# ORAU TEAM
# Dose Reconstruction Project for NIOSH

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☐ New ☒ Total Rewrite ☐ Revision ☐ Page Change

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**PUBLICATION RECORD**

| EFFECTIVE DATE | REVISION NUMBER | DESCRIPTION |
|---|---|---|
| 08/24/2004 | 00 | New technical basis document for the Pantex Plant – Occupational Medical Dose. First approved issue. Initiated by Jerome B. Martin. |
| 12/23/2005 | 01 | Approved issue of Revision 01. Training required: As determined by the Task Manager. Initiated by Dillard B. Shipler. |
| 02/01/2007 | 02 | Approved Revision 02 for organ dose assignment based on site-specific information. Added Section 3-5, Skin Dose Method Description and Section 3-8, Attributions and Annotations. Incorporates internal formal and NIOSH formal review comments. Constitutes a total rewrite of document. This revision results in an increase in assigned dose and a PER is required. Initiated by Robert C. Winslow. |
| 03/20/2014 | 03 | Revision to ensure organ doses are calculated according to current project practices and according to accumulated historical evidence, to add skin doses for all projections and time periods, and to add dose to the B-lymphocytes. Incorporates formal internal and NIOSH review comments. Constitutes a total rewrite of document. Training required: As determined by the Objective Manager. Initiated by Dale D. Thomas III. |

## TABLE OF CONTENTS



## LIST OF TABLES

## ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| AP | anterior-posterior |
| CFR | Code of Federal Regulations |
| cGy | centigray |
| cm | centimeter |
| DCF | dose conversion factor |
| DHHS | U.S. Department of Health and Human Services |
| DOE | U.S. Department of Energy |
| DOL | U.S. Department of Labor |
| EEOICPA | Energy Employees Occupational Illness Compensation Program Act of 2000 |
| ENSD | entrance skin dose |
| ESE | entrance skin exposure |
| EXSD | exit skin dose |
| GE | General Electric Company |
| HVL | half-value layer |
| ICRP | International Commission on Radiological Protection |
| in. | inch |
| kVp | kilovolts-peak |
| LAT | lateral |
| m | meter |
| mA | milliampere |
| mAs | milliampere-second |
| mm | millimeter |
| mR | milliroentgen |
| mrem | millirem |
| NCRP | National Council on Radiation Protection and Measurements |
| NIOSH | National Institute for Occupational Safety and Health |
| ORAU | Oak Ridge Associated Universities |
| PA | posterior-anterior |
| PFG | photofluorography |
| POC | probability of causation |
| R | roentgen |
| RSD | remote skin dose |
| SEC | Special Exposure Cohort |
| SRDB Ref ID | Site Research Database Reference Identification (number) |
| TBD | technical basis document |
| U.S.C. | United States Code |
| § | section or sections |

## 3.1 INTRODUCTION

Technical basis documents and site profile documents are not official determinations made by the National Institute for Occupational Safety and Health (NIOSH) but are rather general working documents that provide historical background information and guidance to assist in the preparation of dose reconstructions at particular sites or categories of sites. They will be revised in the event additional relevant information is obtained about the affected site(s). These documents may be used to assist NIOSH staff in the completion of the individual work required for each dose reconstruction.

In this document the word “facility” is used as a general term for an area, building, or group of buildings that served a specific purpose at a site. It does not necessarily connote an “atomic weapons employer facility” or a “Department of Energy [DOE] facility” as defined in the Energy Employees Occupational Illness Compensation Program Act [EEOICPA; 42 U.S.C. § 7384l(5) and (12)]. EEOICPA defines a DOE facility as “any building, structure, or premise, including the grounds upon which such building, structure, or premise is located … in which operations are, or have been, conducted by, or on behalf of, the Department of Energy (except for buildings, structures, premises, grounds, or operations … pertaining to the Naval Nuclear Propulsion Program)” [42 U.S.C. § 7384l(12)]. Accordingly, except for the exclusion for the Naval Nuclear Propulsion Program noted above, any facility that performs or performed DOE operations of any nature whatsoever is a DOE facility encompassed by EEOICPA.

For employees of DOE or its contractors with cancer, the DOE facility definition only determines eligibility for a dose reconstruction, which is a prerequisite to a compensation decision (except for members of the Special Exposure Cohort). The compensation decision for cancer claimants is based on a section of the statute entitled “Exposure in the Performance of Duty.” That provision [42 U.S.C. § 7384n(b)] says that an individual with cancer “shall be determined to have sustained that cancer in the performance of duty for purposes of the compensation program if, and only if, the cancer … was at least as likely as not related to employment at the facility [where the employee worked], as determined in accordance with the POC [probability of causation[1]] guidelines established under subsection (c) …” [42 U.S.C. § 7384n(b)]. Neither the statute nor the probability of causation guidelines (nor the dose reconstruction regulation, 42 C.F.R. Pt. 82) restrict the “performance of duty” referred to in 42 U.S.C. § 7384n(b) to nuclear weapons work (NIOSH 2010).

The statute also includes a definition of a DOE facility that excludes “buildings, structures, premises, grounds, or operations covered by Executive Order No. 12344, dated February 1, 1982 (42 U.S.C. 7158 note), pertaining to the Naval Nuclear Propulsion Program” [42 U.S.C. § 7384l(12)]. While this definition excludes Naval Nuclear Propulsion Facilities from being covered under the Act, the section of EEOICPA that deals with the compensation decision for covered employees with cancer [i.e., 42 U.S.C. § 7384n(b), entitled “Exposure in the Performance of Duty”] does not contain such an exclusion. Therefore, the statute requires NIOSH to include all occupationally-derived radiation exposures at covered facilities in its dose reconstructions for employees at DOE facilities, including radiation exposures related to the Naval Nuclear Propulsion Program. As a result, all internal and external occupational radiation exposures are considered valid for inclusion in a dose reconstruction. No efforts are made to determine the eligibility of any fraction of total measured exposure for inclusion in dose reconstruction. NIOSH, however, does not consider the following exposures to be occupationally derived (NIOSH 2010):

- Background radiation, including radiation from naturally occurring radon present in conventional structures
- Radiation from X-rays received in the diagnosis of injuries or illnesses or for therapeutic reasons

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1 The U.S. Department of Labor (DOL) is ultimately responsible under the EEOICPA for determining the POC.

