Radiation Exposure From Work-Related Medical X-Rays at the Portsmouth Naval Shipyard

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Background *Previous analyses suggest that worker radiation dose may be significantly increased by routine occupational X-ray examinations. Medical exposures are investigated for 570 civilian workers employed at the Portsmouth Naval Shipyard (PNS) at Kittery, Maine. The research objective was to determine the radiation exposure contribution of work-related chest X-rays (WRX) relative to conventional workplace radiation sources.*
Methods *Methods were developed to estimate absorbed doses to the active (hematopoietic) bone marrow from X-ray examinations and workplace exposures using data extracted from worker dosimetry records (8,468) and health records (2,453). Dose distributions were examined for radiation and non-radiation workers.*
Results *Photofluorographic chest examinations resulted in 82% of the dose from medical sources. Radiation workers received 26% of their collective dose from WRX and received 66% more WRX exposure than non-radiation workers.*
Conclusions *WRX can result in a significant fraction of the total dose, especially for radiation workers who were more likely to be subjected to routine medical monitoring. Omission of WRX from the total dose is a likely source of bias that can lead to dose category misclassification and may skew the epidemiologic dose–response assessment for cancers induced by the workplace.* Am. J. Ind. Med. 47:206–216, 2005.
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KEY WORDS: X-rays; medical surveillance; photofluorography; bone marrow; radiation; occupational exposure; dose

INTRODUCTION

The Portsmouth Naval Shipyard (PNS), a US nuclear naval facility located in Kittery, Maine, has a long history in designing, constructing, and repairing all types of naval ships dating back to 1800. Beginning in the mid-1950s, workers at PNS were trained to construct and overhaul nuclear-powered submarines. Concurrently, PNS implemented a comprehensive dosimetry program to monitor civilian workers who were potentially exposed to radiation and radioactive materials. PNS commissioned its first nuclear-powered submarine in 1958 and nine additional nuclear submarines were built through 1971. Activities associated with the overhaul, repair, and refueling of nuclear submarines commenced during the same time and continue today. Over the course of nuclear work, the magnitude of the labor force ranged between approximately 5,000 and 8,000 workers.

A case-control study being conducted by National Institute for Occupational Safety and Health (NIOSH) is examining the possible association between occupational exposure to external ionizing radiation and leukemia mortality among the civilian workforce. Occupational radiation exposure at PNS occurred during the construction, overhaul, repair, and refueling of nuclear-powered submarines [Rinsky et al., 1980]. An additional source of PNS radiation exposure

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now being considered in this study is medical X-ray examinations that were delivered to workers during routine physical examinations and during diagnosis of illness or injury at the workplace. Work-related X-rays (WRX) are defined as X-ray examinations conducted as a condition of employment such as those performed during pre-employment, termination, and periodic occupational medical examinations. For each subject in the case-control study, NIOSH researchers are assessing worker radiation exposures from: conventional shipyard sources encountered from work assignment; WRX; and other medical X-ray examinations.

This report describes exposures from WRX and other medical X-ray examinations. The specific objectives were to: develop methods for estimating exposure from medical X-ray examinations for an epidemiologic study, estimate doses to the active bone marrow for all study subjects, and evaluate misclassification that may result from the omission of WRX from this assessment.

Historical Medical Monitoring Programs

The US Navy Bureau of Medicine issued guidelines for radiation worker medical screening in 1948 [Bureau of Medicine and Surgery, 1948]. Radiation worker medical examinations began at PNS to establish ‘‘radiological background’’ information in 1957. Later, the Radiation Health Protection Manual described annual physical examinations for health monitoring of radiation workers at PNS starting in 1963 [Bureau of Medicine and Surgery, 1964].

The PNS routine health surveillance program included a periodic medical examination for all radiation workers as a condition of continuing employment. In addition, all workers received examinations prior to employment and at employment termination. The content and frequency of examinations varied with job assignment and employment era. For example, a typical radiation worker hired in 1964 received baseline and annual physical examinations, including a chest X-ray examination [Bureau of Medicine and Surgery, 1964]. However, the same radiation worker employed in 2001 would receive a physical examination at 5-year intervals up to age 50, biannually after age 50, and annually beginning age 60 [Bureau of Medicine and Surgery, 2001].

The posterior-to-anterior (PA) view of the chest similar to conventional medical screening for tuberculosis since the 1930s [Hilleboe and Morgan, 1945] was adopted by PNS for their routine medical monitoring program. Prior to May 1, 1966 nearly all chest X-ray examinations were performed by photofluorography. A retired PNS radiologist confirmed the wide use of the single-view photofluorographic technique for routine chest examinations in the early 1960s. The PNS records did not indicate stereographic photofluorography that was used for screening at US Department of Energy (DOE) facilities through the mid-1950s [Cardarelli et al., 2002].

After May 1, 1966, routine chest examinations were conducted using direct radiography with standard 14 × 17 inch X-ray film. Non-routine chest X-ray examinations, such as those obtained following an injury, illness, or as follow-up from an abnormal routine film, were performed by direct radiography and frequently consisted of multiple views.

METHODS

Case and Control Selection

Four age-matched controls per leukemia case were randomly selected from risk sets defined from the cohort of PNS civilian workers employed between 1952 and 1992 using incidence density sampling [Beaumont et al., 1989]. A risk set consists of all controls who were under observation and who lived to an age greater than the age of the index case at the time of death. Matched controls could be selected more than once. In the epidemiologic analysis, radiation exposure for each control was assessed only to the date the control reached the index case age at death (cutoff date). Among the 575 cases and controls, there were 570 individuals requiring dose reconstruction.

