. Job titles for Hanford workers have previously been coded to the US Bureau of Census occupation codes (Gilbert et al., 1992). Job titles were categorized into 16 occupational groups using census code information.

Nearby Estimation Procedure

For each calendar year in which a person was employed at Hanford according to the work history records, but no annual external dosimetry record was found, an estimated value for the missing annual external dosimetry record was calculated using the nearby method (Watson et al., 1994). Under this method, a series of hierarchical steps are followed in order to calculate an estimated value for each missing annual external dosimetry record (Table 1). If there were not adequate data to calculate an estimated value using the first step in the procedure, an estimated value was calculated using a subsequent step. The first steps of the nearby algorithm use the worker's own annual external dosimetry data from nearby time periods as a basis for calculating an estimated dose. If there were adequate data, the average of the annual external doses recorded within 2 years of the missing value was used to calculate an estimated value for the missing annual external dosimetry record. Each annual external dose

Table 1. Thirteen hierarchical steps in the nearby procedure to estimate a value for missing annual external dosimetry record in calendar year (Year).

Nearby step	Description of nearby step
Step 1	Mean dose in (Year − 1 and Year + 1)
Step 2	Mean dose in (Year − 2 and Year + 1)
Step 3	Mean dose in (Year − 1 and Year + 2)
Step 4	Mean dose in (Year − 2 and Year + 2)
Step 5	Mean dose in (Year − 1 and Year − 2)
Step 6	Mean dose in (Year + 1 and Year + 2)
Step 7	Mean dose in (Year − 1)
Step 8	Mean dose in (Year + 1)
Step 9	Mean dose in (Year − 2)
Step 10	Mean dose in (Year + 2)
Step 11	Mean dose for workers of same gender, occupation, year
Step 12	Mean dose for workers of same occupation, year
Step 13	Mean dose for workers of same occupation

Note: If a worker does not have adequate information to calculate an estimated dose using the first step of the nearby algorithm, a subsequent step is evaluated.

was weighted by the number of days employed in that calendar year. In order to ensure stable estimates, the person-time weighted mean annual external dose in neighboring years had to be based on at least 180 days of employment. If there were not adequate annual external dosimetry data in the nearby years, the average annual external dose for all similar workers (defined by occupation, gender, and calendar year of employment) was used to calculate an estimated value for the missing annual external dosimetry record.

Evaluation of the Reliability of Each Step in the Nearby Procedure

In previous analyses, the reliability of the nearby estimation procedure differed between facilities (Watson et al., 1994). At Oak Ridge National Laboratory (ORNL), values for missing annual external dosimetry records were more reliably estimated by using observed data from nearby years than by using department (or facility) mean annual external doses. In contrast, at the Oak Ridge Y-12 facility, values for missing annual external dosimetry records were more reliably estimated using department mean annual external doses than by using observed data from nearby years (Watson et al., 1994). Therefore, it is important to evaluate the relative reliability of each step in the nearby estimation procedure prior to using this procedure to calculate estimated values.

The relative reliability of each step in the nearby estimation procedure was evaluated by comparing observed annual external dosimetry doses with estimated values. An annual external dosimetry record was treated as missing, and an estimated value was calculated using the nearby method. In order to compare observed and estimated values derived using each step of the nearby procedure, we created a subset of the Hanford annual external dosimetry file that consisted of all records with adequate data to calculate an estimated value using each of the 13 nearby steps. These were annual external dosimetry records for which there were doses recorded in the two preceding and subsequent years, and at least 180 days of employment during each of those neighboring calendar years. A statistical comparison of the reliability of each step in the nearby procedure was conducted by calculating the sums of the squared

Table 2. Number of Hanford workers by gender and study criteria and the number of missing annual external dosimetry records.

	Male, number (%)	Female, number (%)	Total, number (%)
Workers employed at least 180 days, hired between 1943 and 1978 by an operations contractor	26,808	10,662	37,470
Workers with no annual external dosimetry records	1490 (6%)	2517 (24%)	4007 (11%)
Workers employed at least 180 days, hired between 1943 and 1978 by an operations contractor, who have at least one annual external dosimetry record	25,318	8145	33,463
Workers with annual external dose greater than 250 mSv, or involved in a specified radiation accident	4	0	4
Hanford study cohort[a]	25,314	8145	33,459
Workers in the Hanford study cohort[a] with one or more missing annual external dosimetry records	7223 (29%)	3692 (45%)	10,915 (33%)
Total number of calendar years of employment for workers in the Hanford study cohort[a]	320,655	76,369	397,024
Number of missing annual external dosimetry records for workers in the Hanford study cohort[a]	18,699 (6%)	13,624 (18%)	32,323 (8%)

[a]Workers employed at least 180 days, hired between 1943 and 1978 by a Hanford operations contractor, who have at least one annual external dosimetry record, excluding workers with annual external dose greater than 250 mSv and workers considered to be involved in a radiation accident.

differences between observed and estimated annual external doses.

