Paper

BONE MARROW DOSE ESTIMATES FROM WORK-RELATED MEDICAL X-RAY EXAMINATIONS GIVEN BETWEEN 1943 AND 1966 FOR PERSONNEL FROM FIVE U.S. NUCLEAR FACILITIES

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Abstract—**Inclusion of dose from work-related medical x-ray examinations with occupational external dose in an epidemiological study may reduce misclassification of exposures and provide more accurate assessment of leukemia risk from occupational exposure to ionizing radiation. In a multi-site leukemia case-control study, annual bone marrow doses due to work-related x-ray examinations given between 1943 and 1966 were estimated for cases and controls employed at five nuclear facilities. Only active bone marrow dose from photofluorographic chest and routine lumbar spine x rays were included. Bone marrow dose assigned for a single exposure ranged from 1.0 to 1.4 mGy. Mean and median cumulative bone marrow doses for each of the five sites from work-related x-ray examinations ranged from 2.0 to 14 mGy and 2.1 to 8.8 mGy, respectively. Results suggest that bone marrow dose from work-related photofluorographic and lumbar spine x-ray examinations given during the time period of this study may be significant compared to occupational bone marrow dose.**
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Key words: x rays; exposure, occupational; dose assessment; radiation, medical

INTRODUCTION

WORK-RELATED MEDICAL x-ray examinations (WRX) are defined as medical x-ray examinations conducted as a condition of employment, such as those performed during pre-employment, termination, and periodic occupational medical examinations. Absorbed dose from WRX was not included in official individual occupational dose monitoring records at nuclear facilities (ICRP 1966). However, many workers at nuclear facilities were required to have WRX. Some studies have indicated that photofluorographic (PFG) chest x-ray examinations could significantly contribute to the worker's cumulative external dose (Cardarelli et al. 2002; Daniels et al. 2005). There is some evidence that radiation workers have been more likely to receive exposure from WRX than workers without other occupational ionizing radiation exposures (Daniels et al. 2005).

In epidemiological studies, misclassification results when a subject is assigned to an attribute or category, in this case a dose, other than that to which he should be assigned. This can result in an underestimate or overestimate of the dose response to external ionizing radiation and thus, underestimate or overestimate potential leukemia risk from occupational radiation exposure. To reduce misclassification of cumulative occupational external dose in a multi-site leukemia case-control study, annual bone marrow doses from WRX were estimated for 1,269 study subjects who were employed at five U.S. nuclear facilities. The study subjects include 257 leukemia cases, each with four randomly selected age-matched controls. Controls could be selected more than once. All workers in this study were identified in radiation monitoring records at one of the five sites. The facilities were Hanford, Oak Ridge National Laboratory (ORNL) (called Clinton Laboratories until 1948), Savannah River Site (SRS), Los Alamos National Laboratory (LANL) (then known as Los Alamos Scientific Laboratory), and Portsmouth Naval Shipyard (PNS) in Kittery, Maine.

In the 1940's and 1950's, chest x-ray examinations were often done by photofluorography, also known as photoroentgenography or mass miniature radiography. This technique was relatively inexpensive and simple for screening large populations primarily for infectious respiratory disease. Unlike direct radiography, where a film is exposed by the incident x rays passing through the chest, photofluorography uses a fluorescent screen placed next to the patient's chest. Incident x rays cause the screen to fluoresce, forming an image of the internal chest structure. This image was then photographed on either 10.2 by 12.7 cm (4 by 5 inch) film (cut film), or

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35- or 70-mm film (roll film). The typical chest projection was posterior-anterior (PA) (Mason 1944). Many devices produced two projections per examination for stereo imaging (U.S. Naval Medical School 1963).

METHODS

Records collection

The quantity of interest for the epidemiological study was cumulative absorbed dose to the active bone marrow. Active bone marrow dose per WRX projection was calculated using x-ray examination parameters found in a search of historical site documents and the scientific literature. The number of projections assigned to each individual was determined from medical x-ray examination records, if available. However, records capture for the epidemiological study was conducted prior to identifying WRX as a significant exposure source. Therefore, few medical records were available for data abstraction. If medical records were not available, the number of WRX projections was estimated from site-specific program information.

For Hanford and PNS, workers' x-ray examination records and specific operating parameters for the x-ray devices used by the facilities were available. Operating parameters were also available for the x-ray device used at ORNL, but similar information was not located for SRS or LANL. For ORNL, SRS, and LANL, individual medical x-ray examination records were not captured due to feasibility limitations, so medical monitoring practices and work history information were used to estimate examination techniques and frequencies.

PCXMC calculations

Absorbed doses to bone marrow were calculated using PCXMC (Personal Computer program for X-ray Monte Carlo) developed by the Finnish Centre for Radiation and Nuclear Safety (Servomaa and Tapiovaara 1998). The organ doses calculated with PCXMC were compared to organ doses calculated by the National Radiological Protection Board (NRPB) for common x-ray examination projections (Servomaa and Tapiovaara 1998). Agreement between the two was good for all organ doses, including bone marrow dose, although there were slight differences due to the way PCXMC calculates bone marrow dose.