The exposure assessors were blind to case status during dose reconstruction. Doses were initially estimated without regard to cutoff dates and then truncated for the final case and matched controls dataset. Within this report, analyses of study subjects, workers, or individuals are for the 570 workers without duplication or adjustment for cutoff dates. However, analyses pertaining to cases and controls refer to the 575 dose reconstructions with cutoff dates applied.

Records Collection

Medical records for 533 (94%) of the 570 study subjects were obtained. The format and content of information varied with time and were less detailed in early years. Information describing medical X-ray examinations was present for 512 study subjects (90%). Available examination data consisting of examination date, reason (i.e., WRX or nonroutine), type of projection (i.e., body part and orientation), and imaging equipment used (i.e., photofluorographic or direct radiographic) were coded into a relational database.

X-ray equipment and operating parameters used at PNS dating back to 1961 were described in historical documents. Additional data necessary to estimate dose from medical X-ray examinations, such as frequency, type, and technique, were not always found in the medical records. In the absence of definitive information, the observed type and frequency of X-ray examinations used at PNS for the period 1961 through 1973 were extended to all times so that dose evaluations could be performed for this study.

Dosimetry

Medical X-ray examination exposure

The average absorbed dose to the active (hematopoietic) bone marrow per exam was determined for each PNS X-ray examination procedure using mathematical simulations of photon interactions in the body. These values were defined as Dose Conversion Factors (DCFs), which were multiplied by the number of examinations received by a worker to estimate the worker's bone marrow dose. The Monte Carlo analysis, which is based upon the stochastic transport of X-rays as they interact and deposit energy in tissue, used the computer code PCXMC (2000) developed by the Finnish Center for Radiation and Nuclear Safety [Tapiovaara et al., 1997]. Photon transport is modeled using a computational phantom designed by Cristy [1980] after the adult hermaphroditic phantom specified by Snyder et al. [1978]. The bones of the phantom are modeled as a homogeneous mixture of mineral bone, active bone marrow, and other organic constituents of the skeleton. The overall composition of the skeleton is assumed constant over all bones in the body with regional distributions of active bone marrow approximated for a 40-year-old male [Cristy, 1981].

Exam dose estimation required specific knowledge of X-ray geometry, accelerating voltage and current, exposure time, beam filtration, and patient sex, age, and anatomy. The physical arrangement of the X-ray beam and patient were used as described by the US Naval Medical School [1963]. The other parameters necessary for modeling were adopted from historical records and from average values reported by the NCRP [1968, 1989] and Rising and Soldat [1959]. A total of 14 X-ray examination procedures, consisting of 37 separate projection views described in shipyard medical records, were modeled and DCFs assigned.

Conventional sources of exposure

Whole-body penetrating gamma radiation emitted by ^{60}Co and other neutron-activated corrosion products are the primary source of occupational radiation exposure during the overhaul, repair, and refueling of nuclear-powered submarines [Murray and Terpilak, 1983]. Annual radiation doses obtained from dosimetry records for each of the monitored workers were entered into a relational database. The doses were adjusted to account for recognized biases in the measurement process that arise from exposure to heterogeneous radiation fields, calibration methods, dosimeter design, and the dosimeter energy response [Fix et al., 1994; Gilbert and Fix, 1995; Thierry-Chef et al., 2002; Daniels et al., 2004]. Dosimeter-specific conversion coefficients were applied to the adjusted doses to obtain an estimate of the absorbed dose to the active bone marrow. The coefficients were derived as described by Thierry-Chef et al. [2002] who experimented with various dosimeters to obtain information for normalizing dosimetry responses within two specific photon energy ranges (100–300 keV and 300–3,000 keV) and different combinations of anterior-to-posterior, rotational, and isotropic exposure geometries. Active bone marrow doses were determined using the dose conversion coefficients specified in ICRP Publication 74 [1996].

Alternate Estimation Methods

The retrospective assessment of absorbed bone marrow dose from WRX relied on historical medical records. NIOSH discovered historical medical records for only 533 of the 570 PNS study subjects. Only 512 of these medical records contained medical X-ray examination data, so that resulting doses could not be directly determined for 58 subjects. For these individuals, an algorithm estimated absorbed bone marrow dose based upon historical information about the type and frequency of WRX performed.

Statistical Methods

The distribution of the recorded radiation monitoring data for the cases and controls was compared to monitoring data from the whole PNS cohort. A *t*-test was used to examine differences in means. Likewise, a comparison of the medians and standard deviations was performed by Wilcoxon test and *F*-test, respectively.

The absorbed dose to the bone marrow from both medical and conventional sources of radiation exposure was determined for each study subject. Cumulative bone marrow dose distributions from conventional sources of exposure, WRX exposures, and other medical X-ray examinations were examined for radiation worker and non-radiation worker sub-cohorts, as applicable. Changes to the radiation worker cumulative dose distribution from WRX and other medical X-ray exposures were examined by comparative analysis. Likewise, differences between radiation worker and non-radiation worker doses were examined by comparing the distributions of dose from WRX and other X-ray examination exposures.

The algorithm used to estimate exposures in the absence of available medical records was tested using a paired-comparison of the dose distributions from modeled results and the dose distributions from workers with complete records of WRX between 1/1/48 and 12/31/68. These dates include the onset of WRX and the end of annual WRX for radiation workers. The type of X-ray equipment, techniques, and procedures used in the medical monitoring program for this period is documented in the historical records and a complete work history for each person in this group was also available.