Evaluation of the Reliability of the Nearby Procedure for Estimating Doses from Different Historical Periods, and of Differing Magnitudes

Further evaluations of the nearby procedure were conducted in order to examine how reliably values for missing annual external dosimetry records were estimated when observed doses were of differing magnitudes and from different historical periods. For these evaluations, all observed annual external dosimetry records were used. Each annual external dosimetry record was treated as missing, and an estimated value was calculated via the nearby procedure. In order to examine how well estimated values compared to observed doses, box-plots of observed versus estimated doses were created. Additionally, box-plots of the difference between observed and estimated doses by level of observed dose, and by calendar year of monitoring, were created. In these box-plots, upper and lower quartiles are indicated by the ends of the box, while mean and median values are indicated by the star and the horizontal line associated with each box, respectively; the whiskers on each box-plot extend to the fifth and ninety-fifth percentiles.

Results

Of the 37,470 Hanford operations workers employed at least 180 days between 1944 and 1978, 4007 workers (11%) had no annual external dosimetry data (Table 2). Those who had no annual external dosimetry data were primarily hired in the early years of operation; 50% of those with no annual external dosimetry data were hired before 1949, and 75% were hired before 1954. Twenty-four percent (2517 workers) of the female operations workers employed at least 180 days had no annual external dosimetry data; 6% (1490 workers) of the male operations workers employed at least 180 days had no annual external dosimetry data (Table 2).

Hanford Study Cohort

Similar to previous analyses of radiation–cancer associations among Hanford workers, one of the criteria for entering our study cohort was that an individual had to have at least one annual external dosimetry record. Among the 33,459 workers in our study cohort, 10,915 (33%) of the workers had one or more years of employment with missing annual external dosimetry records (Table 2). There were 32,323 missing annual external dosimetry records; these were calendar years in