This computer program calculates organ doses and effective doses using Monte Carlo simulation of stochastic photon transport in a computational phantom (Cristy 1980), which was based on the adult hermaphroditic phantom designed 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 to be constant over all bones in the body with regional distributions of active bone marrow approximated for a 40-y-old male (Cristy 1981). The Monte Carlo method used in PCXMC divides the absorbed energy of the skeleton into two parts and calculates the kerma in the active bone marrow and the remainder of the skeletal material separately. Because of the effect of small cavity size, the active bone marrow dose is increased by a few percent. The absorbed energy in the skeleton is reduced by the same amount the absorbed energy is increased in the active bone marrow (Tapiovaara et al. 1997).

Some changes have been made to the phantoms that allow the user to modify the height and/or weight of any of the phantoms. PCXMC calculates scaling factors from the modified body measurements for the direction of the z-axis (phantom height) and x- and y-axes (phantom width and thickness). The application of these scaling factors changes the size and mass of the organs accordingly. The modification only affects the dimensions in either the horizontal or vertical direction and does not, for example, modify the fat content of a tissue or organ. The origin of the coordinate system for the phantom remains in the center of the trunk (Tapiovaara et al. 1997).

Organ doses can be calculated with PCXMC from entrance air kerma (mGy), entrance exposure (mR), or the product of beam current and time (mAs). Equipment operating parameters and examination conditions can be varied (Tapiovaara et al. 1997). Required parameters include beam size (height and width) on the patient, focus-to-skin distance (FSD), coordinates of the beam on the patient, angle of the projection, kVp, target angle, and quantity and type of added filtration.

PCXMC photon spectra are generated from algorithms for three-phase constant potential x-ray machines. PFG devices in the 1940's and 1950's most likely used full-wave bridge-rectification, which would result in a slight overestimation of bone marrow doses using entrance skin exposures (Verstandig and Ainsworth 1944; Webster and Merrill 1957; ICRP 1982). So the spectra were adjusted by a separate algorithm to account for the voltage ripple expected from the full-wave rectified equipment.[†]

Absorbed doses to the active bone marrow from WRX were estimated only for PFG chest and lumbar spine x-ray examinations due to the large amount of bone marrow dose delivered and their use as routine medical screening procedures. Bone marrow dose from direct radiographic exams was not considered because it is

[†] Unpublished data by D.R. Nestle. 2005.

relatively small (~ 10% of the PFG dose) (Shleien et al. 1978).

Radiation exposure estimates from medical x-ray examination procedures were located for Kadlec Methodist Hospital in Richland, Washington and four medical facilities in Oak Ridge, Tennessee. Similar information for PFG equipment used at PNS were obtained from equipment operating manuals and a U.S. Navy medical x-ray examination procedure manual.

In 1959, gonad and skin doses from various x-ray examination procedures conducted at Kadlec Methodist Hospital were estimated using the x-ray machine purported to be at the hospital from 1946 to 1956. Conditions under which the machine was operated at that time were replicated (Kirklin et al. 1969). The tests utilized an Alderson Research Lab Remab phantom. Only inherent filtration was used during replication of the chest PFG procedure. Measurements were taken with Victoreen R-Meters, Victoreen pocket ion chambers, and thermoluminescent dosimeter discs that had been calibrated against Hanford standard sources (Kirklin et al. 1969). On 8 March 1959, an entrance skin exposure of 3.90×10^{-4} C kg^{-1} (1.51 R) was measured with an R-meter during the PFG procedure. On 12 April 1959, the PFG measurements were repeated resulting in an entrance skin exposure of 3.95×10^{-4} C kg^{-1} (1.53 R).[‡]

For ORNL, a 1956 study of medical x-ray examination doses at area medical facilities reported a measured entrance skin exposure of 3.6×10^{-4} C kg^{-1} (1.4 R) for the chest PFG at Oak Ridge Hospital.[§] Measured entrance skin exposures for AP and lateral lumbar spine x-ray examinations were 5.2×10^{-4} C kg^{-1} (2.0 R) and 1.3×10^{-3} C kg^{-1} (5.0 R), respectively (Lincoln and Gupton 1957). The Health Services Division at ORNL** also identified parameters used for the lumbar spine series.

At PNS, a 1961 memorandum[††] identified a Westinghouse Model PFX machine with a Fairchild motorized 70-mm camera (F 1.5) then in use. The memorandum stated that the PFX was equipped with a WRAS-AA x-ray head with inherent filtration of 0.5 mm Al and installed filtration of 2.0 mm Al. Notes from a 1962 radiation survey[‡‡] indicated standard operations at 85 kVp, 200 mA, for 0.2 or 0.3 s. These settings were consistent with operating methods described by the manufacturer (Westinghouse 1954) and the U.S. Navy (U.S. Naval Medical School 1963). A 1964 industrial hygiene report[§§] indicated that the average of "skin dose measurements on the back of the patient nearest the tube" was 4.4×10^{-4} C kg^{-1} (1.7 R).

In addition, PNS also used a mobile PFG unit for routine chest exams;*** however, the manufacturer and operating parameters for this mobile unit were not available. For this study, it was assumed that the operational characteristics and dose rate from the mobile unit were similar to those estimated for the Westinghouse PFX.

