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ACRONYMS AND ABBREVIATIONS

Al	aluminum
AP	anterior-posterior
cGy	centigray
cm	centimeter
DOE	U.S. Department of Energy
EEOICPA	*Energy Employees Occupational Illness Compensation Program Act of 2000*
ESE	entrance skin *exposure*
Gy	gray
HVL	half value layer
ICRP	International Commission on Radiological Protection
ICRU	International Commission on Radiological Units and Measurements
in.	inch
IREP	Interactive RadioEpidemiological Program
Kev	kilo electron volts
kVp	Peak Kilovoltage, applied kilovoltage
LAT	lateral
mA	milliampere
mAs	milliampere-second
mGy	milligray
mm	millimeter
mR	milliroentgen
mrad	millirad
NCRP	National Council on Radiation Protection and Measurements
NEXT	Nationwide Evaluation of X-Ray Trends
NIOSH	National Institute for Occupational Safety and Health
OCAS	Office of Compensation Analysis and Support
PA	posterior-anterior
PFG	photofluorography
R	roentgen
RMS	root mean square
sec	second(s)
SID	source to image distance
SSD	source to skin distance
TLD	thermoluminescent dosimeter

TSD	target to skin distance
U.S.C.	United States Code
WDH	Washington State Department of Health (Radiation Section)

1.0 INTRODUCTION

Technical Information Bulletins (TIBs) are general working documents that provide guidance concerning the preparation of dose reconstructions at particular sites or categories of sites. They will be revised in the event additional relative information is obtained. TIBs may be used to assist the National Institute for Occupational Safety and Health (NIOSH) in the completion of individual dose reconstructions.

"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 facility" as defined in the Energy Employees Occupational Illness Compensation Program Act of 2000 (EEOICPA) (42 U.S.C. § 7384l(5) and (12))."

An additional contribution to occupational radiation exposure of workers may be from medical diagnostic x-ray procedures that were provided to the worker, at the time of employment and periodically thereafter. Although now considered to be occupationally related, the dose from these exposures was typically not measured nor was it considered or included as a part of the overall occupational exposure of the employee. The National Institute for Occupational Safety and Health considers diagnostic medical x-rays administered in conjunction with routine or special physical examinations, required as a condition of employment, as a valid source of occupational exposure and will include such exposures in the determination or reconstruction of the dose to the worker. Unlike occupational exposures incurred during normal work processes, diagnostic medical x-ray exposures from required medical procedures were not monitored, necessitating reconstruction of the doses acquired in this manner.

A comprehensive guidance document for external dose reconstruction has been developed to assist qualified health physicists in implementation of the EEOICPA (NIOSH, 2002). This TIB supplements and expands the guidance provided in the (NIOSH 2002) document by providing more specific and detailed methodology for dose reconstruction from diagnostic medical x-rays that were sustained by workers as a condition of employment. In addition, this document provides the technical basis for dose reconstruction in the absence of specific dose measurements or records of technique factors. The additional guidance provided in this report is needed because of the lack of available technical data and records specific to medical diagnostic exposures experienced by workers in the DOE weapons program. Where available, actual data files should be used to develop organ doses for specific x-rays exams.

2.0 TECHNICAL FACTORS AFFECTING DIAGNOSTIC X-RAY DOSAGE

A number of factors determine the dose to the patient from a diagnostic x-ray procedure. For a more or less standard medical radiographic (i.e. diagnostic) unit with a tungsten target (anode) and focal spot size of 1 to 2 millimeters (mm), these factors include the basic machine settings used for the exposure, viz. the applied kilovoltage of the beam (kVp, also known as peak kilovoltage or kilovolt peak), beam current (milliampere [mA]), and time of exposure (sec), distance, waveform, amount and kind of filtration used, collimation or use of diaphragms, tube housing characteristics, the type and speed of the film, development procedure, screens, grids and the size of the patient. While the list of factors enumerated looks formidable, in the absence of direct measurements of the beam itself, which are rarely available, the dose to the patient can be estimated with a reasonable degree of accuracy with knowledge of only the three basic machine parameters: applied kilovoltage, current, and time, along with filtration, collimation and waveform characteristics. The implications of these factors insofar as patient dose is concerned are briefly discussed below.

2.1 APPLIED KILOVOLTAGE AND FILTRATION

The energy of the x-ray beam is determined by the applied kilovoltage and the filtration, and is sometimes referred to as beam quality. X-rays, as produced in a typical medical x-ray tube, are bremsstrahlung produced when electrons from the cathode are accelerated into the anode as a result of the potential difference or applied kilovoltage between the two electrodes. As such, x-rays from a medical x-ray tube are a distribution or spectrum of energies ranging from zero to the applied kilovoltage, which refers to the potential between the anode and cathode of the tube. For a typical unfiltered x-ray spectrum, the average energy is about one third of the peak or maximum x-ray energy, which is equal to the applied kilovoltage. Therefore, most of the x-rays produced are very much lower in energy than the applied kilovoltage of the beam, and thus are attenuated by the torso or other portion of the body being radiographed and never reach the film. These low energy x-rays are of little value in radiography but contribute significantly to patient dose.

To reduce the dose to the patient, filtration in the form of a specified thickness of absorbing material is added to the beam port. This has the net effect of absorbing a large fraction of the lower energy x-rays that are of little or no value in making the radiograph while allowing a greater fraction of the more energetic and radiographically useful x-ray photons to pass. In this manner, the dose to the patient is significantly reduced while at the same time radiographic quality may be enhanced. A filtered x-ray spectrum has a correspondingly higher average energy than before it was filtered, although the photon fluence rate and corresponding dose rate is much reduced. Such a beam is said to have been hardened. A corollary to this filtration technique is to use a higher applied kilovoltage, and filter the beam relatively heavily to eliminate most of the low energy radiographically useless photons from reaching the patient.

Beam energy is specified in terms of quality, or hardness, which in turn may be specified in terms of the half value layer (HVL) in millimeters of aluminum. Unfortunately, this parameter is seldom available, and even if known is of limited value, in part because it does not specify the maximum energy of the beam or its true quality, since as the HVL measurement is made, the absorbers act as filters and the beam is further hardened. Thus the first HVL is always smaller than the second HVL beam, which in turn is smaller than the third, and so forth. A useful although rarely available measure is the homogeneity factor, which is simply the ratio of the second and first HVLs. Since the first HVL is always the smallest, the homogeneity factor will always be less than 1, and the closer it approaches unity, the more closely the beam approximates a monoenergetic photon beam whose energy can be determined from the HVL. What is most commonly used, although not always~~,~~ available, is the kVp of the machine and the external or added filtration. All x-ray tubes have so-called inherent filtration, which is the window, aperture or port in the tube enclosure through which the x-ray beam passes or emerges from the x-ray tube. In medical diagnostic units, the window or beam port through which the useful beam emerges is purposely made very thin, typically equivalent to 0.5 mm Al in attenuation, and hence provides little beam hardening. Other than the beam port itself, the tube housing is shielded to eliminate leakage radiation from the tube. Thus the beam port effectively characterizes what might be considered the inherent collimation of the tube.

Although the benefits of filtration with respect to improved radiographic images were known and understood as early as March 1896, within months of the discovery of x-rays (Magie, 1896), initially diagnostic radiographs were made with no added filtration. Recommendations, albeit not specific as to thickness, were put forth in 1937 by the International Committee for Radiological Units and Measurements (ICRU, 1937), which specified aluminum filters for x-rays of 20 to 120 kVp, which incorporated the diagnostic x-ray energy range. This was consistent with, although not as specific as, the 1936 recommendation of the U.S. Advisory Committee on X-Ray and Radium Protection, the forerunner of the National Council on Radiation Protection and Measurements (NCRP), which called

for total filtration 0.5 mm of Al equivalent for radiographic installations, and 1 mm Al for fluoroscopy (NBS, 1936). In general, manufacturers of radiographic x-ray tubes complied with this standard, and medical radiographic tubes in use in the 1940's typically had inherent filtration of 0.5 mm Al (Morgan and Corrigan, 1955, pp. 308-310).

Typical external or added filtration in the 1940's ranged from none to 1 mm Al. In 1949, the NCRP recommended 1 mm of added Al filtration for radiographing thick parts of the body such as the chest (NBS 1949) and was in use during World War II in 100 mA units in larger military hospitals, and hence presumably at the various Manhattan District sites which were under the aegis of the U.S. Army (Olson, Trask and Dessent, 1966). Subsequently, recommended thicknesses were increased not only for patient protection but for improved radiographic image quality; in 1955, the NCRP recommendation for diagnostic x-ray units called for 2 mm total Al filtration for new machines (NBS, 1955), the recommended filtration increased again to 2.5 mm by the 1960's for medical diagnostic units operating above 70 kVp (NCRP, 1968). For machines already in operation, these recommended filter = thicknesses might not have been utilized for some time after the date of the recommendation.

The relationship of beam intensity[1] to applied kVp and to filtration is complex and to some extent is machine specific and hence is best determined empirically. However, in the absence of empirical data for a specific machine, adequate contemporary empirical and theoretical data exist upon which to determine within a reasonable degree of uncertainty, the machine output. Additional filtration reduces the entrance skin *exposure*[2] (ESE), generally in an exponential manner. For a typical single phase half, full or self rectified machine operating in the diagnostic range of 80 –100 kVp, each additional mm of Al filtration will effect a reduction of about 40 per cent in the ESE (Trout et al., 1952; Taylor, 1957). The approximate intensity reduction afforded by any thickness of Al filtration can thus be determined by the following exponential equation:

$$I = I_{(o)}\, e^{-0.5t}$$

or

$$\ln (I/Io) = - 0.5\ t$$

in which t is the thickness of Al, in mm, and I and Io are the beam intensities with and without the filter, respectively. In the absence of specific measurements or empirical data, this correction can be applied to determine the effect of filtration on beam intensity, and is consistent with the guidance put forth in OCAS-IG-001 Revision 1 (2002).

Similarly, increasing the kilovoltage (kVp) will increase the beam intensity or exposure rate. This can be calculated using Kramer's rule, but such calculations are difficult, complex and time consuming, even with high speed computers, and are at best approximations. However numerous empirical studies of beam intensity as a function of the range of (kVp) used in medical diagnosis have been carried out over the years and provide ample credible evidence to show that for a given amount of filtration, increasing the applied kVp will increase the beam intensity according to the 1.7 power of the applied kilovoltage (Handloser, 1951; Trout et al., 1952; Kathren, 1965; Cameron, 1970). In the

[1] As used herein, beam intensity refers to the output of the machine in terms of *exposure* in the special sense per mAs. *Exposure* in the special sense is referenced to ionization in air and as such is not a dose quantity.