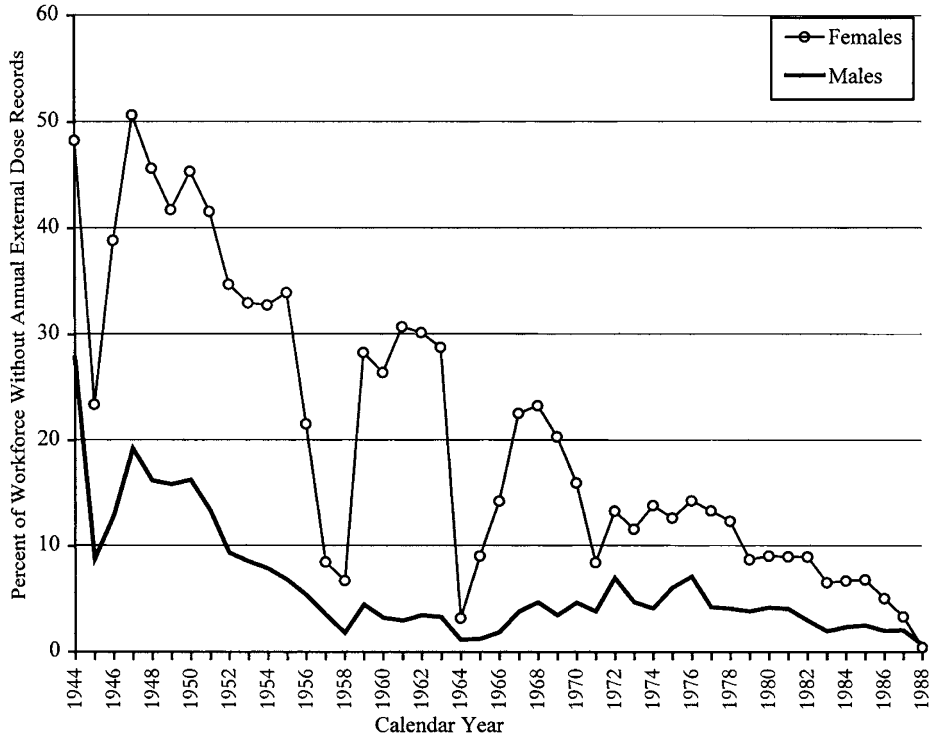

Figure 1. Percentage of workers in study cohort† with missing annual external dosimetry data by calendar year and gender. †Workers employed at least 180 days, hired between 1943 and 1978 by a Hanford operations contractor, who have at least one annual external dosimetry record, excluding workers with annual external dose greater than 250 mSv and workers considered to be involved in a radiation accident.

which employment at Hanford was indicated in the work history file, but for which there were no records of external dosimetry data. Missing annual external dosimetry records were more common among female (18% of annual external dosimetry records were missing) than among male (6% of annual external dosimetry records were missing) workers (Table 2).

While all the workers in our study cohort had at least one annual external dosimetry record, coverage of the work force by the external radiation monitoring program appears to have been less complete in the early years of operation than in later years, particularly for female workers (Figure 1).

People employed as operators, radiation monitors, researchers, and engineers (jobs in which workers tended to receive higher annual radiation doses) had the most complete annual external dosimetry data (Table 3). Conversely, people employed as clerical workers, unskilled and semi-skilled manual workers, and administrative workers, had the least complete annual external dosimetry data; more than half of all missing annual external dosimetry records occur among workers in these jobs. In the later years of operation, coverage of clerical workers by the Hanford dosimetry program appears to have become more complete (Figure 2). However, even in jobs and historical periods with relatively complete dosimetry data, there is evidence that dosimetry data are missing for some workers.

Of the 10,915 workers with missing annual external dosimetry data, nearly half (47%) were missing only one annual external dosimetry record. A small number of workers contributed a large proportion of the total number of missing records. Fifty percent of the missing years of dosimetry data was accrued by 14% of the study cohort. Of the 1563 workers who had more than 5 years of missing dosimetry data, 736 (47%) were female. While workers with large numbers of missing annual dosimetry records were more often employed in clerical and administrative jobs, there were workers in all major occupational categories with three or more years of missing dosimetry data.

Evaluation of the Reliability of Each Step in the Nearby Procedure There was no direct way to evaluate how well the nearby method estimated values for missing dosimetry records. However, it was possible to examine how well the nearby method estimated values for years with observed annual external doses. By treating observed doses as missing values, observed and estimated values could be compared. There were 211,086 observed annual external dosimetry records that were used for this evaluation. Observed annual external doses were compared to values estimated using each step of the nearby method, and the sums of the squared differences between observed and estimated doses were tabulated (Table 4). These values indicate how closely the estimated doses

Table 3. Calendar years of employment with missing dosimetry data by occupation.[a]

Occupation group	Number of years of employment with missing dose data	Percentage of years of employment with missing dose data
Clerical and kindred non-manual workers	13,750	22%
Other semi-skilled manual workers	677	13%
Transportation equip operators and manual unskilled	2320	11%
Technical and mid-level professionals	1290	10%
Administrators and professionals	803	8%
Heath services, security, and unknown occupation	2760	8%
Skilled manual workers	3857	6%
Managers	891	5%
Supervisors	677	5%
Engineers and engineering technicians	3961	4%
Other operators	911	4%
Life and physical science researchers	159	1%
Radiation monitors	54	1%
Process operators	141	1%
Reactor operators	61	1%
Utility operators	11	1%
Total	32,323	8%

[a]Workers employed at least 180 days, hired between 1943 and 1978 by a Hanford operations contractor, who have at least one annual external dosimetry record, excluding workers with annual external dose greater than 250 mSv and workers considered to be involved in a radiation accident.