Table 1 shows the equipment and examination parameters reported for chest PFG examinations at Hanford, PNS, and ORNL, and lumbar spine series examinations at ORNL. Several parameters needed to calculate bone marrow doses with the PCXMC program were imputed. The FSD and beam height and width were not reported for examinations in the ORNL studies, the second Hanford study, or the PNS documentation. PCXMC was used to calculate FSD and beam height and width from estimates of the focus-to-image distance (FID) and image height and width. For Hanford, ORNL, and PNS chest PFGs, an image size of 40.6 by 40.6 cm (16 by 16 inches) and a 5-cm grid were assumed. Both the FSD (76.2 cm) and the FID (101.6 cm) were consistent with results reported in the first Hanford study (Table 1), suggesting a distance of 25.4 cm between the skin entrance on the patient and the image. The trunk thickness of the Cristy adult phantom is 20 cm (Cristy 1980), leaving a remaining distance of 5.4 cm, which could account for a grid.

The thickness and type of x-ray tube filtration was also required for bone marrow dose calculations using PCXMC. This information was not reported for the ORNL study or the first Hanford study although the latter report stated that the x-ray machine was operated with inherent filtration only (Kirklin et al. 1969). The second Hanford study duplicated the earlier measurements and skin exposures in both studies were similar.[§] Therefore, the filtration reported by the second study (1.3 mm Al) was assumed for both studies.

For ORNL, the filtration reported for the lumbar spine series was 1 mm Al (Lincoln and Gupton 1957). It was apparent from data collected from other Oak Ridge facilities that only added filtration was reported. The assumed inherent filtration was 0.5 mm Al, so total

[‡] Rising FL, Soldat JK. Letter to W.D. Norwood. Radiation exposures during diagnostic radiographic examinations at Kadlec Methodist Hospital. 30 April 1959.

[§] Gupton E, Tuck T, Lincoln T. Exposure data—Diagnostic radiography—Oak Ridge Hospital. 1956.

** Phillips JE, Director of ORNL Health Services Division. Memo: ORNL historical x-ray practices and protocols (undated).

[††] Munton A. Letter to file. Medical x-ray facilities; inspectional survey of. U.S. Naval Hospital; 1961.

[‡‡] Munton A. Letter to file. Photofluorographic x-ray unit; survey report on. 1962.

[§§] Portsmouth Naval Shipyard Industrial Hygiene Report (partial record). Kittery, ME; 1964.

*** Athanasiou O. Letter to 740. Mobile photographic unit, radiation survey of. 1961.

Table 1. Parameters reported to be used for PFG chest and lumbar spine series examinations at study facilities.

Site	Hanford	Hanford	ORNL	ORNL	ORNL	PNS
Date of measurement	8 March 1959	12 April 1959	N/A[e]	N/A	N/A	N/A
Type of view	PFG chest	PFG chest	PFG chest	LS-AP	LS-Lat	PFG chest
FID[a] (cm)	100	110	122	Not reported	Not reported	101.6
FSD[b] (cm)	76	Not reported	Not reported	99	99	Not reported
Kilovolts peak (kVp)	100	100	90	80	86	85
Current (mA)	100	200	200	40	40	200
Time (seconds)	0.6	0.3[d]	0.5	4	8	0.2–0.3
Beam current × time (mAs)	60	60	100	160	320	40–60
Filtration (mm A1)	Not reported	1.3	Not reported	1	1	Not reported
Measured ESE[c] (C/kg)	3.90×10^{-4}	3.95×10^{-4}	3.6×10^{-4}	5.2×10^{-4}	1.3×10^{-3}	4.4×10^{-4}

[a] FID = Focus-to-image distance. This refers to the distance between the focal point of the x-ray tube and the point on the film on the central axis of the x-ray beam.
[b] FSD = Focus-to-skin distance. This refers to the distance between the focal point of the x-ray tube and the skin entrance point on the central axis of the x-ray beam.
[c] ESE = Entrance skin exposure.
[d] Inferred from the current and beam current time product.
[e] Dates not available.

filtration for the ORNL PFG chest and lumbar spine examinations was 1.5 mm Al.

Other parameters required for PCXMC calculations include patient age, height, and weight, and the projection angle (90° for PA views, 270° for AP views, and 180° for lateral views). Because actual data on height and weight at the time of the examination were not known for the subjects, the values for the standard adult phantom (Cristy 1980) were used (174 cm; 71.1 kg). Coordinates for the point through which the central axis of the x-ray beam is directed were also required. This point is in reference to a coordinate system with the origin located at the center of the bottom of the phantom trunk section. The reference point (X_{ref}, Y_{ref}, Z_{ref}) used for a PA chest x-ray examination was 0, 0, 52 (cm) (Tapiovaara et al. 1997). The reference point of 0, 0, 22 (cm) for the lumbar spine x-ray examinations was inferred from Kereiakes and Rosenstein (1980).

Uncertainties in calculated bone marrow doses were examined. Multiple bone marrow dose calculations were done varying a single parameter each time. Parameters examined include entrance skin exposure (ESE), added filtration, kVp, FSD, and beam area on the patient. To evaluate uncertainty due to patient weight, Hanford subject weights were evaluated and bone marrow doses were calculated using the 5th and 95th percentile and compared to the standard adult phantom weight.