[2] Throughout this document, italics will be used to differentiate *exposure* in the special sense from exposure in the general sense. Thus *exposure* refers to exposure in the special sense. A brief discussion of exposure in both the general and special sense can be found in numerous publications, including NCRP Report 82 (1985) and International Commission on Radiological Units (ICRU) Report 60 (1998). It is important to note that the definition and application of the quantity exposure and its concomitant unit the roentgen have undergone several important modifications over the years, which have been documented throughout the literature.

absence of specific measurements or empirical data, this function can be applied to determine the effect of applied kilovoltage on beam intensity, and is fully consistent with the OCAS guidance document (NIOSH 2002).

It should be noted that the effects of filtration and kVp tend to offset one another; addition of filtration reduces the *exposure* or dose per milliampere-seconds (mAs), while increasing the kVp increases the *exposure* and dose per mAs. Higher kVp radiographic techniques typically require shorter exposures in terms of milliampere-seconds, and the dose reduction from additional filtration at the recommended level more than offsets the additional dose from using increased kVp. However, there is not a direct correspondence or proportionality between the effects of filtration and kVp.

2.2 CURRENT AND EXPOSURE TIME

Diagnostic x-ray exposures are typically specified in terms of mAs, the product of x-ray tube current and the exposure time. Other factors being equal (e.g. kVp, filtration, film, development and screen combination) radiation exposure and hence dose delivered to the patient is proportional to the number of mAs. The current in an x-ray tube refers to the number of electrons accelerated across the evacuated volume of the x-ray tube, flowing from the cathode to the anode. For a given applied kilovoltage, the number of x-ray photons produced, and therefore the *exposure* will at least in theory be directly proportional to the x-ray tube current, and indeed this is and has been historically true for most medical radiography units over their designed tube current range. Thus, in the absence of measurements or other data or information to the contrary, it is reasonable and consistent with long standing radiographic practice (Sante, 1946, p. 61) to assume linearity of beam intensity and hence patient dose with tube current.

Exposure time refers to the time that the beam was on or the machine was producing x-rays and is, for all practical purposes, linear with exposure. To avoid or minimize image blurring from the beating heart, exposure time was minimized, and the current concomitantly and proportionately increased to obtain the desired exposure in terms of mAs. However, from a dose reconstruction standpoint, it should be noted that earlier medical radiographic units were equipped with mechanical timers whose accuracy was not as good as the electronic timers used on later model machines. Gross bias errors in timer accuracy are unlikely in that these would result in over- or underexposure of the radiograph and so would be quickly detected and corrected. Subtler are small random errors, which might produce uncertainties of perhaps ± 20 per cent in the exposure.

Chest photofluorography (PFG), which resulted in a much greater patient dose from a diagnostic procedure, was used sporadically until as late as the early 1960's. PFG used a smaller film (4 x 5 inches), a smaller SSD (42 inches), and a higher kVp and typically resulted in a several fold greater exposure in terms of mAs. Exposure was regulated by photometers, which utilized the exposure to the film to determine the time of exposure.

2.3 DISTANCE

X-ray beam intensity is a function of distance from the target, approximating inverse square at large distances (i.e. more than a few tens of centimeters) from the tube. Radiographic chest films were taken at a standard source to image distance (SID) of 72 inches; the source refers to the focal spot of the tube and the image to the plane of the film. The distance to the patient, sometimes expressed in terms of the source to skin distance (SSD), is somewhat smaller since the patient is positioned between the source and the film cassette. Therefore, the ESE to the patient is somewhat greater than the exposure at the plane of the film. In addition, patient attenuation would further reduce or attenuate the number of photons reaching the film. To compensate for the increased attenuation provided by a

larger patient, x-ray technicians would sometimes increase the beam settings for a large patient, or, if the machine was so equipped, might use a high speed Bucky diaphragm, likely with a somewhat higher kVp. It thus may be appropriate for an individual dose reconstruction to increase the ESE or skin entrance kerma for a large or stout patient. Based on standard contemporary techniques (Picker, 1941, p 67; Fuchs 1958, p184; Cahoon, 1961, p 183) for patients with a chest thickness of 25-27 centimeters (cm), an increase of +50 % from the ESE to the average patient should be sufficiently conservative; for still larger patients, a factor of 2 would be appropriate. The average worker chest size is taken to be 22-24 centimeters.

2.4 COLLIMATION AND WAVEFORM CHARACTERISTICS

Among the other factors that potentially affect patient organ dose are collimation (i.e. beam size) and waveform. X-ray waveforms are of three types: half wave rectified, which is almost never seen; full wave rectified, which is typical of virtually all medical radiographic units, and constant potential. A half wave rectified machine produces 60 half sinusoidal shape pulses of x-rays per second, each with a duration of 1/120 of a second. A full wave rectified machine produces 120 half sinusoidal pulses of x-rays per second, each with a duration of 1/120 second. Thus, for a given setting of kVp and mA, the intensity of the beam from a half wave rectified machine will be half that of the beam from the full wave rectified type. A constant potential machine produces a more or less steady (i.e. unpulsed) output of x-rays and has a somewhat greater beam intensity (approximately 10 %) as compared with a full wave rectified machine operating at the same kVp and mA.

Collimation refers to the size of the beam. In the early years following the discovery of x-rays, the philosophy was to use a fairly large aperture (i.e. limited collimation) to ensure that the entire area of interest was included in the radiograph. Subsequently, because of patient protection concerns, beams were collimated such that the smallest beam consistent with the area of interest was used, thereby limiting the area of the patient exposed, and, in the case of chest radiography, minimizing dose to organs such as gonads, thyroid, and gastrointestinal tract. A practical check of collimation can be made by reference to the radiograph; a well collimated beam will leave a small unexposed area or penumbra effect at the edges of the radiograph, while a poorly collimated beam will produce a radiograph that is exposed all over its area. Beam diameter limiting cones were widely used in radiography during the 1940's and beyond to improve radiographic image quality by reducing scatter (Glasser et al., 1944, p. 136) and were sometimes equipped with an Al filter of 1 mm in early years and thicker ones later on. A standard albeit largely undocumented practice was to collimate the beam to a size at the receptor (i.e. film) that was about one inch larger in all directions than the beam itself. This would provide a satisfactory picture quality as well as ensuring that the area desired was included in the radiograph. Thus for a 14 x 17 inch chest radiography, a beam diameter of 16 x 19 inch might be used, providing a ratio of (16x19/14x17 = 1.28). Wochos, Detorie, and Cameron (1979) analyzed the 1972-1975 Nationwide Evaluation of X-Ray Trends (NEXT) data and found that at some facilities, primarily internal medicine and general practitioners, the beam area to film area ratio could be as high as 2.0, but more significantly also noted that the beam area to film area was significantly lower at hospitals and radiology facilities where more routine diagnostic x-rays were conducted. To ensure claimant favorability, the beam area to film ratio of 2.0 should be used in the absence of information to the contrary with respect to collimation (Webster 1992). This ratio would be achieved by exposure from an additional 3 inches of exposure and extension of the beam in all directions around a 14"x17" standard radiographic film.

In the absence of measurement data, the beam size at any distance from the tube can be approximated, assuming no external collimation or coning, by the application of geometry, if the size of the beam port and the effective depth of the focal spot are known or can be assumed. If these are known, the diameter of a beam without a cone or other external collimation would, at the location of

the patient, be approximately equal to the SSD times the ratio of effective depth to the beam port diameter. Typically, beam apertures or port diameters did not exceed two inches. The effective depth of the focal spot from the aperture, however, was more variable and typically six inches or so, giving a ratio of about one-third. Thus, for a patient undergoing a standard posterior–anterior (PA) chest procedure, the SSD is about 153 cm and the diameter of a beam with no external collimation or cones would correspondingly be 51 cm or about 20 inches. The ratio of beam size to film area in this case is 1.32, which is consistent with what was observed by Wochos, Detorie, and Cameron (1979). For early years (before 1970), x-ray beam or scatter measurement data, techniques, and beam port information may not be available to estimate the collimation of the x-ray beam. Feldman et al. (1957) noted wide variation in their review of x-ray dose literature in 1957. Through measurements, Feldman et al. (1957) noted a factor of 10 increase in the gonadal dose when no external collimation was used. Lincoln and Gupton (1958) also noted that the gonadal dose varied by a factor of 5 among the eight x-ray facilities at Oak Ridge. Webster and Merrill (1957) discussed the effects of cone size and centering on the gonadal dose, and concluded that filtration, kVp, and the smallest possible cone size were most important to reduce the gonadal dose

If actual dose measurements or inspection of the radiographs that indicate that collimation was used prior to 1970, this information should be used for organ dose determination. However, due to the reported variation in the literature and measurement data on the effects of collimation, the claimant favorable assumption of minimal external collimation of the primary beam should be used when measurement data, technique, or other information to describe the collimation are not available for x-rays taken prior to 1970. This is based on the following claimant favorable assumptions and professional judgment:

1. In the late 1950s, there was significant research into the gonadal dose and the reasons for the observed variation in dose. This research described the effects of filtration, collimation, and centering. By the early 1960s, techniques were being modified incorporating additional collimation. While these techniques were likely fully incorporated at most DOE facilities by 1965, to allow for the possibility that some smaller facilities might not have had the resources to update their equipment and to be claimant favorable, the year 1970 was selected as the cutoff year.

2. In 1968, the NCRP, in Report 33, updated their guidance on medical x-ray protection. While many DOE facilities had probably already incorporated the guidance in this report, some smaller facilities might not have incorporated the guidance by 1968. To ensure that these facilities were in fact in conformance with the 1968 recommendations, an additional two-year period was added, again making 1970 the cutoff year.

3. By the late 1950s, reports in the literature of most of the surveys of medical x-ray facilities revealed low gonadal doses, indicating adequate collimation. A few surveys clearly indicated the use of collimation was limited. Of the eight surveyed facilities at Oak Ridge, only one (13%) had a moderately high male gonadal dose (5 mrad). At all of the other facilities, the male gonadal dose was less than 2 mrad. Variation among the other facilities appeared to be the result of differences in the use of filtration and cone size. Thus most facilities were using some form of collimation by the late 1950s, and by the mid 1960s most, if not all, facilities were probably using some form of collimation. Since references as to when all facilities were using adequate collimation were not found, professional judgment was used to estimate this time period to be the mid 1960s. To fully assure claimant favorability, this assumption has been further expanded by 5 years to 1970 to allow for the uncertainty in professional judgment.

2.5 SCREENS, GRIDS, AND OTHER FACTORS POTENTIALLY AFFECTING PATIENT DOSE

A number of other factors also affect the x-ray exposure required to obtain a proper radiograph and hence the dose to the patient. However, knowledge of these factors is unnecessary for dose reconstruction purposes if beam measurements are available or if the primary machine characteristics of applied kilovoltage (kVp), time (sec) and current (mA) are known along with the amount of primary beam filtration. Although the other factors can be used as additional confirmation of the applicability of the reconstructed dose. Hence, for completeness, only brief mention will be made of these factors, which are: tube housing, type and speed of the film, development procedure, screens, and grids.