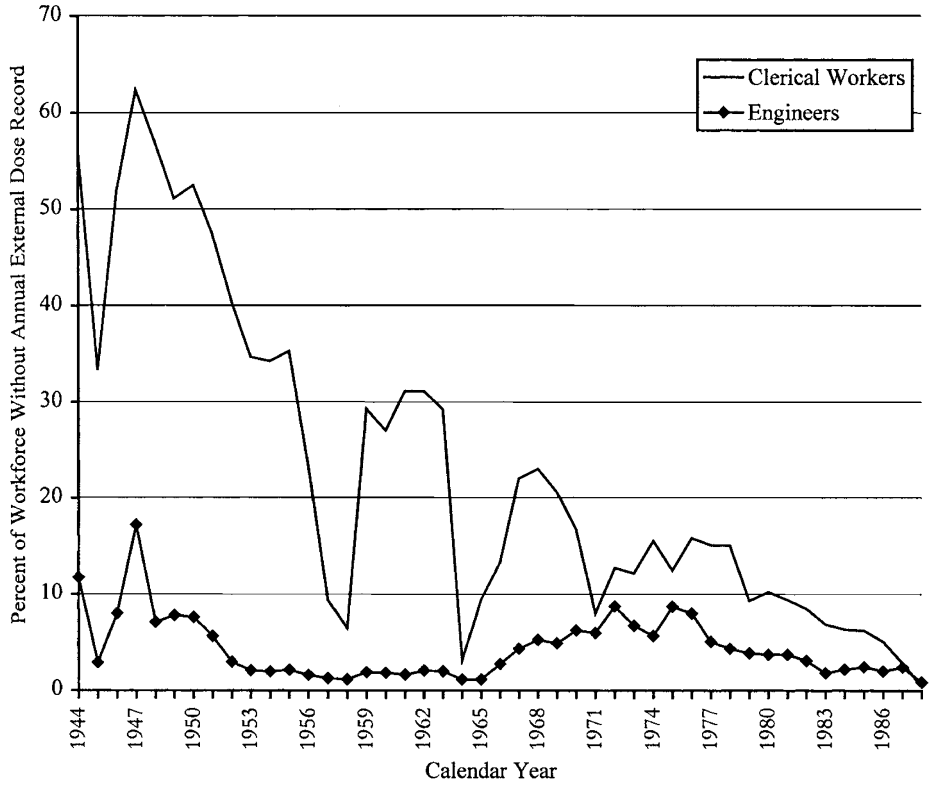

Figure 2. Percentage of study cohort† with missing annual external dosimetry data by calendar year among clerical workers and engineers.†Workers employed at least 180 days, hired between 1943 and 1978 by a Hanford operations contractor, who have at least one annual external dosimetry record, excluding workers with annual external dose greater than 250 mSv and workers considered to be involved in a radiation accident.

approximate observed values when using each step of the nearby method. The first steps used in the hierarchical algorithm provide better estimates of the observed doses than later steps in the algorithm (reflected by a smaller sum of squared differences). The steps that used nearby recorded doses provided better estimates of the observed annual doses than the steps that used mean doses for other workers of the same occupation, gender, and calendar year of employment.

Table 4. Squared difference between 211,086[a] observed annual doses and their estimated values. Comparing each of the 13 steps in the nearby procedure.

Nearby Step	Sum of the Squared Difference between Observed and Estimated Doses
Step 1	1,624,242
Step 2	2,077,035
Step 3	2,066,172
Step 4	2,546,374
Step 5	2,637,888
Step 6	2,606,225
Step 7	2,624,008
Step 8	2,605,444
Step 9	4,036,960
Step 10	3,977,793
Step 11	4,879,151
Step 12	4,963,564
Step 13	5,902,958

[a]Values were estimated for all observed doses that had adequate information to calculate an estimated dose using each step of the nearby algorithm.

In previous analyses of radiation–mortality associations in this population, missing doses contributed nothing to calculations of a worker's cumulative dose. The use of the nearby procedure (Table 4) was compared to the alternative assumption that all missing values were zero. The sum of squared error calculated when all estimated doses were assigned a value of zero was 9,866,932. This indicates that every step in the nearby procedure (Table 3) provided better estimates for the missing doses than treating these doses as zeros.

Evaluation of the Reliability of the Nearby Procedure for Estimating Doses from Different Historical Periods, and of Differing Magnitudes The use of the nearby procedure was evaluated in order to examine how reliably estimated values approximated observed doses of differing magnitudes and doses from different historical periods. These evaluations used all observed annual external dose records. An

estimated value was calculated for each observed annual external dose using the nearby procedure.

The reliability of the nearby procedure for estimating annual external doses of differing magnitudes was examined first. Observed versus estimated values were plotted to examine trends in estimated values (Figure 3). When the true value for a dose was zero, the estimated value was closely approximated by the nearby method; the mean and median estimated values were 0.35 mSv and 0.10 mSv, respectively. When the observed annual external dose was of larger magnitude, the mean and median estimated values tend also to be of larger magnitude (Figure 3).