RESULTS AND DISCUSSION

Exam frequencies

Hanford. Medical x-ray examination records for individual Hanford workers were available, so the quantity and type of x-ray examinations each worker received could be determined. According to medical records, stereoscopic (10.2 by 25.4 cm) PFG, single (10.2 by 12.7 cm) PFG, and direct 35.6 by 43.2 cm (14 by 17 inch) radiography were performed from 1944–1962. Approximately 80% of films from 1944 to about mid-1953 appeared to be stereoscopic PFG chest x-ray examinations. Between mid-1953 and 1962, only single PFG and direct radiography were done.

Pre-employment physical examinations, including a chest x-ray examination, began at Kadlec Methodist Hospital as soon as it opened in June 1944 (Cantril 1946). In addition, employees received annual examinations and termination examinations, which also included chest x-ray examinations.

Of the 507 subjects in the Hanford cohort, 333 subjects had PFG records, 159 subjects had medical records with no evidence of PFG, and 15 subjects did not have available medical records. Of the 159 subjects, 75 started Hanford employment after 31 December 1962, when photofluorography was no longer used. The remaining 84 subjects with work histories prior to 31 December 1962 had medical records that only indicated direct radiography. However, it was assumed PFGs did occur for the 15 workers with missing records at the same frequency observed in other medical records. The job titles and work history dates of these subjects were matched to those with records of chest PFGs, and bone marrow doses were assigned accordingly.

ORNL. ORNL medical x-ray examination records were not captured for this study. However, a medical records specialist at ORNL reviewed the x-ray records of 32 randomly-selected study subjects (~14% of ORNL study subjects) for evidence of PFGs. All seven subjects who received chest PFGs at the start of employment were

hired prior to October 1945. Five of the seven subjects had one stereoscopic chest PFG in their records that was taken at the start of employment. The other two subjects had two stereoscopic chest PFGs approximately one year apart. All PFGs were taken between 1944 and 1945. It appears that workers who were hired from October through January of each year from 1943 to 1945 did not receive PFGs. Additionally, ORNL began exclusively using direct radiography equipment for diagnostic x-ray examinations on 3 October 1947. Prior to that date, all ORNL employees received their WRX at Oak Ridge Hospital.**

Pre-employment lumbar spine x-ray examinations were performed on ORNL craft workers (i.e., construction workers, pipefitters, welders, painters, laborers, carpenters, millwrights, helpers, electricians, mechanics, and craft foremen) from 6 April 1950 to 23 September 1953. The lumbar spine series consisted of an anterior-posterior (AP) view, an AP spot, a lateral view, and a lateral spot.** Spot films are x-ray examinations that focus on the junction between the last lumbar and first sacral vertebrae (Webster and Merrill 1957).

Based on the medical records, each worker hired prior to October 1945 was given a pre-employment stereoscopic PFG. Therefore, subjects who began work at the facility prior to October 1945, except those hired between 1 October 1943 and 1 February 1944, and 1 October 1944 and 1 January 1945, were assigned dose from a pre-employment stereoscopic chest PFG. All other chest x-ray examinations at ORNL were assumed to have been done using direct radiography and were not included in the dose assignment. Additionally, craftsmen who started work between 6 April 1950 and 23 September 1953 received a pre-employment lumbar spine series and were assigned doses from the four procedures.

SRS. No x-ray examination records were available for SRS-employed subjects; however, some documents describing the early medical monitoring program and work histories for each of the subjects were located. This combined information was used to make assumptions regarding the types and frequencies of WRX administered to SRS workers.

Early correspondence between the Du Pont de Nemours and Company and an official of the Atomic Energy Division in 1951 indicated that Savannah River Site planned to have a centralized medical center near the main administration building with first-aid stations in each of the eight manufacturing areas.[†††] Later correspondence identified the main medical area with an x-ray examination section in Building 719-A.[‡‡‡]

In 1954, the Savannah River Site ordered a mobile x-ray unit for routine examination of its some 10,000 employees. This unit was equipped with instruments capable of providing both stereoscopic PFG on 70-mm film and direct radiographs on conventional 35.6 by 43.2 cm (14 by 17 inch) film.[§§§] A letter dated 10 June 1954 suggests that the mobile x-ray unit was not delivered until later that year.****

It appears that only employees who worked in remote areas (i.e., D, C, K, L, P, R, H, and F) received annual WRX in the mobile unit. It was assumed these x-ray examinations were PA stereoscopic chest PFGs. The direct radiography unit located in Bldg. 719-A was most likely used for workers near the administrative area.[‡‡‡]

A 1957 report recommended that 35.6 by 43.2 cm (14 by 17 in) chest radiographs be used in the mobile x-ray unit to "reduce personnel exposure" (E.I. Du Pont Nemours and Company 1957). According to a 1961 memo, the schedule for routine annual x-ray examinations changed sometime in 1957.[‡‡‡] Therefore, it was assumed that SRS ceased using PFG on 31 December 1957.