X-ray tubes used for diagnostic radiography are typically enclosed in a protective lead tube housings with the primary beam brought out through a port or window in the side of the housing. Although some reduction of the dose to the patient is achieved, largely through elimination of scattered radiation and improved collimation, this so-called diagnostic tube protective housing is primarily for the purpose of protection of the operator and unexposed x-ray film and nearby individuals other than the patient. The issue is moot, however, because virtually all x-ray tubes used to x-ray the DOE weapons worker cohort have been equipped with protective tube housings, which limited leakage to less than 0.1 R/hr at one meter from the tube.

The exposure needed for a suitable diagnostic radiograph is in some measure a function of film speed and development. Fine-grain emulsions produce a superior radiographic image but require additional exposure as compared with fast films, which typically have a larger grain size. Underdevelopment of films will also require additional exposure to achieve satisfactory radiographic quality. Intensifying screens are used within the cassette to intensify the radiographic effect and thereby effectively increase film speed and reduce patient dose. Film speeds have typically increased since the 1940's and reduced patient doses appreciably, perhaps by half. Grids, specifically the Potter Bucky diaphragm (colloquially known as a Bucky) are sometimes utilized for thick section radiography, but rarely used for chest radiography except with very large patients. In any case, the above are all factored into the technique (i.e. kVp, mA) that is used and except in rare instances and a virtually complete absence of other data, are not of importance in dose reconstruction.

2.6 SUMMARY AND APPLICATION OF TECHNICAL FACTORS

For convenience and possible application to cases in which other and more suitable data are not available, or for generic use, the effect of various technical factors has been tabulated below in Table 2-1.

Table 2-1. Relationship of beam intensity and various technical factors.

Parameter	Units	Relationship with intensity
Applied voltage	kVp	Intensity proportional to 1.7 power of kVp
Tube current	mA	Linear
Exposure time	sec	Linear
Filtration	mm Al	Intensity decreases by ~40% for each additional mm Al
Patient size (chest thickness)	25-27 mm > 27 mm	Dose increased by factor of 1.5 Dose increased by factor of 2
Distance	d	Approximately inverse square relationship ($1/d^2$) holds for distances > about 30 cm from target
Uncertainty	± 30%	Assumes all errors are positive, + 30% should be used

3.0 RECONSTRUCTION OF DIAGNOSTIC MEDICAL X-RAY DOSES

Not all workers were required to undergo medical diagnostic x-ray examinations as a condition of employment. Among those who were, the procedure was usually limited to a single PA chest film, although a lateral chest film might also have been taken. Stereo chest films also may have been taken on some individuals; this procedure required two separate films with the views slightly displaced and thus required two exposures. Some workers were examined with chest PFG units, which produced a much greater dose than the standard PA radiograph. A very small fraction might have undergone lumbar spine or other specific procedures if there was a medical indication. Pelvic x-rays may have been routinely carried out at some DOE sites for workers that had a potential for exposure to fluoride. A protocol for calculating doses from pelvic x-rays is provided in Appendix A to this document.

The incidence of defective films necessitating retakes is not known, but it is likely to have been very small and certainly no more than a few per cent and probably much less. Trout et al (1973) in their analysis of the rejection rate of chest radiographs obtained during the Coal Mine "Black Lung" program reported an average rejection rate of 3% among 67,000 radiographs. Retakes should serve as a signal to give special consideration to the evaluation of technique factors, and hence the resultant dose calculations. A retake in a very large individual might serve as a signal that the initial radiograph was taken with technique factor settings suitable for a smaller person, and that the second radiograph reflected an additional and larger dose. Retakes in African-Americans may signal that the initial exposure was too great, and indicative of an overriding of the standard or automatic technique factors because of a perception held by some x-ray technicians that African-Americans had greater bone density or other characteristics that required additional exposure. Similarly, retakes in females may be indicative of manually altered settings to increase beam intensity under the misimpression that additional exposure was required for women because of the larger amount of breast tissue. Unless machine settings have been recorded, it is impossible to determine whether the retake was necessitated by an arbitrary manual increase in machine settings to obtain a greater exposure. If machine settings are available, then an adjustment for the increased doses can be made using the data provided in Table 2-1. If machine settings are not available, then to ensure claimant favorability for African-Americans and women whose records indicate retakes, an upward adjustment of the organ doses from the first radiograph is indicated. Increasing doses by a factor of two in these cases should more than compensate for the supposed additional exposure.

Diagnostic medical x-ray dose reconstruction is best accomplished when actual measurements of beam intensity are available. Use of actual measurement data is the simplest and most direct means of assessing diagnostic medical x-ray doses, typically requires few, if any assumptions, and has the least amount of uncertainty. Hence, use of actual measurement data, where available, is preferred for diagnostic medical x-ray dose reconstruction and should be used if available. Actual beam measurements are most likely to provide the most accurate estimates of organ doses.

X-ray output measurements are likely to be unavailable, particularly prior to about 1980. In the absence of suitable measurement data, medical diagnostic x-ray dose reconstruction can be accomplished using technique factors along with published output data that provide beam intensity per mAs as a function of kVp, filtration, and distance. The use of technique factors will typically require a number of assumptions, and these, of course, should be claimant favorable. If both measurement data and technique factors are unavailable or unknown, then dose estimates can be made using the default values shown in Table 3-4. Use of default values is a last resort. To reiterate, the first choice should be to use actual beam measurement data when available.

3.1 RECONSTRUCTION WHEN MEASUREMENTS ARE AVAILABLE

Although beam output measurements may typically be unavailable, diagnostic medical x-ray dose reconstruction using actual measurement data is the preferred method for determining the dose to the worker from this source, so much so that special effort to determine if such measurements have been made is justifiable. Beam output measurements are typically made in terms of exposure and are quantified in units of R, and depending on the measurement device and technique may have a wide range of uncertainty. The best measurements are those made with integrating ionization chambers designed for medical x-ray applications. Until about 1970 or so, there were two such instruments in common usage and availability in the United States, the Victoreen R-meter, or Landsverk L series ion chambers. Subsequently, a wide variety of such instruments have become available. Measurements with R-meters and similar chambers, if properly done, have a high degree of reliability and a low degree of uncertainty. In general, the uncertainty of properly done measurements in the energy region of interest should not exceed +2 % of the measured value (Kathren and Larson, 1969).

Other integrating devices such as film, thermoluminescent dosimeters (TLD) and pocket ionization chambers have also been used for beam output measurements. Measurements made with these types of dosimeters should be used with great caution. All are, to varying degrees, energy dependent, and correction for beam energy is a necessity. This requires knowledge of the x-ray beam energy and the response of the dosimeter as a function of energy. Typically, pocket ionization chambers provide the least reliable measurements with the greatest uncertainty. Therefore, results obtained with these devices are highly suspect and should be used with great caution. Film and TLD, if appropriately calibrated to the beam energy, can provide satisfactory measurements, albeit with a considerable degree of uncertainty. The widely used LiF TLDs, compared with higher Z phosphors and film, show relatively good energy and other response characteristics, and, if properly used can provide uncertainties similar to those of R-meters. Considerably greater uncertainty – perhaps on the order of several tenths of a percent – may apply to film dosimeters. No specific uncertainty values can be provided here, as each film dosimeter and TLD system is different, and reference to the literature is necessary to determine the appropriate values for specific dosimeter systems.

Beam output measurements usually define or directly determine the ESE, or can be corrected to obtain a reasonable estimate of the ESE for a given procedure by using the generic intensity relationships shown in Table 2-1. The ESE will, of course, be in units of R, which must be converted to kerma and then to organ dose. As discussed above, an exposure of 1 roentgen (R) is typically taken to be equal to a kerma of 1 rad (10 mGy); actually, 1R is slightly less than 1 rad (10 mGy) of kerma, but the difference is small and making the numerical equivalence greatly simplifies the dose reconstruction as well as providing a small additional measure of claimant favorability.

Once the ESE has been converted to entrance kerma, doses to a number of different organs from various radiographic procedures can be obtained from tables A2 through A8 of International Commission on Radiological protection (ICRP) Publication 34 (ICRP 1982). ICRP 34 (1982) Tables A2 through A8 do not provide dose conversion factors for un-collimated x-ray machines. Use of these tables requires knowledge of the x-ray beam quality expressed in terms of the HVL in millimeters of Aluminum (Al). If the kVp and filtration are known, HVLs can be estimated from the data given in Table A16 of ICRP Publication 34 (ICRP 1982, p. 77) or Table B.2 in NCRP Report No. 102 (1989 p. 98). In general, the greater the kVp and filtration, the greater the HVL. If the actual beam quality is unknown, as is likely the case, to ensure claimant favorability a higher rather than a lower HVL should be assumed. In the absence of actual data, recommended default values for beam quality are 2.5 mm Al HVL for radiographs taken prior to 1980, and 4.0 mm for subsequent radiographs. These values are likely overestimates of HVL and hence are claimant favorable.

However, Tables A2 to A8 in ICRP Publication 34 (1982) do not include all the organs that have been identified in the Interactive RadioEpidemiological Program (IREP) code. For those organs included in the IREP but not specifically identified in ICRP Publication 34 (1982), use of the dose conversion factors for the organ specified in ICRP Publication 34 (1982) that is anatomically the closest would seem to be a reasonable and simple first order approach that generally would be claimant favorable or neutral. Refer to Figure1 below. Thus, the factor for lung would be applied to all other organs within the thoracic or abdominal cavity that may be intercepted by the primary beam – i.e. thymus, esophagus, stomach, and liver/gall bladder/spleen. Since an appreciable fraction of the skeleton, and in particular the trabecular bone which has a large surface-to-volume ratio and the sternum which is a primary location of the red marrow in the adult, lies within the trunk, the factor for lung would also be applied to the bone surfaces. For organs in the lower abdomen – i.e., urinary bladder, and colon/rectum, – the dose conversion factor for ovary would be used. For the eye/brain, the analogous organ is the thyroid. These relationships are shown in tabular form in Table 3-2. Skin dose can be obtained by reference to Table B.8 in NCRP Report No. 102 (NCRP, 1989, p. 103), which provides backscatter factors for different beam qualities and field sizes. For chest radiography, a backscatter factor of 1.35 is recommended to ensure claimant favorability. (The backscatter factor of 1.35 is for 2.5 mm Al HVL; NCRP Report No.102, 1989, Table B.8, P.103 provides a range of backscatter factors for various HVLs.)

It is useful to prepare a summary table of beam parameters as shown in Table 3-3. This table is taken from actual data and measurements available for the Hanford Site and is shown here as an example of what a summary table should include where measurements are available. The table includes not only the measured values for given time periods, but a reference to those values as well as other salient data pertaining to beam and exposure. It is of interest albeit not unexpected to note that there is a generally decreasing trend of ESE with time, which is wholly consistent with what has been the general experience nationally (Gray 1996). For conservatism in determining or reconstructing doses and in accordance with the guidance put forth in OCAS-IG-001, the ESE should be assumed to have been constant from the time of the measurement until the time of the next measurement.