Differences between observed and estimated values were also plotted. When the observed dose was zero, the difference between the observed and estimated values tended to be positive (with a median difference of 0.10 mSv); this indicates that the nearby procedure tended to slightly overestimate values for missing data when the observed dose was zero (Figure 4). When the observed dose was greater than zero, the difference between the observed and estimated values estimated values tended to be negative; this indicates that the nearby procedure tends to underestimate values for missing data when the observed dose is greater than zero (Figure 4). In the highest dose category (25 mSv or greater), estimated values were, on average, 5.3 mSv less than observed values (the median difference between observed and estimated values in the highest dose category was 3.4 mSv).

Observed and estimated values were also compared for annual external dosimetry records from different historical periods of Hanford's operation (Figure 5). The nearby procedure provided reliable estimates of observed annual external doses for dosimetry records from each calendar year of operation. The largest median difference between observed and expected values was -1.7 mSv in 1965. The interquartile range, which reflects the distribution of error in estimated values, was largest in 1945 and 1964–1967; in these years, the inter-quartile range was greater than 1.5 mSv.

Estimation of Values for Years of Employment with Missing Annual External Dosimetry Records Values were estimated for calendar years of employment for which workers were missing annual external dosimetry records. For years in which there was a recorded dose within 2 years of the period with missing dose data, estimated values were calculated using nearby data. Values for 65% (21,028 years) of the missing annual external dosimetry records could be estimated by the mean of doses within 2 years of the missing record (69% of the missing annual external dosimetry records among male workers, and 59% of the missing annual external dosimetry records among female workers). Values for 10,870 missing annual external dosimetry records were calculated using the mean annual external dose for other workers of the same gender and occupation group during that calendar year. Values for 396

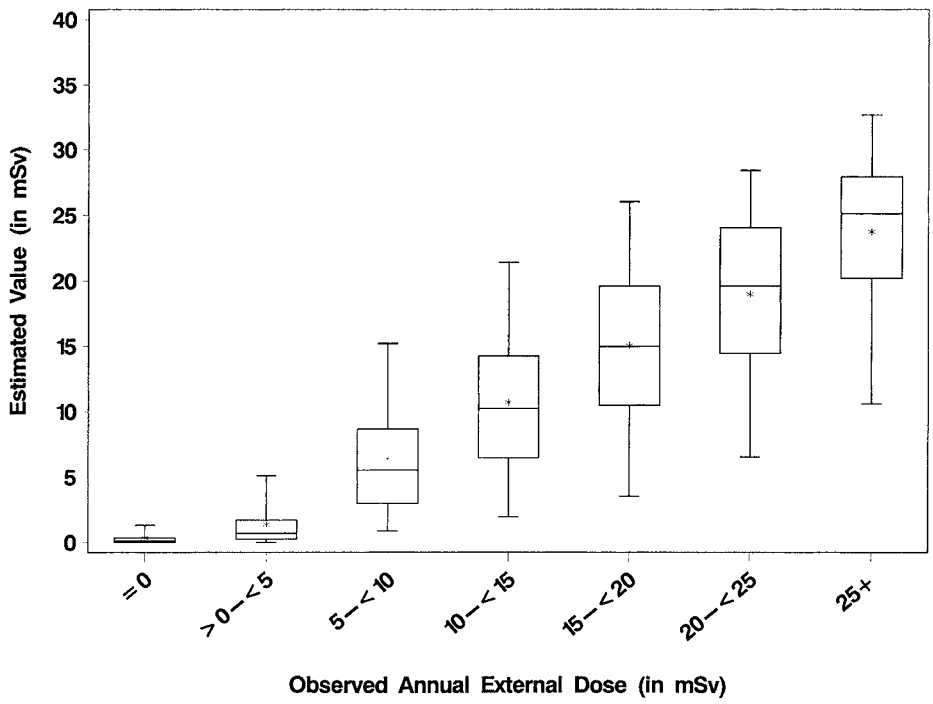

Figure 3. Distribution of estimated values by category of observed annual external dose.