Stereoscopic chest PFGs were assigned for subjects with work histories from 1954 to 1957. Each worker assigned to the remote areas was assumed to have received annual stereoscopic PFGs in the mobile x-ray unit. Workers in areas "A" or "M" or any of the "700" buildings were not assigned bone marrow dose as it was assumed that they received only direct radiography at the medical facility in Building 719-A.

LANL. Incomplete medical records available for several LANL employees indicated routine chest x-ray examinations were administered as part of the facility medical monitoring program. None of these records specified whether PFG or direct radiography was used. Some descriptions of medical monitoring procedures, monthly progress reports from the Occupational Health Group, annual reports of the Health Division, and various letters and memoranda were located. In a 1944 report, the Los Alamos Health Division recommended annual chest

[†††] Smith MH. Letter to unknown recipient. Medical Facilities at Savannah River. 1951.

[‡‡‡] Savannah River Plant Medical Department. Bulletin to All Supervision. 1962 timetable for mobile x-ray unit areas D-C-K-L-P-R-H-F. 11 December 1961.

[§§§] E.I. DuPont de Nemours and Company. Letter to Picker X-ray Corp. Purchase order for mobile x-ray unit. 1954.

**** Roper S. Letter to L.B. LeFevre. Delivery of photofluorographic x-ray equipment. 10 June 1954.

x-ray examinations for workers potentially exposed to radiation and semi-annual chest x-ray examinations for workers potentially exposed to uranium, plutonium, polonium, or beryllium (Hempelmann 1944). A 1947 memorandum recommended that the facility proceed with semi-annual chest x-ray examinations for all technical area personnel.[††††] This memorandum also discussed the possibility of obtaining PFG equipment for the purpose of taking chest x rays.

A January 1948 letter from the Atomic Energy Commission (AEC) implied that Los Alamos had implemented a requirement for pre-employment screening;[‡‡‡‡] however, many of the pre-employment examinations were done by the worker's private physician. It is not clear if the private physicians used PFGs or direct radiographs. A March 1948 memorandum identified potential problems with not performing termination examinations on Zia (a LANL contractor) employees and mandated these examinations beginning 20 March 1948.[§§§§] Another memorandum with the same date discusses the importance of performing pre-employment x-ray examinations on the Zia employees***** while an October 1948 memorandum[†††††] expressed concern about elevated exposures from chest x-ray examinations because of the use of stereography and the number of repeated exams.

There is insufficient evidence that LANL required pre-employment x-ray examinations of all employees, including non-radiation workers, prior to the late 1950's. A September 1947 letter discusses the possibility of obtaining PFG equipment, so clearly no PFGs were done at the site prior to that date.[††††] Occupational Health Group (H-2) Progress Reports indicate that PFG exams (11 to 86 per month) were performed regularly and were definitely done between 20 September 1949 and 20 June 1950 (Grier 1949–1950; Hardy 1950). However, at least through 1951, LANL was having difficulty performing periodic medical examinations on all employees due to a lack of medical staff (Shipman 1952) and the majority of pre-employment examinations were completed by the applicant's personal physician. The monthly reports show that the number of chest PFGs between September 1949 and June 1950 (353) was much less than the number of pre-employment examinations (929).

A 1957 annual report by the Health Division stated that in 1956, the medical group (Industrial Medicine, the H-2 Group of the Health Division) discontinued the use of the photofluorographic equipment at the Medical Center for chest exams and installed standard direct radiography equipment to minimize x-ray exposure. The new device reportedly reduced the exposure per film to about 7.7×10^{6} C kg^{-1} (30 mR) (Shipman 1958).

Personnel with radiation worker status and start dates between 16 March 1948 and 31 December 1956 were assumed to have received pre-employment chest PFGs. If dosimetry and exposure records identified monitoring for uranium, plutonium, polonium, or beryllium, it was assumed that the worker received chest PFGs every 6 mo during the 1948 to 1956 time period. If only external radiation exposure records were found, it was assumed that the worker received chest PFGs once a year during the 1948 to 1956 time period. If no evidence was found of any radiation or beryllium monitoring, it was assumed the worker did not receive any routine chest PFGs.

PNS. Extensive work to estimate exam frequencies at PNS was completed for a previous study (Daniels et al. 2005). Based on these previous findings, dose estimates were limited to exposures from PFG chest x-ray examinations that were conducted prior to 1 May 1966. Examination frequencies were estimated using the algorithm constructed from reviews of medical records, employment data, and onsite dosimetry records (Daniels et al. 2005).

PCXMC parameters and calculations

Table 2 summarizes parameters used to calculate bone marrow doses due to PA chest PFG examinations at Hanford, ORNL, and PNS, and lumbar spine examinations at ORNL. Bone marrow doses were calculated using entrance skin exposure values that were reduced by an assumed backscatter correction factor of 1.3 (Grosswendt 1984; Tapiovaara et al. 1997). This adjustment compensated for the fact that reported entrance skin exposures were typically measured with a phantom in place, whereas the PCXMC software requires exposure inputs without backscatter.