3.2 RECONSTRUCTION USING TECHNIQUE FACTORS

When beam measurement data are unavailable, as is likely to be the case, technique factors can be used to obtain reasonable estimates of exposure. The basic data required are kVp, filtration, exposure in mAs, and distance. Beam output data are available from a number of publications, including NCRP Report No. 102 (NCRP 1989). Table B.3 in this report (p. 99) provides average air kerma rates for medical diagnostic x-ray equipment operating at various kVp with 2.5 mm Al filtration at distances from 30 to 182 cm from the source. Correction for different thickness of Al filtration can be made by reference to Table 3.1, p. 13 in NCRP Report No. 102 1989. As an alternative, Figure

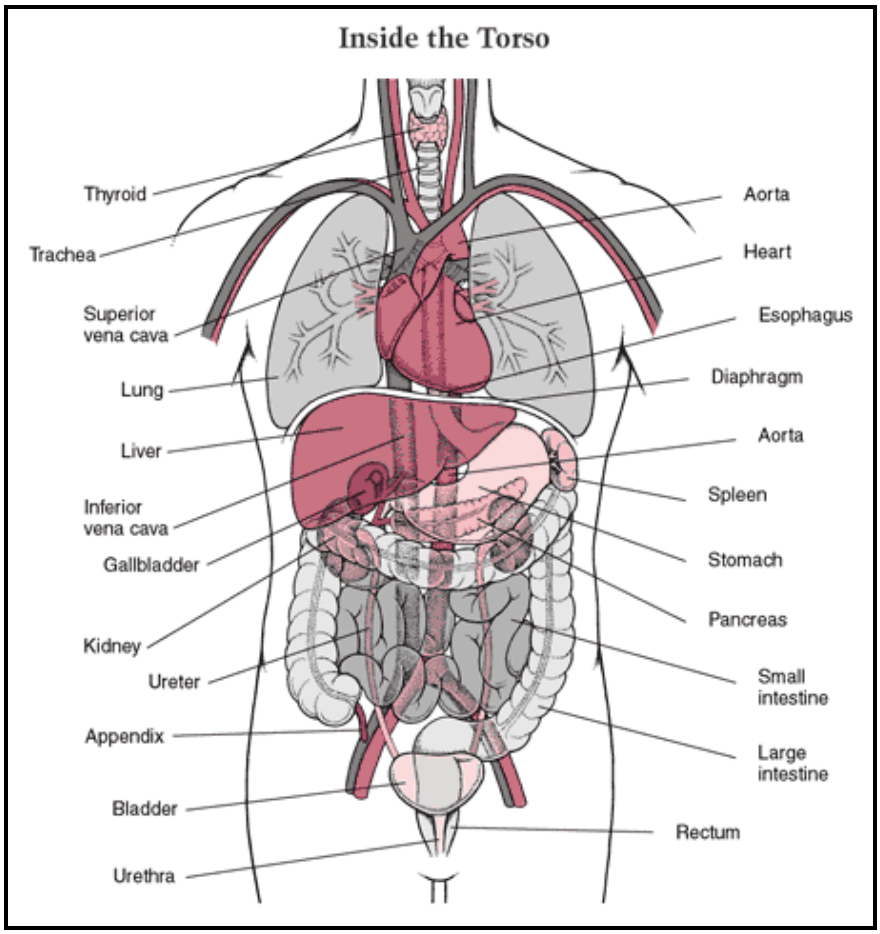

Figure 3-1. Anatomy of a human torso (Merck 2003, Section 1, Chapter 1).[3]

Table 3-2. Analogues for IREP organs not included in ICRP 34.

Anatomical location	ICRP 34 reference organ	IREP organ analogues
Thorax	Lung	Thymus Esophagus Stomach Bone surface Liver/gall bladder/spleen Remainder organs
Abdomen	Ovaries	Urinary/bladder Colon/rectum
Head and neck	Thyroid	Eye/brain

B.1 (p. 109) in NCRP Report No. 102 provides a graphical representation of air kerma at 100 cm for various values of kVp and filter thickness greater than 2.5 mm Al (NCRP 1989, p109). Using these tables, a reasonable estimate of beam output and hence entrance kerma can be obtained. Once the entrance kerma has been determined, organ doses are determined in the manner described above for reconstruction using measurement data.

[3] Source: http://www.merck.com/mrkshared/mmanuel_home/illus/1i1.jsp.

Table 3-3. Example of summary data based on actual beam measurements for the Hanford site.

Date measured	10/18/1999	2/04/98	4/22/1997	11/11/1993	3/30/1990	1/21/1988	1/20/1988	1/28/1983	4/12/1959	2/1/1946	Before 2/46
Procedure	Chest PA 14"×17"	Chest PA 14"×17"	Chest PA 14"×17"	Chest PA 14"×17"	Chest PA 14"×17"	Chest PA 14"×17"	Chest PA 14"×17"	Chest PA 14"×17"	Chest PA 14"×17"	Chest PA 14"×17"	Chest PA 14"×17"
Machine type	XMA - 360	XMA - 360	CONXI Type 12	CONX Type 12	CONX Type 12	CONX Type 12	CONX Type 12	G.E. DXR 750	Unknown	Unknown	Unknown
Machine settings kVp:	110	110	110	110	110	110	110	100	80	80	Unknown
mA	300	300	300	200	200	200	100	200	300	500	Unknown
Exposure time	1/60 sec	1/60 sec	1/30 sec	1/30 sec	1/30 sec	1/20 sec	1/10 sec	1/20 sec	1/30 sec	1/20 sec	Unknown
mAs	5	5	10	6.7	6.7	10	10	10	10	25	Unknown
Added filter	2.7 mm	2.7 mm	2.5 mm	2.5 mm	2.5 mm	2.5 mm	2.5 mm	2.5 mm	1.5 mm	1.5 mm	1.5 mm
Assumed HVL, Al	4.0 mm	4.0 mm	4.0 mm	4.0 mm	4.0 mm	4.0 mm	4.0 mm	2.5 mm	2.5 mm	2.5 mm	2.5 mm
Source to skin distance	72"	72"	72 "	72 "	72 "	72 "	72 "	72 "	72 "	72 "	72 "
Entrance skin exposure	11 mR	11 mR	17 mR	21mR	21 mR (Assumed)	35 mR	35 mR	35 mR	40 mR	79 mR	120 mR
mR/mAs	2.2	2.2	1.7	3.3	3.3	3.5	3.5	3.5	4	3.2	Unknown
Date range		2/98 to date	4/97 to 2/98		3/90 to 4/97			1/83 to 3/90	4/59 to 1/83	2/46 to 4/59	
Reference	Washington State Dept. of Health Measure-ment	Washington State Dept. of Health Measure-ment	Washington State Dept. of Health Measure-ment	Washington State Dept. of Health Measure-ment	Measured at 11.7 mR by State. The 1993 value was used, as it was higher for same settings& machine.	Washington State Dept. of Health Measure-ment	Washington State Dept. of Health Measure-ment	Kathren to Heid memorandum Dated 1/28/83	Rising & Soldat letter to Norwood dated 4/30/59	Mancuso et al. Dated 1966	Based on experience & references of early 1940s x-ray dose. Assumed for Hanford.

3.3 RECONSTRUCTION USING DEFAULT VALUES

Default values of entrance kerma have been developed for the three most commonly used occupational medical diagnostic x-ray procedures: PA chest radiography; lateral (LAT) chest radiography; photofluorographic (PFG) chest films when actual measurement data or knowledge of technique factors are absent. The default values are considered to be maxima or upper limit values developed from review of patient doses as reported in the literature, machine characteristics, and knowledge of x-ray procedures used during the time periods indicated and hence are claimant favorable. Sufficient conservatism was included in the determination of the default values to ensure with near certainty (99+ per cent confidence) that the actual exposures from the specified procedures would not exceed the default values, thus ensuring claimant favorability. In determining these factors, it was assumed that a minimum of filtration was used along with low kilovoltage techniques, slow film speeds with standard development, and no additional collimation or use of cones. The default entrance kerma values for the three procedures are given in Table3-4.

Table 3-4. Default dose values by procedure.

Period	Entrance kerma, cGy PA chest	Entrance kerma, cGy lateral chest	Entrance kerma, cGy photofluorographic chest
Pre-1970	0.20	0.50	3.0
1970-1985	0.10	0.25	
Post 1985	0.05	0.13	

These default values can then be used as described above in lieu of actual measurement data or entrance kerma derived from technique factors, but need to be applied with care. As a rule of thumb, the ESE and entrance kerma for a lateral chest x-ray is assumed to be 2.5 times that from a corresponding PA chest radiograph, a conservative and hence claimant favorable value based on measurements from Hanford (Kirklin et al. 1969) where a factor of 1.94 was observed, and other measured data which suggest that the ratio of ESE from lateral and PA chest radiographs could have been somewhat greater (Cardarelli et al. 2002; Stanford and Vance 1955). To ensure that dose from this source was not underestimated, the moderately conservative factor of 2.5 was assumed for the ratio of ESE from lateral to PA chest radiography for the purpose of organ dose calculations.

This value should be used with the appropriate tables (A.2 through A.8) from ICRP Publication 34 (ICRP 1982) to determine organ doses. It needs to be stressed that it is the entrance kerma or ESE of a lateral view that is 2.5 times the kerma or ESE of a PA view, and not the organ doses. Because of geometry and other considerations, the organ doses for a lateral view do not scale linearly with the ESE for a PA view, and need to be determined accordingly from the ICRP 34 (1982) tables A.2 through A.8.

4.0 APPLICATION AND REPORTING OF OCCUPATIONAL MEDICAL CHEST X-RAY DOSE RECONSTRUCTION

Table 7-6 provides organ dose conversion factors and organ dose calculations for chest radiography dose reconstruction for the default case provided in Table 3-4 above.

5.0 PHOTOFLUOROGRAPHY

Photofluorography (PFG), also known as photoroentgenography, was utilized for routine chest radiography and, as has been well documented in the literature, typically produces higher patient doses than conventional radiography (Braestrup 1958, p. 140; Laughlin et al., 1957; Moeller, Terrill

and Ingraham, 1953). It is reasonable to presume that at least some of the occupational medical diagnostic chest x-rays with the DOE and its predecessor organizations were accomplished by PFG and in the absence of data to the contrary, the use of PFG should be assumed to ensure claimant favorable dose reconstructions. PFG differed from conventional radiography with film in that while kVp and mA settings could be manipulated by the technician, the exposure time was regulated by the amount of light generated in the PFG unit, with a cutoff or maximum exposure time. An exposure of 15 mAs (150 mA for 0.1 second) was sufficient to produce a satisfactory image on 35 mm film; larger film required greater exposures (Sante, 1954, p. 129).