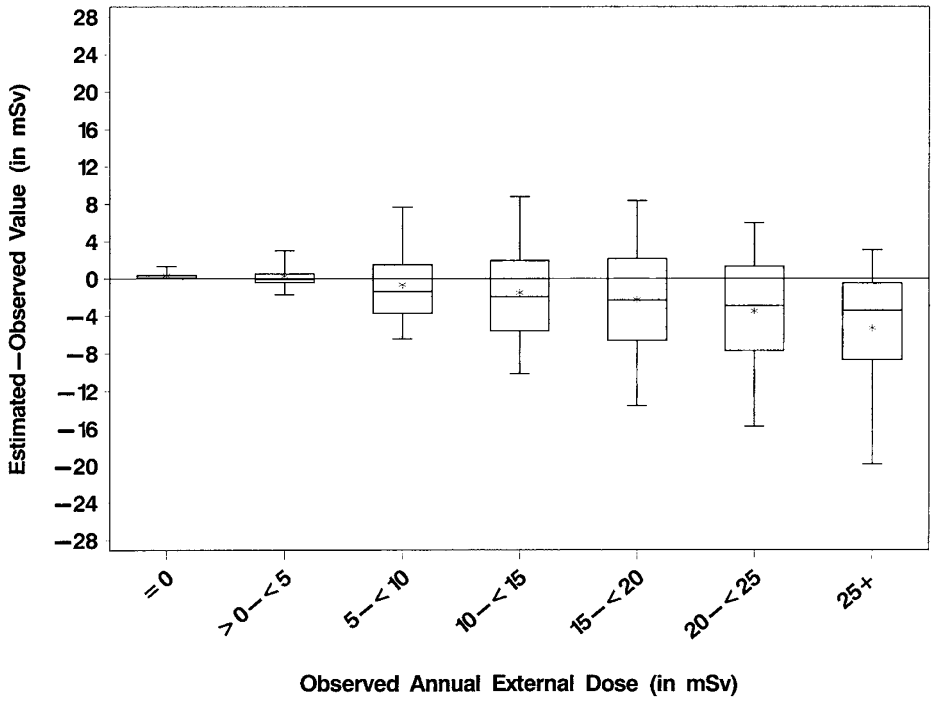

Figure 4. Difference between estimated and observed values by category of observed annual external dose.

missing annual external dosimetry records were estimated using the mean for all workers of the same occupation in that calendar year (since there were no recorded doses for women in that occupation in that year). Values for 29 missing annual external dosimetry records were estimated using the mean for all workers in that occupation.

Values for 34% of the missing annual external dosimetry records were estimated to be 0 mSv, and values for 87% of the estimated annual external dosimetry records were less than 1 mSv. The mean estimated annual external dose was 0.6 mSv, and the maximum estimated annual external dose was 42 mSv. The total cumulative estimated external dose

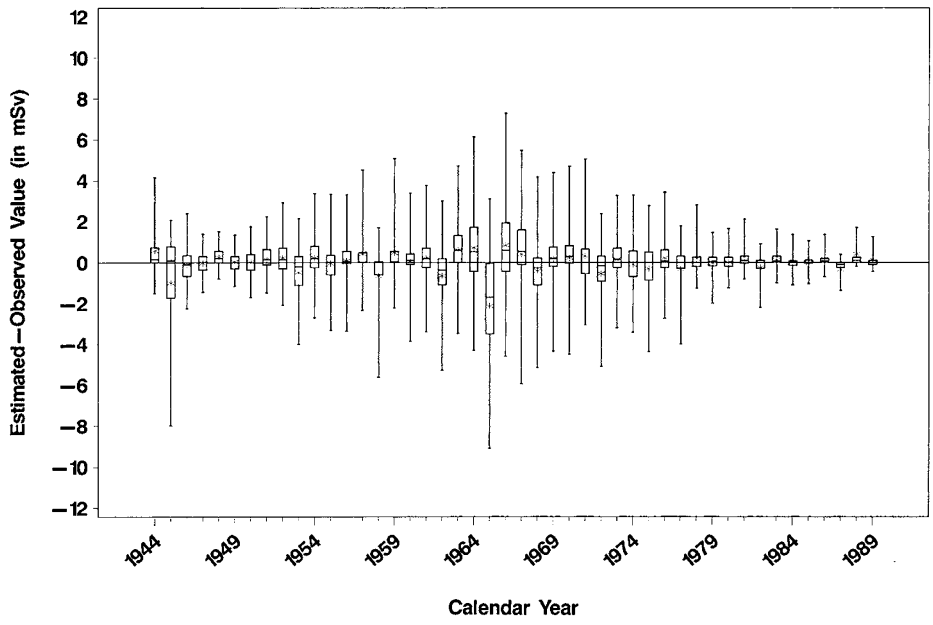

Figure 5. Difference between estimated and observed values by historical period.