Table 3 shows the bone marrow doses calculated with PCXMC using each set of equipment-specific parameters listed in Table 2 and summarizes the type of x-ray examinations assumed for each facility. Bone marrow doses for the chest PFG exams ranged from 1.0 mGy to 1.4 mGy, with an arithmetic mean of 1.2 and a standard deviation of 0.2. Bone marrow doses for the lumbar spine views ranged from 0.21 mGy for the AP view to 0.5 mGy for the lateral view.

[††††] Hempelmann LH. Letter to H.E. Bradbury. Suggested program for physical examination of tech area personnel. 29 September 1947.

[‡‡‡‡] Tyler CL. Letter to A.E. Dyhre. Pre-employment medical examinations. 2 January 1948.

[§§§§] Hardy HL. Letter to Henry Hoyt. Termination medical examinations for Zia employees. 16 March 1948.

***** Hardy HL. Letter to Mr. Hoyt. Pre-employment physicals for Zia employees. 16 March 1948.

[†††††] Hardy HL. Letter to Dr. Whipple, H Division, Lab H-2. 1 October 1948.

Table 2. Parameters used in PCXMC to calculate bone marrow doses from WRX. Italicized numbers indicate assumed values.

Parameter	Hanford PFG chest (3/8/1959)	Hanford PFG chest (4/12/1959)	ORNL PFG chest	ORNL Lumbar AP	ORNL Lumbar Lat	PNS PFG chest
FID (cm)	101.6	106.7	121.9			101.6
FSD (cm)	76.2	*81.28*	*101.9*	99.06	99.06	*76.6*
Beam width (cm)	*30.6*	*31.1*	*32.3*	*24.9*	*19.7*	*30.6*
Beam height (cm)	*30.6*	*31.1*	*32.3*	*24.9*	*19.7*	*30.6*
Projection angle (degrees)	90	90	90	270	180	90
Z_{ref} (cm)	52	52	52	22	22	52
Filter (mm A1)	*1.3*	1.3	*1.5*	*1.5*	*1.5*	*2.5*
Kilovolts peak (kVp)	100	100	90	80	86	85
ESE[a] (C/kg)	3.00×10^{-4}	3.04×10^{-4}	2.78×10^{-4}	3.97×10^{-4}	9.92×10^{-4}	3.38×10^{-4}

[a] Without backscatter.

Table 3. Bone marrow doses assigned for PFG chest and lumbar spine series procedures at study facilities.

Projection	Calculated bone marrow dose (mGy)	Assigned bone marrow dose (mGy)	Date range for assigned doses
Hanford (3/8/1959) (PFG chest)	1.1	1.1[a,d]	1944–1962
Hanford (4/12/1959) (PFG chest)	1.2		
ORNL (PFG chest)	1.0	1.0[d]	1943–1947
ORNL (Lumbar AP)	0.21		
ORNL (Lumbar Lat)	0.51		
ORNL (Lumbar Series)		1.4[b]	1950–1953
SRS (PFG chest)		1.1[c,d]	1954–1957
LANL (PFG chest)		1.1[c,d]	1948–1956
PNS (PFG chest)	1.4	1.4[d]	1948–1966

[a] Average of both Hanford PFG chest measurements.
[b] Includes an AP, AP spot, lateral, and lateral spot.
[c] Average of Hanford and ORNL PFG chest measurements.
[d] This is the dose assigned per exposure. For PFG chest stereoscopic exams, in which two exposures are done, the dose is double this value.

Table 4. Active bone marrow doses from single exposure PFG chest x-ray examinations (PFG) and AP and lateral (Lat) lumbar spine (LS) examinations found in the literature.

Reference	Exam type	kVp	Entrance skin exposure (C kg^{-1})	Added filtration (mm A1)	Active bone marrow dose (mGy)
Antoku et al. (1972)	PFG	80	2.58×10^{-4}	0.5	0.42
Cardarelli et al. (2002)	PFG	NR[a]	6.42×10^{-4}	4.0	3.85
Jankowski (1984)	PFG	70	1.56×10^{-4}	2.9	0.49
Laughlin et al. (1957)	PFG	90	1.34×10^{-4}	2.4	0.98
Antoku et al. (1972)	AP LS	NR	NR	0.5	0.27
	Lat LS	NR	NR	0.5	0.48
Shleien et al. (1978)[b]	AP LS	NR	NR	NR	1.01
	Lat LS	NR	NR	NR	1.57
Antoku and Russell (1971)	AP LS	100	5.30×10^{-5}	2.5	0.17
	Lat LS	120	1.97×10^{-4}	2.5	0.38

[a] NR = not reported.
[b] Average of doses from 1964 and 1970.

Table 4 shows active bone marrow doses from single exposure PFG chest x-ray examinations and AP and lateral lumbar spine examinations from various peer-reviewed studies. Examination parameters and bone marrow doses varied among the studies. Laughlin et al. (1957), Antoku et al. (1972), and Jankowski (1984) reported values from phantom measurements that ranged from 0.42 mGy (Antoku et al. 1972) to 0.98 mGy (Laughlin et al. 1957) for a single PFG exposure. Cardarelli et al. (2002) estimated a bone marrow dose of 3.85 mGy for a single PFG exposure by applying an ESE to bone marrow dose conversion factor from Kereiakes and Rosenstein (1980). The arithmetic mean of the four reported PFG values was 1.4 mGy with a standard deviation of 1.6.