Typical operating parameters reported for 1950's PFG were 24 mAs at 83 kVp at a target to film distance of 36 inches (Braestrup, 1958, p. 143), and 30 mAs at 90 kVp with a target to film distance of 40 inches and 2.4 mm added filtration. In the absence of data, added filtration of 2.5 mm should be assumed for dose determinations and is claimant favorable (Feldman et al., 1958). The reported gonadal doses equated to 0.15 and 0.36 mrad, respectively, for females and males in the United Kingdom (Stafford and Vance 1957), and 1 and 2 mrad, respectively for females and males, in an American study (Laughlin et al.1957). In another study in the United States, (Feldman et al. 1958) reported gonadal *exposures* equivalent to doses of 0.73 for males and 15 mrad for females, the large difference being attributable to assumed collimation. Data in the literature indicate an ESE in the region of about 0.5 to 1 R (Laughlin et al. 1957; Feldman et al. 1958; Moeller, Terrill and Ingraham, 1953). Measurements at the Hanford site indicated that for a 60 mAs PFG exposure at 100 kVp, the ESE was 1.53 R (Rising and Soldat, 1959), which is likely an upper limit value based on a large patient and is consistent with an ESE of about 600-700 mR for a 24-30 mAs exposure at somewhat lower kVp. Thus, although the Hanford measured value is likely an upper limit and hence an overstatement of the actual exposure from photofluorography to the average patient, this 1.53R ESE value should be used in the absence of data to ensure claimant favorability.

Organ doses for chest photofluorography are calculated in a different manner from organ doses calculated for conventional radiography using the entrance kerma values. Table 6-5 provides dose conversion factors for the ICRP organs based on a distance of 102 cm and beam quality of 2.5 mm Al HVL. Where entrance kerma values are unavailable, default values for organ doses should be used; these are given in Table 3-4.

Dose estimates for PFG represent absolute upper limits and must be used to ensure claimant favorability in the absence of more specific information. At sites where measurements or technique factors are available, the organ doses could very possibly be lower.

The use of PFG has been documented for different DOE sites and specific dates. The specific dates for the last documented use of the photofluorography equipment and techniques are listed in Table 7-6. In addition, the table lists the references used for the documentation.

6.0 LUMBAR SPINE

At some sites, lumbar spine radiographs were routinely required for certain classes of male workers to determine the presence of back problems. The frequency of lumbar spine views, if required, was variable. Typically if lumbar spine radiography was required, it was performed as part of the preemployment physical examination, and for many workers this may have been the only occasion on which lumbar spine radiographs were taken. However, the possibility of periodic lumbar spine examinations, including an exit employment physical examination should not be precluded. Lumbar spine examinations for evaluating back problems might have included both an AP and lateral view, and in the absence of data to the contrary, for claimant favorability it should be assumed that both views – a total of 4 views (2 AP and 2 lateral) as indicated in Table 7-7 -- were taken. Recommended

Table 6-5. Organ doses for default entrance kerma values.

Organ	View	Dose conversion factor (mGy per Gy air kerma)[a] HVL 2.5 mm Al for photo-fluorography (PFG)[b] Beam for PFG includes thyroid, and thoracic organs. It does not include gonads, bladder, or colon/rectum.	Organ dose PFG (rem) March 1945 to January 31, 1962	Dose conversion factor (mGy per Gy air kerma)[a] HVL 2.5 mm Al minimal collimation	Organ dose pre-1970 (rem)[c,d] minimal collimation
Thyroid	PA	174(h)	5.22E-01	174 (h)	3.48E-02
	Lat			137	6.85E-02
Eye/brain	PA	32	9.60E-02	32	6.40E-03
	Lat			137	6.85E-02
Ovaries	PA	N/A	2.5 E-02 (g)	N/A	2.5 E-02 (g)
	Lat			N/A	1.3 E-02 (g)
Liver/gall bladder/spleen	PA	451	1.35E+00	451	9.02E-02
	Lat			220	1.10E-01
Urinary bladder	PA	N/A	2.5 E-02 (g)	N/A	2.5 E-02 (g)
	Lat			N/A	1.3 E-02 (g)
Colon rectum	PA	N/A	2.5 E-02 (g)	N/A	2.5 E-02 (g)
	Lat			N/A	1.3 E-02 (g)
Testes	PA	N/A	5.0 E-03 (g)	N/A	5.0 E-03 (g)
	Lat			N/A	2.5 E-03 (g)
Lungs (male)	PA	419	1.26E+00	419	8.38E-02
	Lat			193	9.65E-02
Lungs (female)	PA	451	1.35E+00	451	9.02E-02
	Lat			220	1.10E-01
Thymus	PA	451	1.35E+00	451	9.02E-02
	Lat			220	1.10E-01
Esophagus	PA	451	1.35E+00	451	9.02E-02
	Lat			220	1.10E-01
Stomach	PA	451	1.35E+00	451	9.02E-02
	Lat			220	1.10E-01
Bone surfaces	PA	451	1.35E+00	451	9.02E-02
	Lat			220	1.10E-01
Remainder	PA	451	1.35E+00	451	9.02E-02
	Lat			220	1.10E-01
Breast	PA	49	1.47E-01	49	9.80E-03
	Lat			255	1.28E-01
Uterus (embryo)	PA	N/A	2.5 E-02 (g)	N/A	2.5 E-02 (g)
	Lat			N/A	1.3 E-02 (g)
Bone marrow (male)	PA	92	2.76E-01	92	1.84E-02
	Lat			37	1.85E-02
Bone marrow (female)	PA	86	2.58E-01	86	1.72E-02
	Lat			29	1.45E-02
Skin (e)	PA		4.05E+00		2.70E-01
	Lat				6.75E-01

practice was to use a 5" cone (Sante 1954, p. 207) for improved radiographic quality, thus limiting the beam diameter to 5" at the skin entrance point.

Examples of lumbar spine radiograph technique factors used at Oak Ridge National Laboratory are shown in Table 7-7; Tables 7-8 through 7-10 give values for organ dose calculations and examples of calculated doses based on the ORNL experience. Note that the image receptor size – i.e. the beam size at the film – implies a larger beam diameter than 5" at the skin entrance point and hence is claimant favorable. In the absence of actual site-specific data, the ORNL technique factors and the resultant doses derived from these can be used to provide claimant favorable dose estimates from lumbar spine radiography.

Table 6-5 (Continued). Organ doses for default entrance kerma values.

Organ	Chest view	Dose conversion factor (mGy per Gy air kerma) [a] HVL 2.5 mm Al collimated	Organ dose 1970-1985 (rem) [c,d] collimated	Dose conversion factor (mGy per Gy air kerma) HVL 4.0 mm Al [a] collimated	Organ dose post 1985 (rem) [c,d] collimated
Thyroid	PA	32	3.20E-3	78	3.90E-3
	Lat	115	2.88E-2	164	2.13E-2
Eye/brain	PA	32	3.20E-3	78	3.90E-3
	Lat	115	2.88E-2	164	2.13E-2
Ovaries	PA	1	1.00E-4	5.2	2.60E-4
	Lat	0. 6	1.50E-4	2.5	3.25E-4
Liver/gall bladder/spleen	PA	451	4.51E-2	674	3.37E-2
	Lat	220	5.50E-2	351	4.56E-2
Urinary bladder	PA	1	1.00E-4	5.2	2.60E-4
	Lat	0. 6	1.50E-4	2.5	3.25E-4
Colon/rectum	PA	1	1.00E-4	5.2	2.60E-4
	Lat	0. 6	1.50E-4	2.5	3.25E-4
Testes	PA	0.01	1.00E-6	0.01	5.00E-7
	Lat	0.1	2.50E-5	0.1	1.30E-5
Lungs	PA	451	4.51E-2	674	3.37E-2
	Lat	220	5.50E-2	351	4.56E-2
Thymus	PA	451	4.51E-2	674	3.37E-2
	Lat	220	5.50E-2	351	4.56E-2
Esophagus	PA	451	4.51E-2	674	3.37E-2
	Lat	220	5.50E-2	351	4.56E-2
Stomach	PA	451	4.51E-2	674	3.37E-2
	Lat	220	5.50E-2	351	4.56E-2
Bone surfaces	PA	451	4.51E-2	674	3.37E-2
	Lat	220	5.50E-2	351	4.56E-2
Remainder	PA	451	4.51E-2	674	3.37E-2
	Lat	220	5.50E-2	351	4.56E-2
Breast	PA	49	4.90E-3	116	5.80E-3
	Lat	255	6.38E-2	343	4.46E-2
Uterus (embryo)	PA	1.3	1.30E-4	5.2	2.60E-4
	Lat	0.6	1.50E-4	2.1	2.73E-4
Bone marrow	PA	92	9.20E-3	178	8.90E-3
	Lat	37	9.25E-3	76	9.88E-3
Skin (f)	PA		1.35E-1		7.00E-2
	Lat		3.38E-1		1.82E-1

a. Dose conversion Factors from Tables A.2 through A.8, ICRP Publication 34 (1982).
b. Image Receptor Size (cm) 10.2 x 12.7 or 12.7 x 25.4 for stereo films.
c. Source to Imaged-Distance 183 cm.
d. Image Receptor Size (cm) 35.6 x 43.2
e. Calculated using backscatter factor of 1.35 for HVL of 2.5 mm Al from NCRP Report No.102, Table B-3
f. Calculated using backscatter factor of 1.40 for HVL of 4.0 mm Al from NCRP Report No.102, Table B-3
g. Modified from Webster, if measurement data is available it should be used.
h. Dose Conversion Factor for AP c-spine, corrected for depth by 0.2.

7.0 FLUOROSCOPY

Fluoroscopy, not to be confused with photofluoroscopy previously discussed above in which a photograph is taken of an activated fluorescent screen, involves real time viewing of a fluorescent screen continuously activated by x-rays. Because of the time and limitations of fluoroscopy, this procedure was not generally amenable to mass examinations or to preemployment screening of workers, although it did find occasional application in the occupational setting for examination of the chest. The eminent American radiologist Leo Rigler devoted but a single paragraph, reproduced in its entirety below, under the heading “Chest Fluoroscopy” in his book *Outline of Roentgen Diagnosis*, which was a standard text published in1938 and has but a single paragraph on the topic:

Table 7-6. Use of photofluorography at DOE sites.