Table 5. Mean estimated dose and total estimated dose by occupation.[a]

Occupation group	Mean Estimated Annual Dose (in mSv)	Total Estimated Dose (in mSv)
Administrators and professionals	0.3	274.7
Clerical and kindred non-manual workers	0.3	3502.8
Technical and mid-level professionals	0.4	562.9
Transportation equip operator and manual unskilled	0.4	955.5
Heath services, security, and unknown	0.4	1157.9
Managers	0.5	434.4
Other operators	0.5	496.5
Other semi-skilled manual workers	0.5	315.2
Supervisors	0.8	550.5
Engineers and engineering technicians	0.9	3747.7
Skilled manual workers	1.4	5505.4
Life and physical science researchers	1.7	272.7
Process operators	3.7	519.7
Utility operators	4.2	46.5
Radiation monitors	4.9	261.9
Reactor operators	5.5	333.3
Total	0.6	18,937.5

[a]Workers employed at least 180 days, hired between 1943 and 1978 by a Hanford operations contractor, who have at least one annual external dosimetry record, excluding workers with annual external dose greater than 250 mSv and workers considered to be involved in a radiation accident.

for the study cohort was 18,937.5 mSv which was 2% of the total observed external dose for the Hanford study cohort (872,925.5 mSv). Mean estimated annual external doses were largest for workers employed as reactor operators and radiation monitors (Table 5). When estimated values were cumulated by occupation, the occupations with the largest total estimated external doses were skilled-manual, engineering, and clerical workers (Table 5).

Discussion

The Hanford cohort has been an important source of information for epidemiological studies of the health effects of low-level exposure to ionizing radiation. Evaluations of the available annual external dosimetry data are important for interpretation of these studies, and for design of subsequent analyses (Cardis and Esteve, 1991). Previous evaluations of the Hanford external dosimetry data have given attention to potential underestimated doses due to dosimetry techniques, the nature of exposure (e.g., the angle of exposure, the contribution of neutron, photon, X-ray, and tritium doses), and recording practices at the facility (Gilbert, 1990; Gilbert and Fix, 1995; Gilbert et al., 1996). Missing data, which are a more generic concern in occupational epidemiology studies, have been a subject of less discussion.

Descriptions of the Hanford external dosimetry program have provided little information about the extent of missing annual external dosimetry records, and may have overstated the completeness of coverage of Hanford personnel by the radiation dosimetry program. One report that included data on Hanford workers noted that "It has been usual in Canadian and US facilities during the period under study to issue dosimeters to essentially all personnel and visitors irrespective of their status or of the nature of their work in relation to potential radiation exposure" (Fix et al., 1997). Another report asserted that "It has been Hanford practice to monitor nearly all personnel for external radiation exposure. This includes personnel in facilities where no occupational radiation exposure is received and where the total radiation exposure is essentially equal to natural background radiation levels" (Wilson et al., 1990).

These descriptions should be tempered by the observation that 24% of the female operations workers and 6% of the male operations workers who were employed at least 180 days have no annual external radiation dosimetry data (Table 2). Furthermore, among those workers with at least one annual external dosimetry record (who have been the subject of repeated epidemiological investigations of radiation–cancer associations), we identified 32,323 calendar years of employment with missing annual external dosimetry records.

Workers have been excluded from epidemiological analyses of this occupational cohort if they were never monitored for external radiation exposure (Table 2). Consequently, changing policies and practices of external radiation monitoring for the workforce over time could lead

to changes in the composition of the study cohort. This is particularly true for the workers contributing to the zero, and near zero, dose groups. In the later years of operation, the composition of the Hanford study cohort includes more women, and more workers in clerical and service jobs who primarily contribute person-time and events to the low-dose categories in analyses. Understanding the changing coverage of the workforce by the dosimetry program is also important for interpreting historical trends in the recorded mean and median annual external dose; inclusion over time of more workers with low exposure potential would lead to lower recorded mean and median doses for the Hanford cohort.