### 3.1.1 Purpose

The purpose of this technical basis document (TBD) is to describe what is known about the Pantex Plant occupational medical X-ray machines and practices and to estimate organ doses from these machines for various radiographic examinations Pantex performed for screening. The Oak Ridge Associated Universities (ORAU) Team may use this information to assign occupational medical X-ray doses for EEOICPA claims.

### 3.1.2 Scope

Pantex operations have played an important role in the U.S. nuclear weapons program. Historically, Pantex provided several roles in the assembly, disassembly, retrofit, and modification of nuclear weapon systems (Mitchell 2003). Today, Pantex continues to fabricate high explosives and to assemble nuclear weapons.

Pantex had an occupational health program for its workers since the beginning of its operations, which continues to the present. One of the objectives of the occupational health program has been to screen workers for disease. Any radiographic examinations for screening are eligible for inclusion in dose reconstruction under the EEOICPA (42 CFR Part 82). This TBD provides the technical basis for the estimation of organ doses that have been received by workers from medical X-ray screening procedures at Pantex.

## 3.2 EXAMINATION TYPES AND FREQUENCIES

Pantex required preemployment and routine physical examinations as part of its occupational health and safety program. An early but undated document mentions that Pantex will administer preemployment, periodic, and termination posterior-anterior (PA) chest X-rays (Author unknown, ca. 1952, p. 8). This same document also mentions that anterior-posterior (AP) and lateral (LAT) preemployment lumbar spine X-rays will be taken on men only. A review of a sample of claim file records coincides with this pattern of primarily PA chest X-rays, with lumbar spine examinations on men on preemployment only. There were very few LAT chest X-rays in the sample of claim file records reviewed [1].

The preemployment, periodic, and termination PA chest X-rays continued through about 2004. However, the periodic PA chest X-rays began to be performed less frequently. Interviewees from Pantex stated that the asbestos and beryllium occupational health program started at Pantex around 1970 (Robertson-DeMers 2011, p. 30). As part of this program, workers exposed to beryllium received X-rays every 3 years and other workers received X-rays every 5 years. The specific frequency for asbestos workers was not provided, but might have been more frequent than every 5 years. Interviewees also collectively stated that the preemployment lumbar spine X-rays ended by about 1970.

By 2005, the preemployment PA chest X-rays were discontinued (Robertson-DeMers 2011, p. 30). Physicals were offered to workers until 2008 and included PA chest X-rays every 5 years. Asbestos and beryllium workers might have been X-rayed more frequently to comply with Occupational Health and Safety Administration (OSHA) regulations. Table 3-1 summarizes the types and frequency of X-ray examinations for screening at Pantex.

Dose reconstructors should assign dose based on the examinations that are listed in the claim file records when those exist. In the absence of listed examinations in the claim file records, the dose reconstructor should assign dose according the frequencies in Table 3-1.

Table 3-1. X-ray screening examination frequency.

| Period | Examination | Frequency |
|---|---|---|
| 1952–1970 | PA chest | Preemployment, annual, and termination.[a] |
| | AP lumbar spine | Preemployment for some categories of male workers.[a] |
| | LAT lumbar spine | Preemployment for some categories of male workers.[a] |
| 1971–2004 | PA chest | Preemployment and every 5 years. Might have been more frequent for asbestos or beryllium workers.[b] |
| 2005–2008[c] | PA chest | No preemployment examinations,[c] otherwise every 5 years. Might have been more frequent for asbestos or beryllium workers.[b] Annual physicals might have ended in 2008. |
| 2008-present | PA chest | Asbestos and beryllium workers only[d] according to the following frequency[e]:<br>• >35 years old: every 2 or every 5 years depending on time since first exposure.<br>• 15-35 years old: every 5 years. |

a. Author unknown ca. 1952, p. 8.
b. BWXT Pantex ca. 2000.
c. Robertson-DeMers 2011, p. 30.
d. Scott, 2013, p. 4-5.
e. 20 CFR 1910.1001, 2008.

## 3.3 EQUIPMENT AND TECHNIQUES

Enough historical information about the X-ray equipment at Pantex has been found to allow reasonable determination of organ doses from this site-specific information. The following paragraphs summarize available historical information.

### 3.3.1 Photofluorography

No historical information about photofluorography (PFG) at Pantex has been found, and there is no evidence of it in claim file records.

### 3.3.2 General Electric Equipment, 1952 to 1971

The earliest known record of a specific X-ray machine at Pantex is a September 26, 1967, inspection of medical X-ray facilities by the Public Health Service (PHS 1967). The inspector identified the control panel manufacturer and tube head manufacturer and model as General Electric and identified the film as GAF Supreme with RADLIN T intensifying screens. The listed technique factors for a PA chest X-ray were 60 kVp and 10 mAs for a 20-cm chest. A footnote at the bottom of the technique chart states that the kVp should be increased 2 kVp for each additional centimeter of tissue. Therefore, the technique used for a 23 cm chest (ORAUT 2011) would be approximately 64 kVp and 10 mAs. Another survey of the medical X-ray facilities at Pantex occurred in August 1970; the inspector recorded General Electric equipment and the same technique factors for PA chests as in 1967 (PHS 1970). The 1970 survey mentions the total filtration in the machine as 2.5 mm Al equivalent (PHS 1970, p. 5).