RESULTS

Study Population

The distributions of onsite cumulative whole-body doses from radiation monitoring records were compared between monitored cases and controls ($n = 201$) and all monitored workers within the PNS cohort ($n = 13{,}468$). The arithmetic mean and median whole-body doses for all monitored workers in the cohort were 19.9 and 2.90 mGy, respectively. The arithmetic mean and median values for the monitored cases and controls were 23.2 and 4.52 mGy, respectively. A t-test did not indicate a statistically significant difference between arithmetic means at the 95% confidence level. The F-test indicated there was not a statistically significant difference between the standard deviations of the two samples at the 95% confidence level. A Wilcoxon test of the medians from the two distributions demonstrated there was not a statistically significant difference at the 95% confidence interval.

Medical Monitoring

A total of 3,435 X-ray examinations for 512 subjects were identified in the PNS medical files. There were 2,693 WRX examinations (78%) resulting from pre-employment and termination physicals, mass tuberculosis screening, and routine medical surveillance programs. The remaining 742 X-ray examinations were related to specific diagnoses of disease or injury and were not included in the WRX category. Records of onsite WRX were available for 185 radiation-monitored workers and 320 non-monitored workers. Radiation workers received more onsite WRX exposures than non-monitored workers with 1,484 examination records (57%) for monitored workers and 1,102 examination records (43%) for the non-monitored group. The medical records also included 107 X-ray examinations conducted outside of PNS employment, consisting of 81 (75.8%) from WRX and 26 for other diagnostic reasons.

Chest X-ray examinations predominated with 1,649 (57%) obtained by photofluorography and 1,228 (43%) by direct radiographic procedure (Table I). Greater than 60% of the study subjects employed prior to 1956 received X-ray examinations of the chest.

Most photofluorographic examinations (91%) were conducted prior to May 1966, although 143 additional photofluorographic examinations were conducted up to 1971. The medical records suggest that these later photofluorographic examinations were from a voluntary screening program that appears to have no apparent relationship to radiation monitoring status, job title, shop assignment, or pay scale. The number of annual chest X-ray examinations changed with time at PNS. Most of this variability is linked to radiation worker physicals that required routine examination of the chest. The changes in the number of radiation worker physicals over time are shown in Figure 1.

TABLE I. Portsmouth Naval Shipyard Medical X-Ray Examinations

	Number of X-ray examinations		
Body part and technique	Radiation workers	Non-monitored workers	Total
Abdomen	2	2	4
Arm	3	3	6
Barium enema	1	2	3
Cervical spine	14	5	19
Chest (other diagnostic)	79	137	216
Chest (WRX direct radiography)	763	249	1,012
Chest (WRX photofluorography)	733	916	1,649
Chest CT	1	1	2
Clavicle	0	1	1
Coccyx	0	1	1
Elbow	39	15	54
Facial bones	3	1	4
Foot, toe, ankle	44	47	91
Hand, wrist, or finger	99	53	152
Hip, pelvis	2	4	6
Intravenous pyelogram	1	0	1
Knee	32	19	51
Leg	11	15	26
Lumbar-sacral spine (other diagnostic)	44	23	67
Lumbar-sacral spine (WRX)	4	2	6
Shoulder	18	17	35
Skull	8	6	14
Sternum	0	1	1
Thoracic spine	2	1	3
Upper G.I.	3	8	11
Grand total	1,906	1,529	3,435

WRX, work-related X-ray examination.

Figure 1 also allows comparisons of the number of annual radiation dosimetry records with the number of annual medical examinations conducted for 203 study subjects who had radiation worker physical examinations. The ratio of medical examinations to radiation dosimetry records was highest between 1963 and 1968. Forty-seven workers received radiation worker physicals apparently without performing "radiation work." These workers may have been: disqualified as radiation workers because of a medical problem, reassigned, or terminated before beginning radiation work, or temporarily excluded from radiation work due to other reasons.

Dosimetry Results

Table II lists the DCF values predicted by Monte Carlo analysis for determining bone marrow doses associated with