DOE site	Last documented use of PFG	Comments	Reference
Hanford	January 31, 1962[(a)]	-----	Rising, F. L. and J. K. Soldat, 1959, "Radiation Exposures During Diagnostic Radiographic Examinations at Kadlec Methodist Hospital," letter to Dr. W. D. Norwood, April 30, 1959
K-25	1956	-----	J. J. Cardarelli, "A Potential Consequence of Excluding Work-related X-Ray Exposures when Computing Cumulative Occupational Radiation Dose at a Uranium Enrichment Plant," Dissertation, Univ. Cincinnati, Cincinnati, Ohio, 2000.
LANL	1964	Pre-1964 medical records being reviewed	Shipman, T.L., "Annual Report of the Health Division" 1954, LA-1888, Los Alamos, New Mexico, January 1955.
ORNL	October, 1947	-----	ORNL, 2002, "ORNL Historical X-ray Practices and Protocols," no date
Portsmouth	October 1957	-----	Claimant's medical file
Rocky Flats	Potentially used from 1953 to 1968	-----	Memo: Excel file labeled "X-ray Machine Info from Rocky Flats, 2003" (printed from Rocky Flats medical records database)
Savannah River	Early 1967	-----	Cooley, R. C. Memorandum to E. C. Morris "Progress Report Calibration of Medical X-Ray Machine at the Savannah River Plant" dated November 4, 1966 (Revised November 10, 1966).
Fernald	-----	PFG Not used	Memo from FEMP to DOE dated May 7, 2000
INEEL	-----	PFG Not used	Based on review of records.
Iowa Ordnance Plant	-----	PFG not used	Based on review of records.
Mound	-----	PFG not used	Based on review of records.
NTS	-----	PFG not used	Based on review of records and discussions with Martha DeMarre at the NTS.
Paducah	-----	PFG not used	Interview with site personnel knowledgeable of the history of the medical x-ray program

a. The Hanford x-ray record form listed PFG until 1/31/1962, thus PFG may have been used until that date.

Table 7-7. Example of lumbar spine x-ray operating parameters, dates of use, and frequency of examinations (taken from ORNL ORAUT-TKBS-0012-3 Rev0, P 17).

Dates	X-ray equipment	Location	Techniques	X-ray conditions	People involved
April 6, 1950, to September 23, 1953	Picker 200-mA Control & Generator- Model R-2	ORNL	Lumbar spine series, 4 films: AP, AP spot, Lateral, and Lateral spot	AP & AP spot Filter=0.04 mm Al, 80 kVp, 40 mA, 4 sec @ 99 cm. distance, w/ 20-cm cone	Craft workers
				Lat & Lat spot Filter=0.04 mm Al, 86 kVp, 40 mA, 8 sec @ 99 cm distance, w/ 20-cm cone	

Table 7-8. Values used to calculate organ dose, AP and lateral lumbar spine.

Years included	Examination	Workers affected	ESE (rem)	HVL (mm Al)
1950-1953	LS AP[a]	Preplacement for craft workers	4.0E+00 [c]	2.0
1950-1953	LS Lat[b]	Preplacement for craft workers	1.0E+01	2.0

a. The ESE for the LS AP represents both the AP and spot AP exposures (i.e., 2 exposures). Values in Table 7-9 also indicate organ doses from both exposures.
b. The ESE for the LS Lat represents both the Lat and spot Lat exposures (i.e., 2 exposures). Values in Table 7-9 also indicate organ doses from both exposures.
c. This value rounded up to 4.0E+00 rem from 3.8 E+00 rem (2X1900) listed in Table VII Lincoln & Gupton (1958b).

Table 7-9. Example of average absorbed dose per unit entrance air kerma for AP and lateral lumbar spine X-ray views, organs DCFs, and beam quality,[a] April 6, 1950 to September 23, 1953.

Organ	View [b]	Source-image distance (cm)	Image receptor size (cm)	Dose conversion factor (mGy per Gy air kerma) for HVL = 2.0 mm Al
Thyroid	LS AP	99	35.6 × 43.2	0.2
	LS Lat.	99	35.6 × 43.2	0.01
Eye/Brain	LS AP	99	35.6 × 43.2	0.2
	LS Lat.	99	35.6 × 43.2	0.01
Ovaries	LS AP	99	35.6 × 43.2	N/A (d)
	LS Lat.	99	35.6 × 43.2	N/A (d)
Testes	LS AP	99	35.6 × 43.2	N/A (d)
	LS Lat.	99	35.6 × 43.2	N/A (d)
Lungs	LS AP	99	35.6 × 43.2	62
	LS Lat.	99	35.6 × 43.2	10
Breast	LS AP	99	35.6 × 43.2	18 (c)
	LS Lat.	99	35.6 × 43.2	9.5 (c)
Uterus (embryo)	LS AP	99	35.6 × 43.2	217
	LS Lat.	99	35.6 × 43.2	20
Bone marrow	LS AP	99	35.6 × 43.2	24
	LS Lat.	99	35.6 × 43.2	15
	LS Lat.	99	35.6 × 43.2	--
Skin (e)	LS AP	99	35.6 × 43.2	1.32 (e)
	LS Lat.	99	35.6 × 43.2	1.32 (e)

a. Dose conversion factors (DCFs) for an HVL of 2.0 mm Al are from Tables A.2 through A8 of ICRP 34 (1982), assuming good collimation of the beam, unless otherwise noted.
b. LS = lumbar spine.
c. Dose conversion factors for lumbar spine examination not given in ICRP 34. Values for the respective Upper G.I. exams (i.e., AP and Lat) were used instead.
d. Organ dose values for the testes and ovaries for lumbar spine for 1950 – 1953 reflect actual measurement reported in (Lincoln and Gupton 1958b).
e. Skin dose values include backscatter factors of 1.32 from Table B.8 of NCRP Report No.102 (1989).

> *"This is of value in determining the movements of the diaphragms, the position and motion of the mediastinum, the aeration of various parts of the lung, in detecting and localizing gross changes especially pleural encapsulation, abscess, extensive tuberculosis. It is of little value in the detection of early lung changes and in the diagnosis of early tuberculosis." (Rigler 1938)*

In his book *A Handbook of Roentgen Diagnosis—The Chest",* second edition published in 1954, Rigler had this to say (p. 18): "In consideration of the value of fluoroscopy it should be borne in mind that its usefulness is largely related to the grosser lesions of the thorax." (Rigler1954). Contemporary diagnostic radiology texts of the time are more or less consistent with the views succinctly expressed by Rigler [de Lorimer et al. (1953); Rabin (1968)]. One standard textbook of radiology of the time, widely used in medical schools, while noting that "Fluoroscopic methods of examination have a definite place in the x-ray analysis of chest conditions" qualified this statement by further noting that the value of chest fluorography was only in the detection of the character of movements and also cautioned "The substitution of fluoroscopy for radiographic methods is neither wise, safe, nor even defensible now that photofluorographic apparatus is available". (Hodges, Lampe, and Holt 1947).

Even so, although fluoroscopy was a little used and certainly not a standard routine preemployment or occupational diagnostic procedure for the chest, even in the early 1940's, there are indications that fluoroscopic examinations of the chest were conducted and required at least one site (Linde Ceramics) during the 1942-43 time frame, and it is possible that such examinations were also

Table 7-10. An example of organ dose estimates for ORNL AP and lateral lumbar spine radiographs to be used as IREP inputs.[a]

Organ	View	Organ dose (rem) 1950–1953
Thyroid	LS AP	8.00E-04 (b)
	LS Lat.	1.00E-04 (b)
Eye/brain	LS AP	8.00E-04 (b)
	LS Lat.	1.00E-04 (b)
Ovaries	LS AP	1.12E+00 (b) (d)
	LS Lat.	1.52E+00 (b) (d)
Liver/gall bladder/spleen	LS AP	2.48E-01 (b)
	LS Lat.	1.00E-01 (b)
Urinary bladder	LS AP	1.12E+00 (b) (d)
	LS Lat.	1.52E+00 (b) (d)
Colon/rectum	LS AP	1.12E+00 (b) (d)
	LS Lat.	1.52E+00 (b) (d)
Testes	LS AP	5.40E-02 (b) (d)
	LS Lat.	1.12E-01 (b) (d)
Lungs	LS AP	2.48E-01 (b)
	LS Lat.	1.00E-01 (b)
Thymus	LS AP	2.48E-01 (b)
	LS Lat.	1.00E-01 (b)
Esophagus	LS AP	2.48E-01 (b)
	LS Lat.	1.00E-01 (b)
Stomach	LS AP	2.48E-01 (b)
	LS Lat.	1.00E-01 (b)
Bone surfaces	LS AP	2.48E-01 (b)
	LS Lat.	1.00E-01 (b)
Remainder	LS AP	2.48E-01 (b)
	LS Lat.	1.00E-01 (b)
Breast	LS AP	7.20E-02 (b)
	LS Lat.	9.50E-02 (b)
Uterus (embryo)	LS AP	8.68E+00 (b)
	LS Lat.	2.00E-01 (b)
Bone marrow	LS AP	9.60E-02 (b)
	LS Lat.	1.50E-01 (b)
Skin (c)	LS AP	5.28E+00 (b)
	LS Lat.	1.32E+01 (b)

a. The exposures for various date ranges should be matched to the X-ray examinations listed in Table 7-7.
b. Value is doubled to account for two exposures.
c. Skin dose values include backscatter factors of 1.32 from Table B.8 of NCRP Report No.102 (1989).
d. Organ dose values for the testes and ovaries for lumbar spine for 1950 – 1953 reflect actual measurement reported in (Lincoln and Gupton 1958b).

conducted elsewhere. Typical fluoroscopes of the 1940's and 1950's operated at 100 kVp and 4 mA (Braestrup 1958; Files 1956; Sante 1954). As early as 1936, recommended added filtration was 1 mm Al (NBS Handbook HB20). Machine output was highly variable, producing an ESE rate to the patient ranging from about 2 R/min for a well operated 'modern' unit with appropriate filtration to several tens of R/min for older, poorly maintained units with short target to panel distances and also which may not have had adequate filtration. Typically, exposure rates at the panel (i.e. ESE) did not exceed 10 R/min. However, the total exposure to the patient was dependent not only on machine output but also on exposure time, which in turn was a function of the radiologist. Some radiologists

applied the x-rays in short bursts, others just “put their pedal to the metal” and basically kept their foot on the switch throughout the entire procedure. Inadequate dark adaptation by the radiologist would result in higher exposures largely as a result of longer exposure times. For this reason, many machines were equipped with timers to restrict exposure, normally to 25 R at the panel, for any given examination. For most examinations, total exposure times probably were less than a minute—perhaps 15-30 seconds, although exposures of a minute or more were not uncommon with some radiologists.

A claimant favorable estimate of dose can be made by assuming an exposure time of two minutes (high) and an ESE rate of 20 R/min. The assumed ESE rate is also high and presumes no image amplification and a short target to skin distance (TSD). The result is a highly claimant favorable ESE of 40 R, which is probably high by at least a factor of two, and at the upper end of the range of exposures encountered in chest fluoroscopy. However, in the absence of additional research or other data to the contrary, an ESE of 40 R should be taken as the likely claimant favorable exposure.