An early General Electric (GE) technique chart (GE ca. 1941, pp. 3–4) was provided to project researchers in 2003 (Strom 2003). The PA chest technique factors on this chart are the same as those recorded during the 1967 and 1970 inspections (60 kVp and 10 mAs for a 20-cm chest). Therefore, it seems reasonable to assume that the GE equipment was probably used from the start of operations in 1952. The organ doses from the PA chest projection are based on these technique factors.

Using the technique factors of 64 kVp and 10 mAs for a 23-cm chest, and the average air kerma rates in National Council on Radiation Protection and Measurements (NCRP) Report 102 (NCRP 1997), the incident air kerma is $1.39 \times 10^{-2}$ cGy. The half-value layer (HVL) is assumed to be approximately 2.0 mm Al for 2.5 mm Al equivalent total filtration and 64 kVp (NCRP 1997).

The lumbar spine technique factors on the GE technique chart are 58 kVp, 100 mA, and 1 second for the AP lumbar spine projection (18-cm abdomen), and 74 kVp, 100 mA, and 2 seconds for the LAT projection (28-cm abdomen) at 40 in. source-to-image distance (GE ca. 1941, pp. 3–4). The technique chart suggests adding 2 kVp for each additional centimeter of tissue thickness, so the modified technique factors for a 24- and 34-cm abdomen for the AP and LAT lumbar projections, would be 70 kVp, 100 mA at 1 second and 86 kVp, 100 mA at 2 seconds, respectively. The organ doses from the AP and LAT lumbar spine projections are based on these modified technique factors. Using the modified technique factors and the average air kerma rates in National Council on Radiation Protection and Measurements (NCRP) Report 102 (NCRP 1997), the incident air kerma is $7.305 \times 10^{-1}$ cGy and 2.771 cGy for the AP and LAT lumbar spine projections, respectively. The half-value layer (HVL) is assumed to be approximately 2.0 mm Al (rounded) for 2.5 mm Al equivalent total filtration and 70 or 86 kVp (NCRP 1997). Poor collimation is assumed for this period.

### 3.3.3 Picker Equipment, 1972 to 1983

New X-ray equipment was installed at Pantex in 1972. The machine manufacturer is not identified on the installation documents (Alexander 1972c), but is identified on other documents from this period. An inspection of the Pantex equipment in 1977 identifies the machine as a Picker machine (Horton 1977). The technique factors for PA chest X-rays are reported to be 70 kVp, 300 mA, and 1/30 second. There are several other inspection results for this machine in 1978, 1981, and 1983 (Horton 1978, Bolinger 1981, and Ikenberry 1983). Kodak BB-5 Blue brand film and DuPont Par screens were used (Ikenberry 1983). Some of these documents show enough raw data to demonstrate compliance with minimum filtration requirements in NCRP Report 33 (NCRP 1973) for a machine operating above 70 kVp, but there is not enough data to actually determine the HVL [2]. Timer problems with this machine persisted through its replacement in the spring of 1984 (Ikenberry 1984).

Using the technique factors of 70 kVp and 10 mAs, the average air kerma rates in NCRP Report 102 (NCRP 1997), the incident air kerma is $1.53 \times 10^{-2}$ cGy. The HVL is assumed to be approximately 2.5 mm Al at 70 kVp for the minimum recommended amount of filtration of 2.5 mm Al equivalent total filtration for a machine operating above 90 kVp (Bolinger 1981, p. 3, NCRP 1973, p. 13). Proper collimation is assumed for this period.

### 3.3.4 Universal Equipment, 1984 to 1994

A Universal X-Ray machine was first surveyed in May of 1984 (Hill 1984, p. 56). The same film-and-screen combination that was used with the Picker machine, the Kodak BB-5 Blue brand film and DuPont Par speed screens, was used until about 1990, when surveys report the combination as DuPont Cronex 7 film and Cronex Quanta III screens (Kelly 1990, p. 4). The measured HVL was about 3.0 mm Al at 70 kVp (Hill 1984, p. 60). The first entrance skin exposure (ESE) for PA chest radiography was 4.4 mR measured on September 16, 1993, for a 23-cm-thick phantom at 72 kVp, 300 mA, and 0.016 second with no grid (Slayton 1993, p 6). The measured HVL was 3.6 mm Al at 90 kVp (Slayton 1993, p 24), or about 3.0 mm Al at 70 kVp (NCRP 1997, p 98).

The organ doses for this period are based on the measured ESE of 4.4 mR converted to incident air kerma according to the equations in ORAUT-OTIB-0006, *Dose Reconstruction from Occupational Medical X-Ray Procedures* (ORAUT 2011) and an HVL of 3.0 mm Al for 70 kVp for the PA chest. Proper collimation is assumed for this period.

### 3.3.5 Continental Equipment, 1995 to 2006

A Continental X-ray machine was installed between November 1, 1993 (Slayton 1993), and November 6, 1995 (Huddleston 1995). Even though several measurements of X-ray exposure at 30 in. for selected kVps between 60 and 100 in increments of 10 were performed on November 6, 1995, (Huddleston 1995), none of these data can be definitively linked to chest technique factors or measurements specific to chest X-rays. Pantex does not have more technical information to provide about this period (McLaurin 2013, p 10).

The doses for this period can be bounded, however, by the existing information. Huddleston (1995 p. 6) mentions in his survey report that the “entrance skin exposures are within limits”, and cites the State of Texas regulations. While he does not provide the limits in this report, he does provide them in a later 2012 report of a different X-ray machine. Pantex, as a federal facility, would not have been required to comply with state regulations, but Huddleston used them to evaluate the Pantex X-ray machine. The State of Texas ESE limit for a non-grid PA chest is 20 mR (Huddleston 2012, p 8). It is reasonable to assume that the limits were the same in the 1995-2006 period. As a matter of fact, a 2003 document published by the Conference of Radiation Control Program Directors lists the ESE limit for the State of Texas as 20 mR (CRCPD 2003, p 20). This ESE limit is equal to 1.75E-02 cGy after conversion to incident air kerma, and will be used to determine organ doses for this period. An HVL of 4.0 mm Al is assumed.