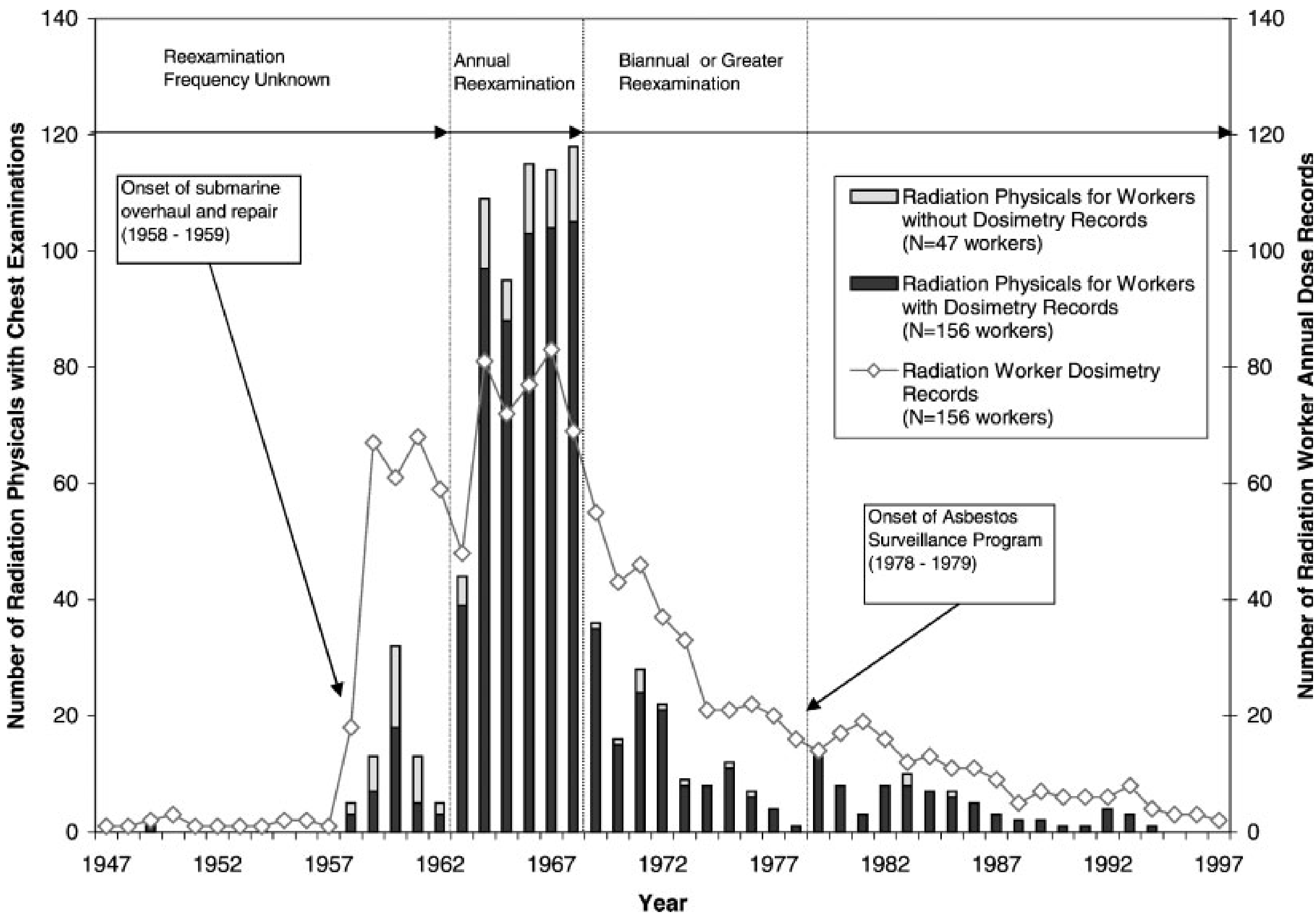

FIGURE 1. Radiation physical examinations that include a single view (posterior-anterior) chest X-ray examination ($n = 203$ workers).

X-ray procedures for all study subjects. Except for photofluorographic examinations, the DCFs were calculated assuming available equipment and technique descriptions. The dose to the active bone marrow for a single-view PA photofluorographic examination of the chest is 1.50 mGy per exam assuming that the tube voltage, current, exposure time, and effective aluminum filtration thickness was 100 kVp, 200 mA, 0.3 s, and 2.5 mm, respectively. These values were specified in procedures and descriptions of equipment for photofluorography [Hilleboe and Morgan, 1945; Rising and Soldat, 1959; US Naval Medical School, 1963].

A collective absorbed dose to the active bone marrow of 2.86 person-Gy was estimated from the available X-ray examination records for all study subjects. This dose consisted of 2.53 person-Gy from WRX and 0.33 person-Gy from non-routine X-ray examinations. Photofluorography and direct radiography of the chest account for 2.47 person-Gy and 0.06 person-Gy (0.04–0.07 mGy/exam), respectively. Radiation workers ($n = 185$) received 1.33 person-Gy from medical X-rays while the collective dose to non-monitored workers was 1.53 person-Gy.

The cumulative bone marrow absorbed dose statistics for radiation monitored and non-monitored workers by the different sources of exposures and are shown in Table III. These dose estimates exclude offsite exposures and are based on all available medical and exposure records. Each cumulative dose was calculated by summing the doses for each study subject without adjustment for case-control cutoff dates.

Summing bone marrow absorbed dose contributions from both WRX and workplace exposures for the radiation workers ($n = 185$) results in a distribution with arithmetic mean, and median values of 24.55 and 11.15 mGy, respectively. A Kolmogorov–Smirnov Test indicates the maximum difference in the cumulative distributions (i.e., with and without WRX) occurs in the low dose region. There is little observed effect for cumulative doses greater than 20 mGy. The summed dose distribution was fit to a lognormal distribution (Kolmogorov approximate p value of 0.06) with estimated mean and standard deviation values of 26.8 and 53.5 mGy, respectively (Fig. 2). True exposures less than the measurement sensitivity were recorded as zero, resulting in

TABLE II. Final Dose Conversion Factors for Portsmouth Naval Shipyard X-Ray Examinations

Modeled examination series	Final DCF assignment (mGy per exam)	Dose assigned by Preston-Martin and Pogoda [2003] (mGy per exam)[a]	Dose range from Preston-Martin and Pogoda [2003] (mGy per exam)[b]
Abdomen	0.72	0.42	0.11–5.12
Barium enema	4.72	6.33	1.87–76.75
Cervical spine	0.15	0.11	0.01–0.52
Chest, MX (multi projection)	0.07	0.05	0.01–0.54
Chest, WRX direct radiography (single view)	0.04	0.05	0.01–0.54
Chest, WRX photofluorography	1.50	N/A	0.69–3.85
Coccyx	1.22	1.70	0.88–2.51
Intravenous pyelogram (IVP)	2.04	2.10	0.02–11.60
Lumbar spine	2.29	1.52	0.10–4.10
Lumbosacral spine	3.50	1.07	0.54–4.50
Pelvis	0.46	0.60	0.39–0.81
Shoulder	0.08	0.06	0.02–0.60
Skull	0.31	0.46	0.12–1.22
Sternum	0.98	0.60	0.60–0.60
Thoracic spine	0.94	0.72	0.17–4.70
Upper G.I.	3.34	3.64	0.66–11.80

[a]Preston-Martin and Pogoda [2003].
[b]Except for the WRX chest photofluorographic examination, the range of values was determined by a literature search conducted by Preston-Martin and Pogoda [2003]. For chest photofluorography, the range of values is taken from [Quinn, 1945; Hodges, 1948; Webster and Merrill, 1957; Rising and Soldat, 1959; Gritlin and Lawrence, 1966; Cardarelli et al., 2002].

the lack of fit at lower doses [Strom, 1986]. The departure from lognormal at higher doses results from administrative controls that limit conventional sources of occupational radiation exposure [Daniels et al., 2004]. Kumazawa and Numakunai [1981] suggest that a hybrid lognormal distribution is the best statistical model to fit this dose pattern.