We have relied upon available work history information to determine whether workers were employed in calendar years for which they were missing annual external dosimetry records. Previous epidemiological analyses have used the Hanford work history records to identify people for inclusion in the study cohort based upon duration of employment and date of hiring. Work history records have also been used to define social status groups based upon job titles (Gilbert et al., 1992; Cardis et al., 1995a,b). In addition, work history records previously have been used as a basis for editing the annual external dosimetry file, reflecting a judgement about the comparable quality of the available external dosimetry and work history data (Gilbert et al., 1992). While there may be errors in the work history information, these records, which were collected for accounting and management purposes, are believed to be a relatively reliable source of information for purposes of defining periods of employment and for defining broad classifications of workers by occupation (Gilbert et al., 1992). Furthermore, for these updated analyses of the Hanford cohort, these work history records were subjected to a detailed review and editing procedure in order to resolve problems such as discrepant or missing hire and termination dates. Based upon these edited work history records, our findings suggest that the occurrence of missing annual external dosimetry records conforms to expectations about the incomplete coverage of the Hanford workforce by the dosimetry program. Similar to findings from evaluations of the dosimetry program at ORNL, coverage of the Hanford workforce was more complete for male workers than for female workers; and, coverage was more complete in later historical periods than in earlier years of operation. Eighteen percent of the years of employment among female workers included in the Hanford study cohort had missing annual external dosimetry records (Table 2). The percentage of missing annual external dosimetry records among male Hanford workers (6%) is comparable to the 5% missing annual external dosimetry records reported among white male workers at ORNL (Wing et al., 1991).

While workers in jobs that involved lower potential for radiation exposure were most likely to have missing annual external dosimetry records (Table 3), missing information is a possible source of bias in estimates of radiation–cancer associations. Identifying workers with missing annual external dosimetry records may help to assess this potential bias. One approach to evaluating the effect of these missing data on estimates of radiation–mortality associations would be to consider analyses for a sub-cohort of workers with the most complete annual external dosimetry data.

In addition to documenting the extent of missing annual external dosimetry records among Hanford workers, this report presents an evaluation of one approach to estimating values for these missing records. In previous analyses, missing annual external radiation dosimetry records contributed zero dose to calculations of cumulative radiation dose. In contrast, using a nearby estimation approach, we have estimated values for missing annual external dosimetry records. The nearby estimation procedure avoids making extreme assumptions about the values of missing annual external dosimetry records and provides estimates which may be used in analyses of radiation–cancer associations.

Our evaluations of the nearby approach, which compared estimated values to observed annual external doses, indicate that this method generally provides reliable estimates for missing dosimetry records. The sum of squared differences between observed and expected values was substantially smaller for the first steps of the nearby procedure than for the last steps of the algorithm (Table 4). Therefore, the rank ordering of steps in the nearby procedure (Table 1) was not changed when calculating estimated values for missing annual external dosimetry records. It should be noted that our evaluations of the nearby method used data for workers with observed annual external dosimetry records, while workers with missing annual external dosimetry records were most often employed in jobs that received low average annual external doses (Table 3). Consequently, in contrast to the data used in our evaluation, values for 86% of the missing annual external dosimetry records were estimated to be less than 1 mSv. Therefore, the advantages of the nearby method, when compared to the previous implicit assumption that values for missing records were zero, should not be overstated.

The nearby approach described in this paper has been applied to the computerized annual external dosimetry data. Missing records may also occur among the periodic dosimetry records that were summed within calendar years to determine annual external doses. If a worker in the Hanford dosimetry program had a missing dosimetry measurement during a periodic dosimeter exchange (for example, due to a lost dosimeter), an investigation was typically conducted in order to determine an estimated value that was recorded by the dosimetry staff (Wilson et al., 1990; Fix et al., 1997). Unfortunately, these periodic dosimetry records were not available in computerized form.

This research increases our understanding of the limitations of available annual external dosimetry data for Hanford workers used in epidemiologic cohort analyses investigating the effects of low-level exposure to ionizing radiation. This investigation of the Hanford annual external dosimetry data is part of a larger research project to examine associations between low levels of external ionizing radiation and specific causes of death among workers at Hanford. The nearby procedure provides a reliable approach to estimating values for these missing annual external dosimetry records. Estimation of values for missing annual external dosimetry records may help to reduce exposure misclassification in future epidemiological analyses.

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