### 3.3.6 Quantum Medical Imaging Equipment, 2007 to present

A Quantum Medical Imaging computed radiography machine was installed at Pantex in 2007 (Scott 2013). The X-ray generator is a Quest high frequency generator (Huddleston 2013). An inspection report from 2012 is available for this machine that provides the necessary information for determining the organ doses (Huddleston 2012). The HVL is 4.0 at 80 kVp, and the measured ESE is 11.9 mR. The incident air kerma is 1.04 E-02 cGy after converting this exposure measurement using the equations in ORAU-OTIB-0006 (2011). The kVp used for chest X-rays is not recorded in the inspection report, so an HVL of 4.0 will be assumed for dose reconstruction.

## 3.4 ORGAN DOSE CALCULATIONS

Organ and skin dose equivalents for each chest projection were calculated as described in ORAUT-OTIB-0006 (ORAUT 2011a) using the site-specific information from Pantex that is described in the previous sections. The organ dose equivalents are listed in Tables 3-2 and 3-5, which appear after Section 3.6. The skin dose guidance for determining dose equivalent for the skin is found in Tables 3-3 and 3-6, and the skin dose equivalents to all areas of skin are listed in Tables 3-4 and 3-6. The B-lymphocyte cells are the tissue at risk for chronic lymphocytic leukemia. The dose equivalent to the B-lymphocytes was determined using the method in ORAUT-OTIB-0082, *Dose Reconstruction Method for Chronic Lymphocytic Leukemia* (ORAUT 2012), site-specific information, and International Commission on Radiological Protection (ICRP) Publication 34 dose conversion factors (DCFs) (ICRP 1982). The dose distributions and corresponding statistical parameters for the dose to the B-lymphocytes for each projection and period is listed in Table 3-7.

## 3.5 UNCERTAINTY

ORAUT-OTIB-0006 (ORAUT 2011) lists the major sources of uncertainty in X-ray output intensity and their subsequent effects on dose to the worker. The five sources of uncertainty are:

1. X-ray beam measurement error (±2%),
2. Variation in peak kilovoltage (±9%),
3. Variation in X-ray beam current (±5%),

4. Variation in exposure time (±25%), and
5. Variation in source-to-skin distance as a result of worker size (±10%).

The 10% uncertainty in output intensity as a result of worker size was based on an inverse square correction of output intensity changes from differences of standard chest thickness of ±7.5 cm.

These uncertainties are assumed to be random; therefore, the combined statistical uncertainty was calculated as the square root of the sum of the squares of all the uncertainties, which is ±28.9%. Rounding this up to ±30% provides an adequate and suitably conservative indication of uncertainty. Therefore, a total combined standard uncertainty of ±30% can be assumed for a derived dose equivalent to an individual organ other than the B-lymphocytes. Dose reconstructors should, therefore, input the organ dose equivalent as the mean of a normal distribution with a standard uncertainty of ±30%.

## 3.6 ATTRIBUTIONS AND ANNOTATIONS

Where appropriate in this document, bracketed callouts have been inserted to indicate information, conclusions, and recommendations provided to assist in the process of worker dose reconstruction. These callouts are listed here in the Attributions and Annotations section, with information to identify the source and justification for each associated item. Conventional References, which are provided in the next section of this document, link data, quotations, and other information to documents available for review on the Project's Site Research Database (SRDB).

[1] Thomas, Elyse M. Principal Medical Dosimetrist. Oak Ridge Associated Universities (ORAU) Team. September 2013.
Review of a sample of claim file records for Pantex.

[2] Thomas, Elyse M. Principal Medical Dosimetrist. ORAU Team. September 2013.
The HVL results show enough raw data to demonstrate compliance with minimum filtration requirements, but there is not enough to actually determine the HVL.

Table 3-2. Organ dose equivalents (rem) for PA chest X-rays, 1952 to present.

| Organ | PA chest 1952–1971 | PA chest 1972–1983 | PA chest 1984–1994 | PA chest 1995–2006 | PA chest 2007–present |
|---|---|---|---|---|---|
| Thyroid | 2.09E-03 | 4.90E-04 | 1.77E-04 | 1.37E-03 | 8.11E-04 |
| Eye/brain | 2.09E-03 | 4.90E-04 | 1.77E-04 | 1.37E-03 | 8.11E-04 |
| Ovaries | 1.60E-03 | 1.53E-05 | 6.94E-06 | 9.11E-05 | 5.41E-05 |
| Liver/gall bladder/spleen/pancreas | 4.93E-03 | 6.90E-03 | 2.06E-03 | 1.18E-02 | 7.01E-03 |
| Urinary bladder/prostate | 1.60E-03 | 1.53E-05 | 6.94E-06 | 9.11E-05 | 5.41E-05 |
| Colon/rectum | 1.60E-03 | 1.53E-05 | 6.94E-06 | 9.11E-05 | 5.41E-05 |
| Testes | 7.92E-05 | 1.53E-07 | 3.86E-08 | 1.75E-07 | 1.04E-07 |
| Lungs (male) | 4.66E-03 | 6.41E-03 | 1.91E-03 | 1.10E-02 | 6.53E-03 |
| Lungs (female) | 4.93E-03 | 6.90E-03 | 2.06E-03 | 1.18E-02 | 7.01E-03 |
| Thymus | 4.93E-03 | 6.90E-03 | 2.06E-03 | 1.18E-02 | 7.01E-03 |
| Esophagus | 4.93E-03 | 6.90E-03 | 2.06E-03 | 1.18E-02 | 7.01E-03 |
| Stomach | 4.93E-03 | 6.90E-03 | 2.06E-03 | 1.18E-02 | 7.01E-03 |
| Bone surfaces | 4.93E-03 | 6.90E-03 | 2.06E-03 | 1.18E-02 | 7.01E-03 |
| Remainder | 4.93E-03 | 6.90E-03 | 2.06E-03 | 1.18E-02 | 7.01E-03 |
| Breast | 4.45E-04 | 7.50E-04 | 2.66E-04 | 2.03E-03 | 1.21E-03 |
| Uterus | 1.43E-03 | 1.99E-05 | 8.87E-06 | 9.11E-05 | 5.41E-05 |
| Bone marrow (male) | 9.59E-04 | 1.41E-03 | 4.51E-04 | 3.12E-03 | 1.85E-03 |
| Bone marrow (female) | 8.76E-04 | 1.32E-03 | 4.32E-04 | 3.01E-03 | 1.79E-03 |