Comparison of the cumulative bone marrow absorbed dose distribution from WRX performed for radiation workers ($n = 185$) and non-radiation workers ($n = 320$) demonstrates that radiation workers received greater WRX exposure than non-radiation workers (Fig. 3). This finding is consistent with medical monitoring procedures at PNS that required radiation workers to receive periodic chest X-ray examinations in order to continue as a radiation worker [Bureau of Medicine and Surgery, 1948, 1964]. On the other hand, all workers had similar potential to receive exposure from other

TABLE III. Cumulative Absorbed Bone Marrow Dose by Source of Exposure at Portsmouth Naval Shipyard

Source of radiation exposure	Number of study subjects[a]	Arithmetic mean (mGy)	Median (mGy)	Minimum (mGy)	Maximum (mGy)	SE
Workplace[b]	205	17.64	3.51	<0.01	222.7	2.42
Medical X-ray exams	510	5.61	5.02	0.04	24.68	0.17
WRX[c]	505	4.95	4.50	0.04	16.54	0.15
Radiation worker	185	6.16	6.16	0.04	15.08	0.26
Non-monitored worker	320	4.25	4.50	0.04	16.54	0.16
Other medical X-rays[c]	169	1.67	0.22	0.07	21.16	0.21
Radiation worker	76	2.24	0.31	0.07	21.16	0.40
Non-monitored worker	93	1.20	0.21	0.07	8.13	0.19

[a]Dose estimates limited to the number of study subjects with exposure and/or X-ray examination records available. Doses are not adjusted for cutoff dates.
[b]Workplace refers to exposures resulting from actual work conducted at the shipyard.
[c]X-ray examinations are limited to those conducted onsite.

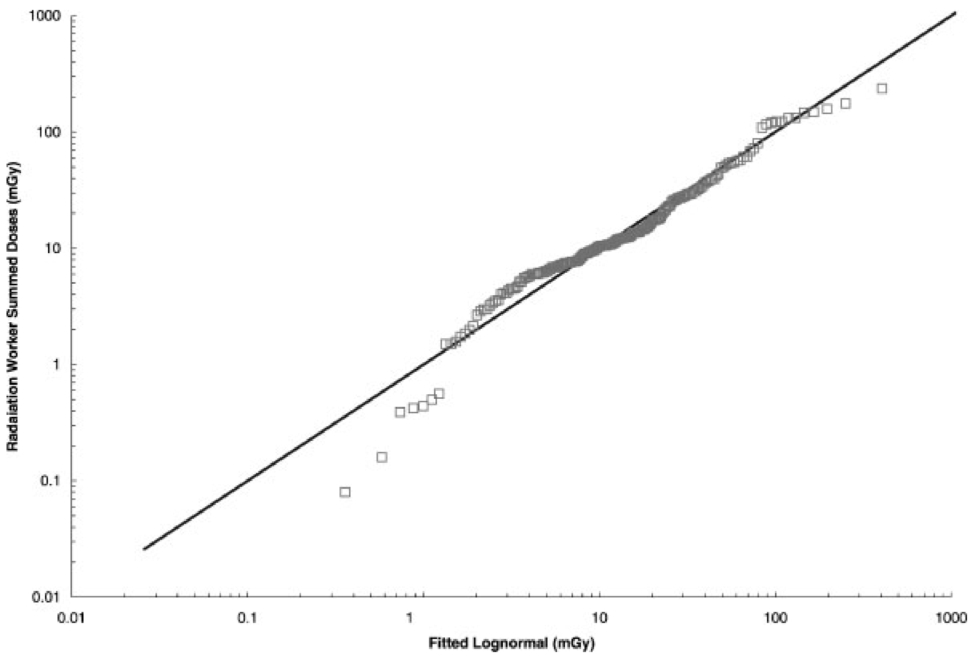

FIGURE 2. Quantile-Quantile plot of cumulative absorbed doses from all known sources of exposure fitted to a lognormal distribution.

types of diagnostic X-ray examinations (Fig. 4). Although a slight difference exists between the two distributions, the difference shown in Figure 4 is far less than that shown in Figure 3. For example, there is no significant difference between the median values at the 95% confidence level (Wilcoxon test). This finding suggests that the frequency of non-routine X-ray examinations was not significantly influenced by radiation worker status.

WRX exposure was greatest during the time when photofluorography was used to obtain chest X-rays and was also a relatively greater component of total work-related exposures prior to 1959 (Fig. 5). Before 1959, PNS exposures to ionizing radiation were limited to medical monitoring and occupations involving industrial radiography, instrument maintenance and calibration. A large increase in collective dose is realized with the onset of overhaul and refueling activities in 1959 [Daniels et al., 2004]. The ratio of WRX to conventional workplace sources of external radiation exposure for radiation workers is greatest prior to 1966, after which the photofluorographic technique was replaced by direct radiography. After cessation of annual chest X-rays in 1969, the contribution of WRX to the total dose is minor when compared to the dose from radiological work practices.