As a practical matter, all fluoroscopic beams were equipped with diaphragms and hence collimated; cross-section was usually rectangular. However, for claimant favorability, maximum beam size without diaphragms can be estimated by geometry. Assuming the aperture and distance from the focal spot (target) to the aperture are equal, the beam diameter would be equal to the TSD. Assuming a large TSD (50 cm) to maximize the beam size, the beam diameter in this case would be 50 cm or about 20 inches, which would be about the upper limit on beam size.

Note that ICRP Publication 34 is relatively recent (1982) and calls for an air kerma rate at the patient of 50 mGy/min (about 5 R/min) which is about double the standard or rule of thumb used back in the 1950’s. However, if the ratio of skin dose from fluoroscopy to skin dose from radiography given in ICRP 34 holds for earlier years, then the ESE of 40 R given above is certainly claimant favorable and perhaps at the upper end (or even somewhat beyond) of what is realistic.

8.0 RECONSTRUCTION OF ORGAN DOSE FROM RADIOGRAPHY EQUIPMENT USING MINIMAL COLLIMATION

Prior to about 1970, x-ray measurement data, techniques, or beam port information may not be available to estimate the collimation of the x-ray beam. Several papers in the literature have considered the effects of cone size and centering on organ doses, and concluded that filtration, kVp, and the smallest possible cone size were most important to reduce these doses. Due to the reported variation in the literature and measurement data on the effects of collimation, it is claimant favorable to assume minimal or no additional external collimation was used when measurement data, technique, or other information to describe the collimation are not available for x-ray procedures performed prior to 1970.

Without collimation, organs normally outside of the primary beam, are exposed to the primary beam. This necessitates the use of dose conversion factors from ICRP 34 (ICRP1982) other than those for a PA or lateral (lat) chest x-ray, since ICRP 34 (1982) dose conversion factors are based on properly collimated beams. For minimally collimated beams used prior to 1970, the substitute dose conversion factors in Table 9-11 were used.

9.0 UNCERTAINTY ANALYSIS FOR DIAGNOSTIC MEDICAL X-RAY DOSES

Error (deviation from the correct, true, or conventionally accepted value of a quantity) and uncertainty (defined in terms of the potential range of a stated, measured, assumed, or otherwise determined

Table 9-11. Substitute dose conversion factors. (For some x-ray exams performed prior to 1970).

Organ of interest	Substitute view and organ for which dose conversion to use for minimally collimated beams
Thyroid	AP Cervical spine corrected for depth by a factor of 0.2 (NCRP 102, Table B-8, P. 103) Lat Cervical spine
Eye/brain	PA and lat Skull, or PA chest, whichever is larger.
Ovaries and analogues, testes, and uterus	PA and lat Abdomen

value of a quantity) provide an indication of the confidence or validity of the dose estimates. Error implies knowledge of what the correct or actual value is, which is, of course, not known. Therefore, the more appropriate factor is uncertainty, which is expressed in terms of a confidence level, which in turn is expressed as a percent. Thus, the 99% confidence level indicates that the correct or true value, although not actually known, has a 99% probability of falling within the range cited. The statement of confidence level typically includes all potential sources of error, both random and systematic; the precision or reproducibility of the measurement; and accuracy, or how close the measurement or estimate of dose comes to the actual or correct value.

In theory, a large number of factors can introduce uncertainties or affect the x-ray machine output intensity and dose to the worker. However in practice only five factors can be reasonably considered to have a meaningful or significant impact on dose uncertainty. These are:

1. Measurement error
2. Variation in applied kilovoltage (kVp)
3. Variation in beam current (mA)
4. Variation in exposure time (mAs)
5. Distance from the worker to the source of the X-rays (SSD)

The influence of such other factors as use of screens, grids, reciprocity failure, film speed, and development, while potentially variable, do not affect the beam output intensity per se except indirectly insofar as these may determine the exposure settings (i.e. kVp, mA, and time) used.

Medical x-ray doses, when measured, were largely derived from actual measurement of x-ray machine output with R-meters or similar ionization chamber devices suitably designed for measurement of photons in the medical x-ray energy range. If properly calibrated and used, R-meters and similar instruments typically and historically have had an uncertainty of $\pm$ 2% for photon energies below 400 keV (Kathren and Larson, 1969). Although more recent versions of these instruments might provide a somewhat smaller uncertainty, perhaps on the order of $\pm$ 1% (NBS, 1985; 1988), for conservatism, the uncertainty range of $\pm$ 2% should be applied to measurements of x-ray intensity.

Theoretically, for a given set of machine settings and parameters, x-ray output should be constant and unvarying. However, this is not true in practice. Although output is essentially constant unless focal spot loading occurs, as might be the case when the power rating of the machine is exceeded, it is unlikely that power ratings were ever exceeded because such an event would be difficult to achieve in practice and could result in damage to the x-ray tube. However, even with the use of constant voltage transformers to control line voltages, slight variations might occur in line voltage input or other internal voltages, which in turn could alter the kVp of the output beam. In general, for a given kVp setting, variation in kVp falls within $\pm$ 5% of the machine setting (Seibert et al., 1991). Since as noted above, beam intensity is approximately proportional to the 1.7 power of the applied kilovoltage; this translates to an uncertainty of approximately $\pm$ 8.6% with respect to output beam intensity in the 80 to 100 kVp range used for diagnostic chest radiographs. For conservatism, this is rounded up to $\pm$ 9%.

Similarly, slight variations in tube current are normal; as a tube ages, or heats up from use, current can change and typically will drop. With all other factors constant, beam intensity will be reduced in direct proportion to the change in tube current. Typically, the reduction in beam output from current variation is not more than a few percent under normal operating conditions; large decreases are readily detectable and manifest themselves as underexposed radiographs and result in maintenance on the machine to restore the output or, as a temporary measure, an increase in the current or kVp to provide the necessary intensity for proper radiography. For a given kVp setting, the output of the beam is a function of the tube current, which in turn is measured by a milliammeter, which measures average tube current. The measurement is subject to uncertainties; there might be minor changes in output as the tube heats from normal use. These variations are typically small, and the estimated uncertainty in beam intensity or output attributable to current variation is $\pm$ 5%.

Another parameter that has potential to affect the dose from a diagnostic radiograph, perhaps significantly, is the time of exposure. The potential importance of this parameter is underscored by noting that virtually all medical diagnostic medical x-ray units used in the DOE complex were of the full wave rectified type. A full-wave rectified machine produces 120 pulses of x-rays per second. Thus, in a typical radiographic exposure time of 1/20 of a second, only six pulses would result. A small error in the timer that resulted in a change of only ± 1 pulse would correspondingly affect the output by ± 17%; for an exposure time of 1/30 of a second, the change in output corresponding to a deviation of + 1 pulse is ± 25%. Early mechanical timers were notoriously inaccurate; accuracy improved significantly with the introduction of electronic timers. Measurements of reproducibility made in the late 1980s and beyond by the State of Washington for the machines at Hanford suggest that the timers, and indeed the entire x-ray output, were fairly constant. However, for conservatism, the assumed uncertainty in beam output attributable to timers has been taken to be ± 25%.

The final factor likely to affect worker dose relates to distance from the source of the X-rays, which is an important determinant of the entrance skin exposure (ESE) from which organ doses are calculationally derived. For a given individual, the SSD will be determined largely by the body thickness of the worker and the accuracy of the positioning. For a typical worker, the estimated variation in SSD is no more than a few centimeters, with an upper limit of perhaps 7.5 cm. Using inverse square, this indicates an uncertainty of ± 10% from this source.

There are two approaches to determine the combined uncertainty from the five potential sources of dose uncertainty listed above. The first, and most conservative in that it gives the greatest range, would be to assume that the uncertainties are additive, which would give an uncertainty range of 2 + 9 +5 + 25 + 10 = ± 51%. However, a more reasonable approach would be to assume that the uncertainties are in fact random, and to compute the statistical root mean square (RMS) value. The RMS value is simply the square root of the sum of the squares, and computes as ± 28.9%. Rounding this up to $\pm$ 30% would seem to provide an adequate and suitably conservative indication of uncertainty. Thus, for an individual ESE or derived organ dose, an uncertainty of ±30% at one sigma can be assumed; for further conservatism it might be appropriate to assume that errors are all positive, and only + 30% should be used.

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APPENDIX A
ORGAN DOSES FROM PELVIS AP X-RAYS IN THE 1940S

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APPENDIX A
ORGAN DOSES FROM PELVIS AP X-RAYS IN THE 1940S

During the early years of atomic weapons work, the Manhattan Engineering District (MED) and the Atomic Energy Commission (AEC) sometimes required that pelvis x-rays be taken of personnel who worked with materials containing fluorine, to detect bone changes due to fluorosis (Van Horn 1943; Osinski 1947; Key et al 1977, p. 321).

This Appendix provides estimates of organ doses for use in dose reconstruction from AP pelvis radiography developed with the aid of dose conversion factors (DCF) in ICRP Publication 34 (ICRP 34 1982). To account for the possibility that x-ray practices in the 1940s may not have been as effective in minimizing doses as those on which ICRP 34 (1982) is based, the beam is assumed to have been less well collimated and possibly displaced from the location assumed in ICRP 34 (1982). Scattered radiation is considered in estimating doses to portions of the body outside the beam.

Dose reconstructors are cautioned to verify that the assumptions in this Appendix are applicable before using the doses estimated here. If conditions are known to have been different from those assumed here, then doses based on the actual conditions should be calculated. The methodology of this section may be used as a guideline for the calculation.

A1.0 DATA

Table A-1 displays data for AP pelvis x-ray exams reported by Lincoln and Gupton (1958). The letters B, G, and F in the Table refer to x-ray practices at medical facilities in and near Oak Ridge National Laboratory. The reported doses at these facilities were based in part on measurements made using Landsverk L-82 thimble ion chambers inserted into cavities in a tissue-equivalent phantom. Data for the cases (facilities) denoted by numbers are based on literature reports cited by Lincoln and Gupton dated 1955 to 1957.

Table A-1. Pelvis AP x-ray doses reported by Lincoln and Gupton.

Data reported by Lincoln and Gupton[a]								
Case[b]	Year of report	Cone diameter (cm)	Filter (mm Al)	kVp	mAs	Dose (mrad)		
						Skin	Testes	Ovaries
B	1957	16	None	54	250	4700	160	660
G	1957	None	None	54	300	4000	450	560
F	1957	20	1.0	80	160	2400	640	650
1	1955	— [c]	— [c]	65	100	4700	1100	210
3	1957	— [c]	— [c]	66	100	500	550	200
4	1956	— [c]	— [c]	— [c]	— [c]	— [c]	279	690
5	1955	— [c]	— [c]	— [c]	— [c]	— [c]	1080	400
6	1957	Spec.	3.0	75	80	480	20	80

a. Data from Lincoln and Gupton 1958.
b. Letters refer to medical facilities in or near Oak Ridge National Laboratory. Numbers refer to literature references in Lincoln and Gupton 1958 from which the listed values were taken.
c. No data or not applicable.