| | | | | | |
|---|---|---|---|---|---|
| Entrance skin[a] | 1.84E-02 | 2.07E-02 | 5.36E-03 | 2.45E-02 | 1.46E-02 |

a. Entrance skin dose equivalent (ENSD) is determined by multiplying the incident air kerma by the backscatter factors of 1.32, 1.35, 1.39, and 1.40 for HVLs of 2.0, 2.5, 3.0, and 4.0 mm Al, respectively, from NCRP Report 102 (NCRP 1997, Table B-8). Skin doses for all areas of skin are provided in Table 3-4.

Table 3-3. Skin dose guidance for PA chest projections.[a]

| Area of skin | PA chest 1970 and before | PA chest after 1970 |
|---|---|---|
| Right front shoulder | EXSD | EXSD |
| Right back shoulder | ENSD | ENSD |
| Left front shoulder | EXSD | EXSD |
| Left back shoulder | ENSD | ENSD |
| Right upper arm to elbow | ENSD | 10% ENSD |
| Left upper arm to elbow | ENSD | 10% ENSD |
| Left hand | ENSD | 10% ENSD |
| Right hand | ENSD | 10% ENSD |
| Left elbow, forearm, wrist | ENSD | 10% ENSD |
| Right elbow, forearm, wrist | ENSD | 10% ENSD |
| Right side of head including ear and temple | 10% ENSD | 10% ENSD |
| Left side of head including ear and temple | 10% ENSD | 10% ENSD |
| Front left thigh | RSD (0.52 m) | RSD (0.52 m) |
| Back left thigh | RSD (0.52 m) | RSD (0.52 m) |
| Front right thigh | RSD (0.52 m) | RSD (0.52 m) |
| Back right thigh | RSD (0.52 m) | RSD (0.52 m) |
| Left knee and below | RSD (0.86 m) | RSD (0.86 m) |
| Right knee and below | RSD (0.86 m) | RSD (0.86 m) |
| Left side of face | Eye/brain | Eye/brain |
| Right side of face | Eye/brain | Eye/brain |
| Left side of neck | ENSD | 10% ENSD |
| Right side of neck | ENSD | 10% ENSD |
| Back of head | 10% ENSD | 10% ENSD |
| Front of neck | Eye/brain | Thyroid |
| Back of neck | ENSD | 10% ENSD |
| Front torso: base of neck to end of sternum | EXSD | EXSD |
| Front torso: end of sternum to lowest rib | EXSD | EXSD |
| Front torso: lowest rib to iliac crest | EXSD | 10% EXSD |
| Front torso: iliac crest to pubis | 10% EXSD | 10% EXSD |
| Back torso: base of neck to mid-back | ENSD | ENSD |
| Back torso: mid-back to lowest rib | ENSD | ENSD |
| Back torso: lowest rib to iliac crest | ENSD | 10% ENSD |
| Back torso: buttocks (iliac crest and below) | 10% ENSD | 10% ENSD |
| Right torso: base of neck to end of sternum | ENSD | ENSD |
| Right torso: end of sternum to lowest rib | ENSD | ENSD |
| Right torso: lowest rib to iliac crest | ENSD | 10% ENSD |
| Right torso: iliac crest to pubis (right hip) | 10% ENSD | 10% ENSD |
| Left torso: base of neck to end of sternum | ENSD | ENSD |
| Left torso: end of sternum to lowest rib | ENSD | ENSD |
| Left torso: lowest rib to iliac crest | ENSD | 10% ENSD |
| Left torso: iliac crest to pubis (left hip) | 10% ENSD | 10% ENSD |

a. ENSD = entrance skin dose; EXSD = exit skin dose; RSD = remote skin dose.

Table 3-4. Skin dose equivalents (rem) for PA chest projections, 1952 to present.[a]