COMPLETED EXPOSURE ASSESSMENT

The final exposure assessment contains estimates of annual bone marrow absorbed doses from radiation monitoring results, WRX, and other medical X-ray examinations for each of the 570 workers that comprise the 575 cases and controls in the leukemia mortality study. Cumulative doses were truncated for matched controls at the attained age of associated cases. Doses were derived from worker exposure

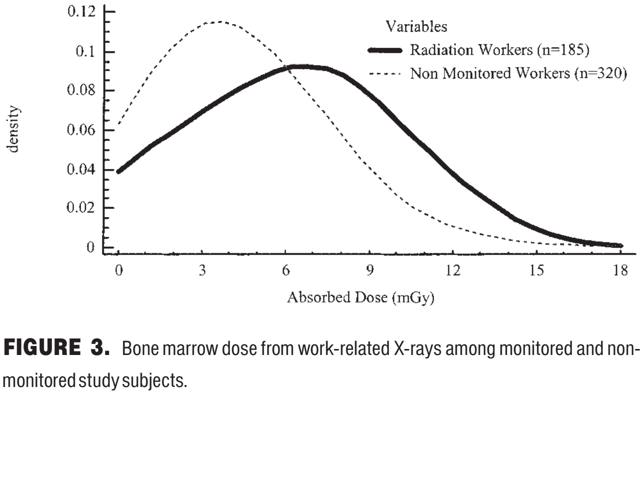

FIGURE 3. Bone marrow dose from work-related X-rays among monitored and non-monitored study subjects.

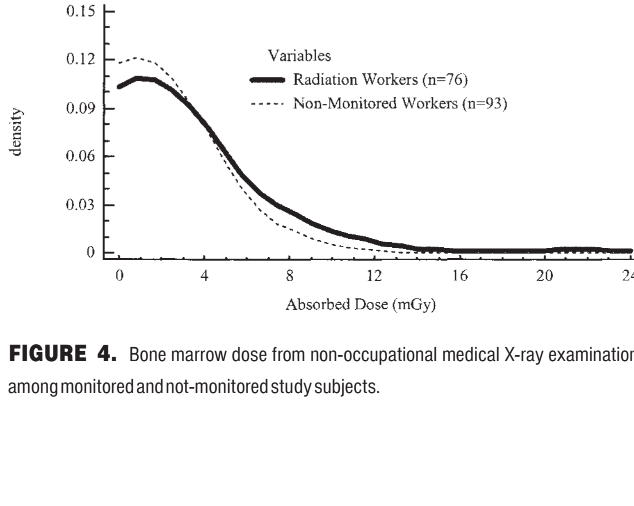

FIGURE 4. Bone marrow dose from non-occupational medical X-ray examinations among monitored and not-monitored study subjects.

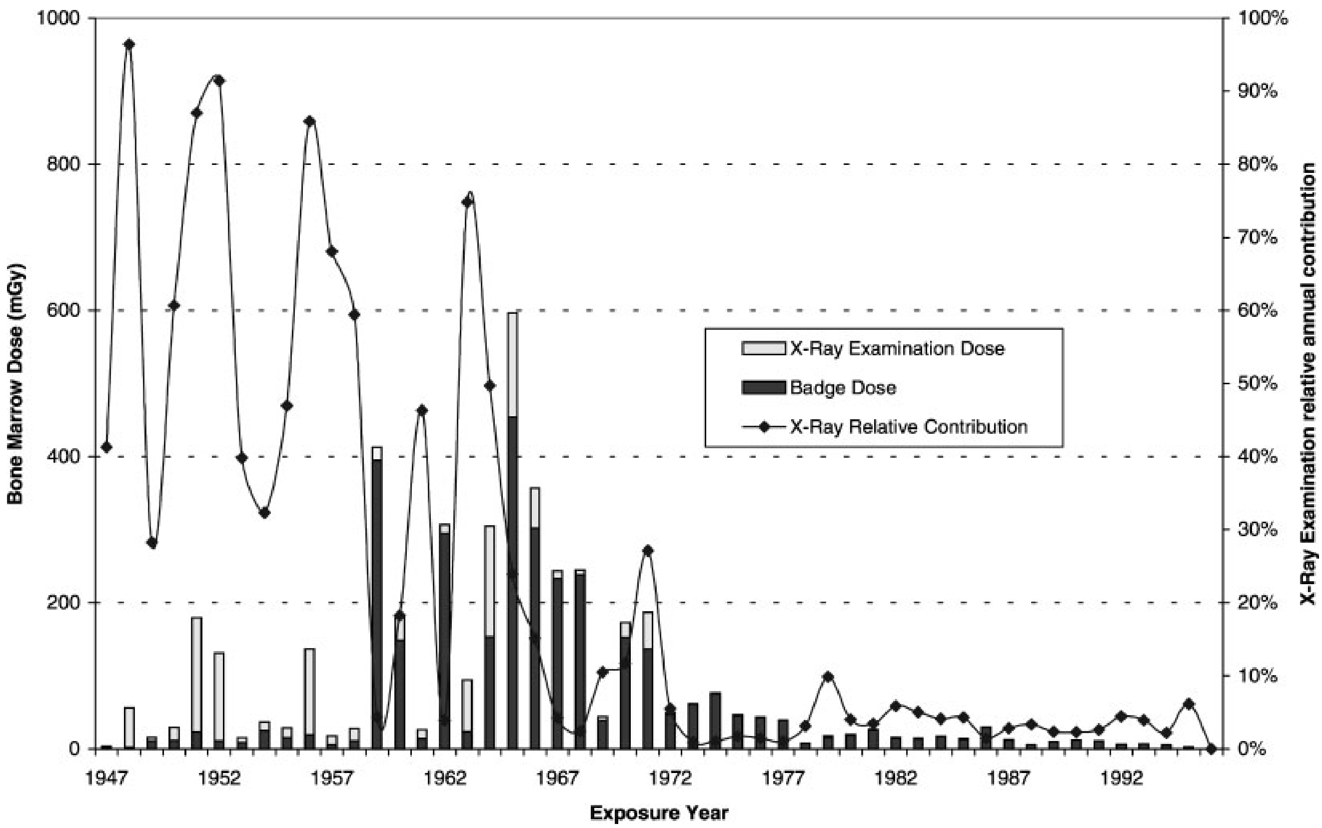

FIGURE 5. Collective bone marrow absorbed dose by year and the relative contribution from chest X-ray examinations for radiation workers at the Portsmouth Naval Shipyard ($n = 184$).