Bone marrow doses from AP and lateral lumbar spine examinations found in the literature varied between

0.17 mGy and 1.01 mGy for a single exposure AP lumbar spine, and varied between 0.38 mGy and 1.57 mGy for a single exposure lateral spine examination (Antoku and Russell 1971; Antoku et al. 1972; Shleien et al. 1978). The arithmetic means and standard deviations were 0.5 ± 0.5 mGy and 0.8 ± 0.7 mGy for the AP and lateral lumbar spine examinations, respectively.

Dose assignment

Table 3 also shows the bone marrow doses assigned for each facility. For the Hanford subjects, the bone marrow dose assigned for a single chest PFG was assumed to be the average of the two calculated estimates (1.1 and 1.2 mGy) using the measured entrance skin exposures. This resulted in an assigned bone marrow dose of 1.1 mGy for a single PFG exposure and 2.3 mGy for a stereoscopic PFG.

For the ORNL subjects, the bone marrow dose of 1.0 mGy was calculated for a single chest PFG using the entrance skin exposure. All chest PFGs done at ORNL were assumed to be stereoscopic, resulting in an assigned bone marrow dose of 2.0 mGy per examination. The bone marrow doses calculated for the lumbar spine views were 0.21 mGy for the AP view and 0.51 mGy for the lateral view. The AP spot and lateral spot doses were assumed to be equal to the AP view and lateral view, respectively. This resulted in a total bone marrow dose of 1.4 mGy for the lumbar series examination.

For PNS subjects, the bone marrow dose assigned per PFG single exposure examination was 1.4 mGy. This dose is higher than those estimated for the other facilities due to the higher entrance skin exposure and higher beam filtration used in the calculation.

Because there was no specific information regarding equipment operating parameters and examination equipment used at SRS and LANL, the bone marrow doses assigned to these subjects were based on the PFG equipment used at Hanford and ORNL. The calculated average bone marrow dose was 1.1 ± 0.1 mGy for a single PFG. All exams at SRS and LANL were assumed to be stereoscopic PFGs, resulting in an assigned bone marrow dose of 2.2 mGy per exam.

Table 5 shows the results of the assignment of bone marrow doses for each of the five study facilities. ORNL had the lowest mean and median cumulative dose and the lowest variation in the doses, due to the assumption that each worker only received a single pre-employment PFG chest x-ray examination or a single lumbar spine series, but not both. LANL had the highest median and highest variation in dose.

Cumulative bone marrow doses for Hanford ranged from 1.1 mGy to 20 mGy with a mean of 4.9 mGy and a median of 4.5 mGy. Because of the availability of individual x-ray examination records for the Hanford cohort, which were assumed to be complete, the assigned bone marrow doses are reasonably certain compared to ORNL, SRS, and LANL.

For the PNS cohort, the arithmetic mean and median worker cumulative doses were 6.8 and 7.0 mGy, respectively. Cumulative bone marrow doses ranged from 1.4 to 15 mGy. Using a method suggested by Daniels et al. (2005), bias (B) for the dose estimates was investigated by the ratio of the predicted exams (P) to actual exams (A) extracted from medical records. There were 34 study subjects identified with records of examination data for comparison. The values of the ratio of P to A were lognormally distributed so the geometric mean was selected as the best measure of central tendency. A bias factor (B) of 1.12 was determined from the geometric mean of the ratio of P to A which is in reasonable agreement with the value of 1.34 obtained by Daniels et al. using a larger sample of 463 (Daniels et al. 2005).

Cumulative doses for ORNL workers ranged from 1.5 to 4.2 mGy with a mean of 2.0 mGy and a median of 2.1 mGy. Originally, no x-ray examination records were captured for the ORNL cohort. Workers were assigned dose from occupational x-ray examinations based on

Table 5. Descriptive statistics for cumulative bone marrow doses (in mGy) due to WRX by facility.

	Hanford	ORNL	SRS	LANL	PNS
No. of study subjects	507	224	194	167	177
No. of subjects with assigned WRX dose	348	50	119	97	162
Arithmetic mean (mGy)	4.9	2.0	7.7	14	6.8
Median (mGy)	4.5	2.1	8.8	6.6	7.0
Variance	9.2	0.26	3.7	200	8.2
Geometric mean (mGy)	4.0	2.0	7.3	7.3	6.2
Geometric standard deviation	1.9	1.2	1.4	3.3	1.6
Minimum (mGy)	1.1	1.5	2.2	2.2	1.4
Maximum (mGy)	20	4.2	8.8	40	15
Collective dose (person-Gy)	1.7	0.10	0.92	1.4	1.1

assumptions regarding the medical monitoring program and information from medical records for 32 workers.

Cumulative bone marrow doses assigned for SRS ranged from 2.2 to 8.8 mGy with a mean of 7.7 mGy and a median of 8.8 mGy. There were no x-ray examination records available for SRS workers. Bone marrow doses were based on each subject's work location (determined from work history information) and an assumed time period of four years for the use of PFG at the site.