| Area of skin | PA chest 1952–1971 | PA chest 1972–1983 | PA chest 1984–1994 | PA chest 1995–2006 | PA chest 2007–present |
|---|---|---|---|---|---|
| Right front shoulder | 4.E-04 | 5.E-04 | 1.E-04 | 8.E-04 | 5.E-04 |
| Right back shoulder | 1.84E-02 | 2.07E-02 | 5.4E-03 | 2.45E-02 | 1.46E-02 |
| Left front shoulder | 4.E-04 | 5.E-04 | 1.E-04 | 8.E-04 | 5.E-04 |
| Left back shoulder | 1.84E-02 | 2.07E-02 | 5.4E-03 | 2.45E-02 | 1.46E-02 |
| Right upper arm to elbow | 1.84E-02 | 2.1E-03 | 5.E-04 | 2.5E-03 | 1.5E-03 |
| Left upper arm to elbow | 1.84E-02 | 2.1E-03 | 5.E-04 | 2.5E-03 | 1.5E-03 |
| Left hand | 1.84E-02 | 2.1E-03 | 5.E-04 | 2.5E-03 | 1.5E-03 |
| Right hand | 1.84E-02 | 2.1E-03 | 5.E-04 | 2.5E-03 | 1.5E-03 |
| Left elbow, forearm, wrist | 1.84E-02 | 2.1E-03 | 5.E-04 | 2.5E-03 | 1.5E-03 |
| Right elbow, forearm, wrist | 1.84E-02 | 2.1E-03 | 5.E-04 | 2.5E-03 | 1.5E-03 |
| Right side of head including ear and temple | 1.8E-03 | 2.1E-03 | 5.E-04 | 2.5E-03 | 1.5E-03 |
| Left side of head including ear and temple | 1.8E-03 | 2.1E-03 | 5.E-04 | 2.5E-03 | 1.5E-03 |
| Front left thigh | 5.E-06 | 6.E-06 | 2.E-06 | 1.E-05 | 6.E-06 |
| Back left thigh | 5.E-06 | 6.E-06 | 2.E-06 | 1.E-05 | 6.E-06 |
| Front right thigh | 5.E-06 | 6.E-06 | 2.E-06 | 1.E-05 | 6.E-06 |
| Back right thigh | 5.E-06 | 6.E-06 | 2.E-06 | 1.E-05 | 6.E-06 |
| Left knee and below | 2.E-06 | 2.E-06 | 6.E-07 | 4.E-06 | 2.E-06 |
| Right knee and below | 2.E-06 | 2.E-06 | 6.E-07 | 4.E-06 | 2.E-06 |
| Left side of face | 2.1E-03 | 4.90E-04 | 2.E-04 | 1.4E-03 | 8.E-04 |
| Right side of face | 2.1E-03 | 4.90E-04 | 2.E-04 | 1.4E-03 | 8.E-04 |
| Left side of neck | 1.84E-02 | 2.1E-03 | 5.E-04 | 2.5E-03 | 1.5E-03 |
| Right side of neck | 1.84E-02 | 2.1E-03 | 5.E-04 | 2.5E-03 | 1.5E-03 |
| Back of head | 1.8E-03 | 2.1E-03 | 5.E-04 | 2.5E-03 | 1.5E-03 |
| Front of neck | 2.1E-03 | 4.90E-04 | 2.E-04 | 1.4E-03 | 8.E-04 |
| Back of neck | 1.84E-02 | 2.1E-03 | 5.E-04 | 2.5E-03 | 1.5E-03 |
| Front torso: base of neck to end of sternum | 4.E-04 | 5.E-04 | 1.E-04 | 8.E-04 | 5.E-04 |
| Front torso: end of sternum to lowest rib | 4.E-04 | 5.E-04 | 1.E-04 | 8.E-04 | 5.E-04 |
| Front torso: lowest rib to iliac crest | 4.E-04 | 5.E-05 | 1.E-05 | 8.E-05 | 5.E-05 |
| Front torso: iliac crest to pubis | 4.E-05 | 5.E-05 | 1.E-05 | 8.E-05 | 5.E-05 |
| Back torso: base of neck to mid-back | 1.84E-02 | 2.07E-02 | 5.4E-03 | 2.45E-02 | 1.46E-02 |
| Back torso: mid-back to lowest rib | 1.84E-02 | 2.07E-02 | 5.4E-03 | 2.45E-02 | 1.46E-02 |
| Back torso: lowest rib to iliac crest | 1.84E-02 | 2.1E-03 | 5.E-04 | 2.5E-03 | 1.5E-03 |
| Back torso: buttocks (iliac crest and below) | 1.8E-03 | 2.1E-03 | 5.E-04 | 2.5E-03 | 1.5E-03 |
| Right torso: base of neck to end of sternum | 1.84E-02 | 2.07E-02 | 5.4E-03 | 2.45E-02 | 1.46E-02 |
| Right torso: end of sternum to lowest rib | 1.84E-02 | 2.07E-02 | 5.4E-03 | 2.45E-02 | 1.46E-02 |
| Right torso: lowest rib to iliac crest | 1.84E-02 | 2.1E-03 | 5.E-04 | 2.5E-03 | 1.5E-03 |
| Right torso: iliac crest to pubis (right hip) | 1.8E-03 | 2.1E-03 | 5.E-04 | 2.5E-03 | 1.5E-03 |
| Left torso: base of neck to end of sternum | 1.84E-02 | 2.07E-02 | 5.4E-03 | 2.45E-02 | 1.46E-02 |
| Left torso: end of sternum to lowest rib | 1.84E-02 | 2.07E-02 | 5.4E-03 | 2.45E-02 | 1.46E-02 |
| Left torso: lowest rib to iliac crest | 1.84E-02 | 2.1E-03 | 5.E-04 | 2.5E-03 | 1.5E-03 |
| Left torso: iliac crest to pubis (left hip) | 1.8E-03 | 2.1E-03 | 5.E-04 | 2.5E-03 | 1.5E-03 |

a. Values less than 0.1 mrem shown to one significant digit.