records whenever historical data were available or from the NIOSH algorithm whenever medical records were incomplete or unavailable. The algorithm was constructed from the following assumptions based on previous results:

- All WRX received before 1966 were produced by photofluorography and thereafter by direct radiography.
- All employees in 1948, 1951, 1952, and/or 1956 received an annual photofluorographic chest examination for mass tuberculosis screening.
- Workers hired between 1948 and 1968 received at least one pre-employment medical examination that included an X-ray examination of the chest in the year of hire.
- Radiation workers employed between 1958 and 1962 received a baseline medical examination that included a chest X-ray examination.
- Radiation workers employed between 1963 and 1968 received a medical examination that included a chest X-ray each year for which at least one occupational dose record is reported.

Bias (B) for the algorithm-based WRX exposure estimates was determined by the ratio of the predicted dose (P) to that based on specific X-ray examination evidence in the medical records (A). The standards for comparison were defined as the cumulative absorbed dose to the active bone marrow from WRX for study subjects with available records between 1948 and 1969. Multiplicative regression was used to identify six records as outliers based on studentized residuals in excess of 3.0 in absolute value. Data set A consisted of 453 values of cumulative doses for comparison. The ratios of P to A were lognormally distributed so the geometric mean was chosen as the best measure of central tendency. A bias factor (B) of 1.34 was determined from the geometric mean of P:A. The geometric standard deviation (S) of P:A was 1.72. Uncertainty (K) was calculated by $K = S^{1.96}$ and equaled 2.88. The 95% confidence interval of the estimate was expressed as ($0.26P$, $2.15P$).

Large differences between P and A occurred most frequently when annual chest X-ray examination forms for radiation workers did not appear in their medical records. This type of discrepancy might occur when medical records have been previously retrieved from storage and portions removed to support a petition, such as a disability claim. These records may have been returned to storage at a later time but not combined with the original file. Based on the overall consistency of the X-ray examinations records with the stated PNS policies, adjustments for bias within this exposure assessment were not completed.

The final collective dose estimates from onsite conventional sources of exposure, WRX, and other medical X-rays were 3.43, 2.63, and 0.28 person-Gy, respectively. Work-related photofluorographic examinations conducted prior to 1966 resulted in 2.39 person-Gy, which is 82% and 38% of the collective dose from medical exposures and all onsite exposures, respectively.

Of the cases and controls that were monitored for radiation exposures ($n = 201$), 197 received 1.18 person-Gy from WRX exposures while 355 non-monitored workers of 374 received 1.45 person-Gy. There were 23 cases and controls without records of WRX examinations or work history indicating onsite employment between 1948 and 1969. A summary of the results for cases and controls is shown in Table IV.

DISCUSSION

Compared to direct radiography, the photofluorographic X-ray technique delivers a relatively large bone marrow dose and is reported by Cardarelli et al. [2002] to be responsible for a significant fraction of the cumulative, work-related medical X-ray dose for workers at a DOE plant. A comprehensive review of the literature finds that estimates of the dose delivered to the bone marrow from a photofluorographic examination of the chest for the period from 1945 through 1964, range from 3.85 [Cardarelli et al., 2002] to 0.69 mGy [Hodges, 1948]. The stereoscopic techniques used at DOE facilities in the 1940s and 1950s were not used at PNS. Stereo exams essentially double the exposure per examination when compared to non-stereoscopic examinations. Thus, estimates of WRX exposure for the PNS study subjects are much lower than those in the previous NIOSH analysis for DOE workers [Cardarelli et al., 2002].

The modeled X-ray examination DCFs are within the range of DCF values summarized by Preston-Martin and Pogoda [2003] (Table II). They used interviews and literature citations to assemble a list of active bone marrow dose estimates for X-ray procedures. The median estimate of the cited values for each procedure was used by Preston-Martin and Pogoda [2003] to assess exposures for a study of acute myelogenous leukemia in Los Angeles County (Table II). For most procedures, there was a large variation in dose estimates from different sources. The difference in dose estimates between NIOSH researchers and Preston-Martin and Pogoda [2003] were attributed to the variability in the cited literature and dissimilar estimation methods used by the researchers.

Epidemiologists often consider radiation exposures received during diagnostic and therapeutic medical examinations to be randomly distributed throughout the working population [Cardarelli et al., 2002]. Medical exposures would not cause substantial bias in radiation risk estimates unless they were strongly correlated with conventional sources of occupational exposure [Gilbert and Fix, 1995]. They recognized possible bias from routine chest X-ray examinations, but only to the extent that long-term workers would receive more X-ray examinations than shorter-term workers. Potential bias from greater X-ray examination frequencies due to radiation work was not previously recognized. Dose distributions for PNS cases and controls (Fig. 3) indicate that radiation workers were more likely to receive radiation exposure from work-related medical X-rays than non-radiation workers.