Uncertainties and limitations

Factors that contributed to uncertainty in bone marrow dose calculations were numerous. Several parameters used in the PCXMC calculations were unknown and had to be imputed, such as the amount and type of added filtration, the FSD, beam height and width, and the size of the patient. There was likely measurement uncertainty in the reported ESEs and the backscatter factors used to adjust the ESE. Several aspects of the algorithm used to simulate the spectrum of a full-wave rectified device were dependent upon knowledge of the x-ray tube specifications. This lack of specific information such as filament emission data, target angle, and inherent tube filtration introduced uncertainty in the spectrum.

Weight and height were not known for all subjects, so reference values for an adult phantom were used. Analysis of weight and height of workers reported for the Hanford cohort shows that weights reported in medical records were lognormally distributed with a median of 74.2 kg (range 45.4–115 kg) and a GSD of 1.2. Reported heights were also lognormally distributed with a median of 175 cm (range 150–206 cm) and a GSD of 1.1. The phantom weight and height used in the dose calculations were 71.1 kg and 174 cm, respectively (Cristy 1980).

To evaluate uncertainty in bone marrow dose estimates due to subject weight, each set of PFG examination parameters in Table 3 were analyzed with PCXMC using subject weights of 53.5 kg and 98 kg (5^{th} and 95^{th} percentile) and the phantom height (174 cm). The 25% decrease in weight resulted in an increase in bone marrow dose of 16% for the ORNL PFG and 14–16% for the Hanford PFG. The 38% increase in weight resulted in a decrease in bone marrow dose of 23% for the ORNL PFG and 22% for the Hanford PFG. For lumbar spine series examinations, a 25% decrease in weight resulted in an increase in bone marrow dose of 30% for the AP lumbar spine exam and 25% for the lateral lumbar spine exam. An increase in weight of 38% results in a decrease of 32% for the AP lumbar spine exam and 27% for the lateral exam.

To determine the effects of varying other parameters, the PCXMC program was run multiple times, each time changing a single parameter. ESEs reported in the literature for PFG chest examinations varied from 1.34×10^{-4} to 6.42×10^{-4} C kg^{-1}. The relationship between the ESE and the active bone marrow dose is linear. Thus, keeping all other parameters the same, a 50% increase in ESE results in a 50% increase in active bone marrow dose.

For added filtration, an increase of 1 mm Al from 0.5 mm Al results in an increase of about 40% in active bone marrow dose, whereas increasing the added filtration from 1 mm Al to 2 mm Al resulted in an increase of about 25% in dose. Increasing added filtration from 0.5 mm Al to 4 mm Al resulted in an increase of 120% in bone marrow dose.

Values of kVp for PFG chest examination varied between 85 and 100 in this study and 70 to 90 in the literature. Keeping all other parameters the same, a 30% decrease in kVp could result in a 45% decrease in active bone marrow dose.

Uncertainty was also introduced by imputation of FSD and the beam area on the patient. FSD values varied by as much as 34% in this study, and 5% in the literature. Variation of 34% in the FSD results in a variation of the bone marrow dose of only about 1%. Variation in beam area on the patient was 71% resulting in a variation in dose of 24%.

Lack of available medical x-ray records for ORNL, SRS, and LANL workers required assumptions to be made regarding the site medical programs, time period for use of PFG at the site, and examination frequency. These assumptions introduced perhaps the largest uncertainty. For example, the number of PFG stereoscopic examinations assigned to LANL workers ranged from one (cumulative dose of 2.2 mGy) to 18 (cumulative dose of 40 mGy). If a worker who was assigned 18 stereoscopic examinations over a period of nine years actually received only one, his assigned dose would be 1700% too high. There was also the possibility that workers were exposed multiple times during a medical exam ("retakes") due to error. Retake rates were unknown for all five facilities.

The uncertainty in these dose estimates is large given numerous factors, some of which were described in the preceding text. It was not feasible to appropriately quantify the uncertainty for this study. However, the effects of uncertainty will be evaluated in the proposed epidemiological analyses by examining the relative goodness-of-fit of statistical models of dose-response with and without contributions from WRX and also using dose distributions created under various assumptions.

CONCLUSION

Bone marrow doses due to WRX were assigned for workers at Hanford, ORNL, SRS, LANL, and PNS. Using PCXMC, calculated bone marrow doses for x-ray examinations ranged from 1.1 mGy for a single chest PFG examination at Hanford to 1.4 mGy for a single

chest PFG examination at PNS. Mean cumulative bone marrow doses across the sites from WRX ranged from 2.0 to 14 mGy and collective dose ranged from 0.10 to 1.7 person-Gy.

Although specific information on quantity and type of x-ray examinations received by Hanford subjects was available, retake rates were unknown and uncertainty in Hanford bone marrow doses could be greater than 100%. Some records were available for PNS subjects and a bias factor of 1.12 was determined for the ratio of the number of predicted exams to the number of actual exams for each subject. No individual x-ray examination records were available for SRS and LANL, and uncertainty in the dose estimates for these two facilities could be significantly greater than 100%. Partial information was available for 32 individuals in the ORNL study group, and a dose assignment algorithm for this facility was based on x-ray examination records of these workers. Uncertainty for this group could be significantly reduced by examining the medical x-ray records of the remaining group.

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