Table 3-5. Organ dose equivalents (rem) for AP and LAT lumbar spine radiography, 1952 to 1971.[a]

| Organ | AP lumbar spine 1952–1971 | LAT lumbar spine 1952–1971 |
|---|---|---|
| Thyroid | 1.46E-04 | 2.77E-05 |
| Eye brain | 1.46E-04 | 2.77E-05 |
| Ovaries | 1.17E-01 | 8.59E-02 |
| Liver/gall bladder/spleen/pancreas | 1.17E-01 | 8.59E-02 |
| Urinary Bladder/prostate | 1.17E-01 | 8.59E-02 |
| Colon/Rectum | 1.17E-01 | 8.59E-02 |
| Testes | 1.83E-03 | 1.39E-03 |
| Lungs male | 4.53E-02 | 2.77E-02 |
| Lungs female | 4.53E-02 | 2.77E-02 |
| Thymus | 4.53E-02 | 2.77E-02 |
| Esophagus | 4.53E-02 | 2.77E-02 |
| Stomach | 1.17E-01 | 8.59E-02 |
| Bone Surfaces | 1.17E-01 | 8.59E-02 |
| Remainder | 1.17E-01 | 8.59E-02 |
| Breast | 2.35E-03 | 5.54E-03 |
| Uterus | 1.59E-01 | 5.54E-02 |
| Bone Marrow male | 1.75E-02 | 4.16E-02 |
| Bone Marrow female | 1.75E-02 | 4.16E-02 |
| Skin | 9.642E-01 | 3.66E+00 |

a. Entrance skin dose equivalent (ENSD) is determined by multiplying the incident air kerma by the backscatter factors of 1.32, 1.35, 1.39, and 1.40 for HVLs of 2.0, 2.5, 3.0, and 4.0 mm Al, respectively, from NCRP Report 102 (NCRP 1997, Table B-8). Skin doses for all areas of skin from the lumbar spine projections are provided in Table 3-6.

Table 3-6. Skin dose guidance and skin dose equivalents (rem) for AP and LAT lumbar spine projections, 1952 to 1971.[a,b]

| Area of skin | AP lumbar spine 1970 and before | AP lumbar spine 1952–1971 | LAT lumbar spine 1970 and before | LAT lumbar spine 1952–1971 |
|---|---|---|---|---|
| Right front shoulder | 10% ENSD | 9.64E-02 | 10% ENSD | 3.66E-01 |
| Right back shoulder | 10% EXSD | 1.8E-03 | 10% ENSD | 3.66E-01 |
| Left front shoulder | 10% ENSD | 9.64E-02 | 10% EXSD | 1.4E-03 |
| Left back shoulder | 10% EXSD | 1.8E-03 | 10% EXSD | 1.4E-03 |
| Right upper arm to elbow | 10% ENSD | 9.64E-02 | 10% ENSD | 3.66E-01 |
| Left upper arm to elbow | 10% ENSD | 9.64E-02 | 10% EXSD | 1.4E-03 |
| Left hand | ENSD | 9.64E-01 | 10% EXSD | 1.4E-03 |
| Right hand | ENSD | 9.64E-01 | 10% ENSD | 3.66E-01 |
| Left elbow, forearm, wrist | ENSD | 9.64E-01 | 10% EXSD | 1.4E-03 |
| Right elbow, forearm, wrist | ENSD | 9.64E-01 | 10% ENSD | 3.66E-01 |
| Right side of head including ear and temple | Eye/Brain | 1.E-04 | Eye/Brain | 3.E-05 |
| Left side of head including ear and temple | Eye/Brain | 1.E-04 | Eye/Brain | 3.E-05 |
| Front left thigh | 10% ENSD | 9.64E-02 | 10% EXSD | 1.4E-03 |
| Back left thigh | 10% EXSD | 1.8E-03 | 10% EXSD | 1.4E-03 |
| Front right thigh | 10% ENSD | 9.64E-02 | 10% ENSD | 3.66E-01 |
| Back right thigh | 10% EXSD | 1.8E-03 | 10% ENSD | 3.66E-01 |
| Left knee and below | RSD (0.60 m) | 2.E-04 | RSD (0.60 m) | 3.E-04 |
| Right knee and below | RSD (0.60 m) | 2.E-04 | RSD (0.60 m) | 3.E-04 |
| Left side of face | Eye/Brain | 1.E-04 | Eye/Brain | 3.E-05 |
| Right side of face | Eye/Brain | 1.E-04 | Eye/Brain | 3.E-05 |
| Left side of neck | Eye/Brain | 1.E-04 | Eye/Brain | 3.E-05 |
| Right side of neck | Eye/Brain | 1.E-04 | Eye/Brain | 3.E-05 |
| Back of head | Eye/Brain | 1.E-04 | Eye/Brain | 3.E-05 |
| Front of neck | Eye/Brain | 1.E-04 | Eye/Brain | 3.E-05 |
| Back of neck | Eye/Brain | 1.E-04 | Eye/Brain | 3.E-05 |
| Front torso: base of neck to end of sternum | 10% ENSD | 9.64E-02 | Lung | 2.77E-02 |
| Front torso: end of sternum to lowest rib | ENSD | 9.64E-01 | Lung | 2.77E-02 |
| Front torso: lowest rib to iliac crest | ENSD | 9.64E-01 | Lung | 2.77E-02 |
| Front torso: iliac crest to pubis | ENSD | 9.64E-01 | Lung | 2.77E-02 |
| Back torso: base of neck to mid-back | 10% EXSD | 1.8E-03 | Lung | 2.77E-02 |
| Back torso: mid-back to lowest rib | EXSD | 1.85E-02 | Lung | 2.77E-02 |
| Back torso: lowest rib to iliac crest | EXSD | 1.85E-02 | Lung | 2.77E-02 |
| Back torso: buttocks (iliac crest and below) | EXSD | 1.85E-02 | Lung | 2.77E-02 |
| Right torso: base of neck to end of sternum | 10% ENSD | 9.64E-02 | 10% ENSD | 3.66E-01 |
| Right torso: end of sternum to lowest rib | ENSD | 9.64E-01 | ENSD | 3.66E+00 |
| Right torso: lowest rib to iliac crest | ENSD | 9.64E-01 | ENSD | 3.66E+00 |
| Right torso: iliac crest to pubis (right hip) | ENSD | 9.64E-01 | ENSD | 3.66E+00 |
| Left torso: base of neck to end of sternum | 10% ENSD | 9.64E-02 | 10% EXSD | 1.4E-03 |
| Left torso: end of sternum to lowest rib | ENSD | 9.64E-01 | EXSD | 1.39E-02 |
| Left torso: lowest rib to iliac crest | ENSD | 9.64E-01 | EXSD | 1.39E-02 |
| Left torso: iliac crest to pubis (left hip) | ENSD | 9.64E-01 | EXSD | 1.39E-02 |

a. ENSD = entrance skin dose; EXSD = exit skin dose; RSD = remote skin dose.
b. Values less than 0.1 mrem shown to one significant digit.