Contrary to common perception, WRX received by workers in this study represents a large fraction of their total dose. Omitting WRX from the total dose estimate could lead to misclassification of exposure, especially for a low dose facility such as PNS. An example potential misclassification appears in Table V, which shows changes in dose category assignments for study subjects who were classified as radiation workers.

Limitations

The study population was chosen based on selection criteria established by the nested case-control study design. If the outcome is associated with radiation exposure, the study population may have higher doses given that all known cases are selected. Likewise, consider that controls are matched to the attained age of the cases. For outcomes that manifest late in life the cases and controls are likely to be older on average than the cohort population. This age

TABLE IV. Final Absorbed Dose Estimates for Cases and Controls Resulting From Medical X-Ray Exposures at Portsmouth Naval Shipyard

Sub-populations of cases and controls	Doses[a] (mGy) from WRX estimated from medical records					Doses[a] (mGy) from WRX estimated by Algorithm (1948–1969 only)					Doses[a] (mGy) from other medical X-ray examination extracted from medical records				
	N	Mean	Median	Max	SE	N	Mean	Median	Max	SE	N	Mean	Median	Max	SE
Monitored (n = 201)	180	6.01	6.12	15.08	0.27	17	5.61	6.12	12.12	1.08	72	2.29	0.30	21.16	0.42
Non-monitored (n = 374)	324	4.13	4.5	16.54	0.16	31	3.77	3.00	9.00	0.45	90	1.23	0.21	8.13	0.20
Combined (n = 575)	504	4.80	4.5	16.54	0.14	48	4.43	4.50	12.12	0.49	162	1.71	0.22	21.16	0.22

[a]Absorbed dose to the active bone marrow.

TABLE V. Changes in Absorbed Dose Categories From Work-Related X-Ray Examinations at Portsmouth Naval Shipyard

Dose (D) category[a] (mGy)		Number of workers in dose category[b]		Category adjustments[c]						
				Excluding WRX						
CAT	Limits	Excluding WRX	Including WRX	1	2	3	4	5	CAT	
1	D = 0	24	0	*0*	0	0	0	0	1	Including WRX
2	0 < D <1	47	8	3	*5*	0	0	0	2	
3	1 D < 10	54	72	17	33	*22*	0	0	3	
4	10 D < 50	43	84	4	9	32	*39*	0	4	
5	D 50	18	22	0	0	0	4	*18*	5	

[a]Absorbed dose (D) to the active bone marrow.
[b]WRX, work-related X-ray examinations.
[c]The number of workers assigned to CAT (i) from dose estimates excluding dose from WRX compared to the number or workers assigned to CAT (i) with the additional dose from WRX. Values shown in italics represent the number of workers in which there is no change in category assignment. Values below and to the left of the italicized values represent upward category adjustments.

difference may be translated into a longer work history, which is often correlated with exposure duration. Hence, the study population may have higher doses on average than the cohort. Although general comparisons have been made that demonstrate similarities in radiation exposures between the study population and the cohort, estimating cohort exposures from medical X-ray examinations based on these similarities alone is not recommended.

Examination types and frequencies were derived from existing medical records resulting in exposure estimation uncertainties for workers with incomplete or inaccurate records. Although medical records were obtained for a high percentage (90%) of study subjects, the availability of pertinent data within the records varied considerably. This variation, in part, was due to differences in recording practices by attending physicians and changes in record management policies throughout the years. An underestimate of examination frequencies is a likely source of error and may also help to explain the observed bias in the NIOSH algorithm.

A number of factors affect the actual dose to workers from a diagnostic X-ray procedure. Factors such as applied voltage (kVp), beam current (mA), time of exposure, distance, waveform, amount and kind of filtration used, collimation, tube housing characteristics, type and speed of the film, development procedure, screens, grids, and patient age, sex, and anatomy play important roles. Values for these factors were taken from reference literature when records were insufficient to determine actual values. Differences between actual values and reference values may have resulted in some bias. Insufficient information is available at this time to test the magnitude of any bias or to sufficiently describe uncertainties in the estimates.

Estimating organ doses from both medical and conventional sources provided a simple approach to normalizing exposure data. Although similar computational techniques were used to determine doses, uncertainties result from the simplified assumptions needed to model photon transport and interaction. These uncertainties are further amplified given the complexity of the human body and the two extremes presented. For example, workplace exposures typically resulted from whole body irradiation by photons with energies greater than 100 keV. In contrast, the dose associated with medical X-ray examinations results from photon spectra below 100 keV and is delivered mostly to that portion of the body exposed to the X-ray beam. The dose from medical sources is highly dependent on the active marrow distribution throughout the skeleton, which varies greatly with sex, age, and anatomy [Cristy, 1981].

CONCLUSION

Historical records of X-ray procedures, techniques, and X-ray equipment used in routine medical monitoring at PNS provided the technical basis for developing a set of dose conversion factors for estimating bone marrow dose delivered to workers who were required to receive chest X-ray examinations as a condition of employment. The use of photofluorography in medical monitoring between 1948 and 1966 is responsible for the majority of the exposure delivered to workers who received WRX at PNS. This analysis shows that bone marrow dose from WRX can represent a significant fraction of the total dose delivered to workers, especially for radiation workers who were more likely to be subjected to medical monitoring than other categories of workers. Omission of WRX from the total bone marrow dose is a likely source of bias that can lead to misclassification of dose category, especially for a facility where traditional sources of occupational radiation exposure are low. A model has been developed that uses an algorithm to combine information from work histories and descriptions of procedures, techniques and X-ray equipment used in the medical monitoring program to predict the total bone marrow dose for all workers at PNS, even if some fraction of their medical monitoring data was missing or unavailable. These methods may be useful for estimation of exposure from WRX in other occupational settings.

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