Table 3-7. IREP dose distributions and corresponding statistical parameters for the dose to the B-lymphocytes.

| Projection and Period | IREP Distribution | Parameter 1 | Parameter 2 | Parameter 3 |
|---|---|---|---|---|
| PA Chest 1952-1971 | Weibull 3 | 2.823142 | 0.002904 | 9.83936E-06 |
| PA Chest 1972-1983 | Weibull 3 | 2.060253 | 0.002911 | 6.74303E-06 |
| PA Chest 1984-1994 | Weibull 3 | 2.054837 | 8.77845E-04 | 3.93136E-06 |
| PA Chest 1995-2006 | Weibull 3 | 2.101617 | 0.005112 | 4.74997E-05 |
| PA Chest 2007-present | Weibull 3 | 2.125324 | 0.003069 | 1.58803E-06 |
| AP Lumbar Spine 1952-1971 | Weibull 3 | 3.233980 | 0.103640 | -6.64010E-04 |
| LAT Lumbar Spine 1952-1971 | Normal | 0.073585 | 0.022848 | - |

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## GLOSSARY

**absorbed dose**

Amount of energy (ergs or joules) deposited in a substance by ionizing radiation per unit mass (grams or kilograms) of the substance and measured in units of rads or grays

**anterior-posterior (AP)**

Physical orientation of the body relative to a penetrating directional radiation field such that the radiation passes through the body from the front to the back.

**entrance skin exposure (ESE)**

Exposure in air, measured in units of roentgens, at the point of entry into the body (without backscatter).

**filtration**

The process of filtering an X-ray beam, usually with millimeter thicknesses of aluminum material between the X-ray source and the film that preferentially absorbs photons from the beam. Usually measured in equivalent millimeters of aluminum.

**half-value layer (HVL)**

Thickness of a specified substance, usually specified in millimeters of aluminum, which, when introduced in the path of a given beam of radiation, reduces the kerma rate by one-half. See *filtration*.

**incident air kerma**

Sum of the kinetic energy of all charged particles that are liberated per unit mass of air at the point where an X-ray beam enters the skin surface (without backscatter). The unit is the gray; 1 gray equals 1 joule per kilogram. See *entrance skin exposure*.

**kerma**

Measure in units of absorbed dose (usually grays but sometimes rads) of the energy released by radiation from a given amount of a substance. Kerma is the sum of the initial kinetic energies of all the charged ionizing particles liberated by uncharged ionizing particles (neutrons and photons) per unit mass of a specified material. Free-in-air kerma refers to the amount of radiation at a location before adjustment for any external shielding from structures or terrain. The word derives from <u>k</u>inetic <u>e</u>nergy <u>r</u>eleased per unit <u>ma</u>ss.

**lateral (LAT)**

Orientation of the body during an X-ray procedure in which the X-rays pass from one side of the body to the other. See *exposure geometry*.

**photofluorography (PFG)**

Historical radiographic technique to produce chest images for screening a large number of people in a short period of time. The X-ray image produced on a fluorescent screen was photographed on 4- by 5-inch film. PFG was the primary method of screening large populations for tuberculosis before the advent of nonradiographic screening methods. Also called fluorography or mass miniature radiography. Not to be confused with fluoroscopy.

**posterior-anterior (PA)**

Physical orientation of the body relative to a penetrating directional radiation field such that the radiation passes through the body from the back to the front.

**radiograph**

Static images produced on radiographic film by gamma rays or X-rays after passing through matter. In the context of EEOICPA, radiographs are X-ray images of the various parts of the body used to screen for disease.

**radiography**

The process of producing images on film (or other media) with radiation.

**roentgen (R)**

Unit of photon (gamma or X-ray) exposure for which the resultant ionization liberates a positive or negative charge equal to $2.58 \times 10^{-4}$ coulombs per kilogram (or 1 electrostatic unit of electricity per cubic centimeter) of dry air at 0 degrees Celsius and standard atmospheric pressure. An exposure of 1 R is approximately equivalent to an absorbed dose of 1 rad in soft tissue for higher energy photons (generally greater than 100 kiloelectron-volts).

**rem**

Traditional unit of radiation dose equivalent that indicates the biological damage caused by radiation equivalent to that caused by 1 rad of high-penetration X-rays multiplied by a quality factor. The sievert is the International System unit; 1 rem equals 0.01 sievert. The word derives from roentgen equivalent in man; rem is also the plural.

**technique**

Combination of X-ray machine settings (technique factors) used to produce radiographs, which consists of the kilovoltage, tube current (milliamperes), and exposure time (seconds). The last two parameters are often multiplied to yield the electric charge that has crossed the X-ray tube during the exposure in units of milliampere-seconds. Any combination of time and tube current that produces a given product in milliampere-seconds produces the same exposure for a fixed peak kilovoltage. Also called technic.

**X-ray radiation**

Electromagnetic radiation (photons) produced by bombardment of atoms by accelerated particles. X-rays are produced by various mechanisms including bremsstrahlung and electron shell transitions within atoms (characteristic X-rays). Once formed, there is no difference between X-rays and gamma rays, but gamma photons originate inside the nucleus of an atom.