A2.0 DOSE CALCULATION

A2.1 ICRP PUBLICATION 34 (1982) METHODOLOGY

The methodology of ICRP Publication 34 (1982) is used to estimate many of the organ doses. This is judged preferable even for determination of gonadal doses (for which Table A-1 provides values

measured on a phantom) because the methodology is based on elaborate Monte Carlo calculations for detailed anthropomorphic models that appear to be more representative of the human body than the phantom used by Lincoln and Gupton (1958). In ICRP 34 (1982) methodology, organ dose (OD) is obtained as the product of entrance kerma (EK) and a dose conversion factor (DCF):

$$OD = EK * DCF \quad \text{(A-1)}$$

Entrance kerma is defined in ICRP 34 (1982) as "air kerma in air without backscatter." The DCF values depend on the x-ray projection, the organ, and the quality [expressed as the half-value layer (HVL)] of the x-ray beam.

A2.2 DETERMINATION OF ENTRANCE KERMA

Lincoln and Gupton provided entrance skin dose (ESD) in units of mrad based on measurement from a tissue equivalent phantom. Since the measurement was on a phantom, backscatter was included. Therefore, to obtain entrance kerma (EK), the measured dose should be corrected for backscatter, which can be done by dividing by the appropriate backscatter factor obtained from NCRP Report 102 (1989).

A2.3 SELECTION OF ESD AND HVL FOR ORGAN DOSE DETERMINATION

To avoid underestimating doses, and based on direction from NIOSH (Taulbee 2004 a, b), 2400 mrad was used from the Oak Ridge facility, case F for calculating organ doses and 4700 mrad from case B for skin dose. These cases correspond to the highest organ and skin dose values and are used, on this basis, for organ and skin dose determination. To identify the most claimant favorable case, Table A-1 provides data for cases from Lincoln and Gupton as shown above. Case 6 was added to show the reduction in dose that would occur by increasing the filtration and kV and reducing the mAs. As stated above Case F corresponds to the highest organ doses. For Case F, the ESD is 2400 mrad, and its calculated HVL is 1.5 mm Al assuming 0.5 mm Al inherent filtration. To allow for variability of x-ray technical factors, an upward adjustment of this HVL to 2 mm Al as recommended by NIOSH [direction from NIOSH in Davidson email on June 9, 2004 (Davidson 2004)] was made when determining organ doses. The entrance kerma (EK) corresponding to this value was calculated by

$$EK\ (Gy)(air) = 10^{-5} f * ESD / BF$$

$$EK\ (Gy)(air) = 10^{-5}\ 0.93 * 2400/1.32 = 0.0169$$

where ESD is the entrance skin dose in mrad = 2,400 per Lincoln and Gupton (1958)
BF is the backscatter factor per Table B.8 of NCRP Report No. 102 (NCRP 1989) = 1.32;
f is the ratio of energy deposition in air and soft tissue for a given exposure = 0.93, and
10^{-5} is a constant to convert from mrad to Gy.

The above is applicable only for internal organ dose determination. For skin dose, to ensure claimant favorability the maximum value reported by Lincoln and Gupton (1958; see Table A-1) of 4700 mrad was used (Davidson 2004).

A2.4 DOSE CONVERSION FACTORS

A2.4.1 For ICRP 34 (1982) Beam

The DCFs in ICRP 34 (1982) are based on a reference adult patient defined in Kereiakes and Rosenstein (1980), Table 94 and Figures 2 and 3. For a pelvis AP x-ray, the DCF values in ICRP 34 (1982) are based on the assumptions that the image receptor is 102 cm from the x-ray source, that the beam is collimated to an image receptor size of 43.2 cm x 35.6 cm (where 35.6 cm represents the dimension parallel to the height of the patient), and that the field center of the beam is 80 cm below the top of the head of the reference patient (see Table 95 of Kereiakes and Rosenstein 1980). Dose conversion factors from a pelvis AP x-ray for organs treated in ICRP 34 (1982) are shown in Table A-3.

The ICRP 34 (1982) beam would impact some organs of interest that are not explicitly addressed in ICRP 34 (1982). These additional organs were identified by overlaying a transparency with an outline of the beam cross-section on anatomy drawings to which the beam outline had been scaled. Each of the additional organs is in the abdominal region. Based on the guidance on organ analogues in Table 3-2 of the main text, each is assigned the ICRP 34 (1982) factor for dose to the ovaries for a pelvis AP x-ray. Table A-4 lists the organs and the assigned DCFs.

A2.4.2 For Modified Beam

To account for the possibility that x-ray practice in the 1940s may not have been in conformance with the assumptions on which ICRP 34 (1982) is based, and thus ensure claimant favorability, a modified beam was postulated. The modified beam assumed minimal collimation (Taulbee 2004b) and thus was larger in area than the ICRP 34 (1982) beam and had a circular rather than a rectangular cross-section. Further, the beam was assumed to be possibly displaced vertically by positioning errors and was characterized by the following assumptions:

- Circular cross-section;
- Beam area at the film equal to twice the film area. (See above)

Additional organs impacted by the enlarged beam were identified by overlaying a transparency with an outline of the beam cross-section on anatomical drawings to which the beam outline had been scaled. To avoid underestimating the impact on organs near the exit plane of the beam, the beam outline represented the size of the beam at the image receptor. The center of the modified beam was postulated to be displaced by ± 3 cm vertically from the location assumed in ICRP 34 (1982) — upward for identifying additional organs above the ICRP 34 (1982) location and downward for identifying organs below the location.

Beam patient geometry assumptions used for analysis are specified in Table A-2. Figure A-1 shows the ICRP 34 (1982) beam and the modified beam superimposed on an anatomical representation of the body.

Table A-2. Beam/patient geometry parameters assumptions.

Parameter	Value	Basis
Distance, beam focus to image receptor	102 cm	ICRP 34 (1982)
Body thickness	23 cm	Assumed average worker pelvic thickness
Gap between patient and film	5 cm	Kereiakes and Rosenstein (1980), p. 189

From the above, the following parameters were calculated:

Parameter	Value	Basis
Distance, beam focus to mid-point of body	85.5 cm	= 102 – 5 – 11.5
Distance, beam focus to entrance surface of body	74 cm	= 102 – 5 – 23

Any beam dimension (e.g., radius) in a plane parallel to the image receptor can be obtained by multiplying the value of that dimension in the image receptor plane by a reduction factor. The value of the reduction factor is the distance from the beam focus to the plane of interest divided by the distance from the beam focus to the image receptor: Reduction factors for selected planes are as follows:

Parameter	Value	Basis
Reduction factor for plane through mid-point of body	0.838	= 85.5/102
Reduction factor for plane at entrance surface of body	0.725	= 74/102

Figure A-1 shows the ICRP 34 (1982) beam and modified beam superimposed on an anatomical representation of the body.

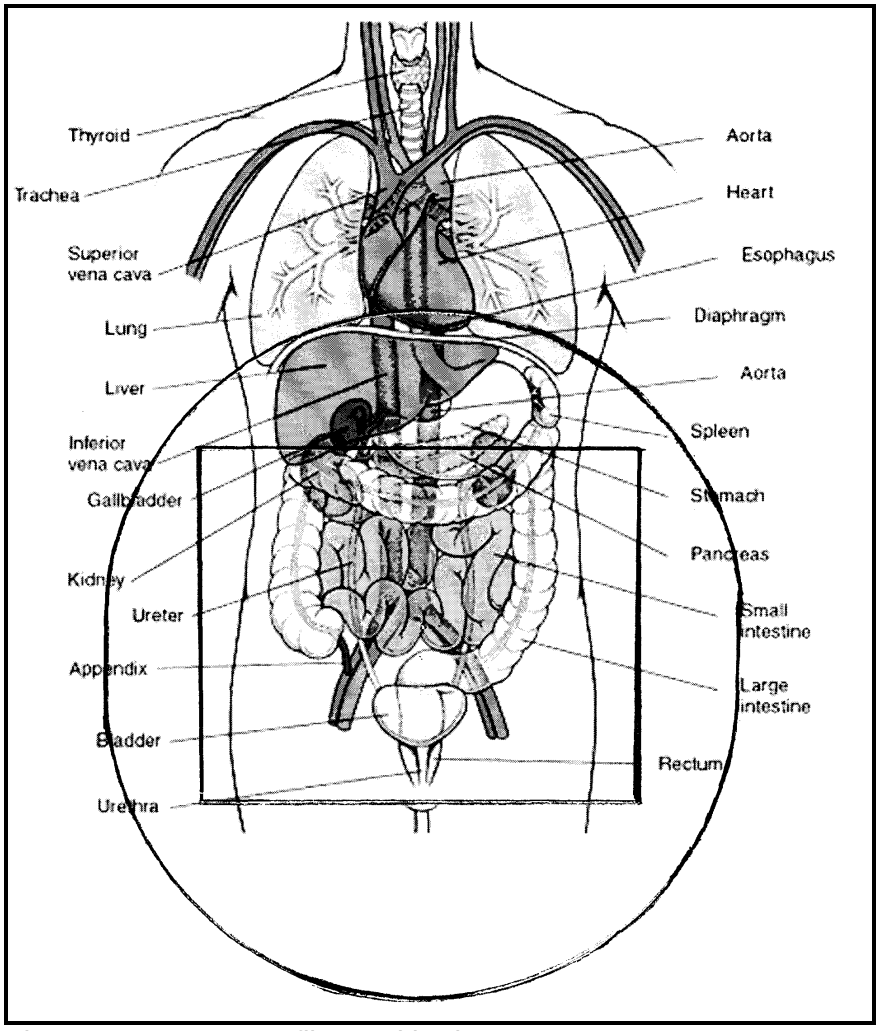

Figure A-1. Beam profiles and body anatomy.

The rectangle in Figure A-1 represents the area of the ICRP 34 rectangular collimated beam. The elongated circle represents the area of the minimally collimated modified beam. The modified beam

is circular in cross-section with the elongation from an assumed ± 3 cm vertical displacement or variation of the beam center with respect to anatomical location (see Section A.2.4.2). The beam sizes are those at the image receptor surface.

A2.4.2.1 Organs Above the ICRP 34 Field Center

Table A-5 lists additional organs above the ICRP 34 (1982) field center that are brought into the beam by its assumed enlargement and displacement. The table also indicates the percentage of the volume of each organ that was estimated to be inside the boundaries of the modified beam.

For a case in which all of an organ is in the modified beam, the DCF is obtained from an ICRP 34 (1982) case in which the organ is fully in the beam, if such a case is available. For a case in which a substantial part of the organ is outside the beam, a reduced DCF is assigned. This reflects the lower deposition of energy in the organ and the fact the DCF in ICRP 34 (1982) was calculated by dividing the energy deposited in the organ by the total organ mass, thus if less of the organ is in the beam, less energy is deposited and the DCF is lower. (Kereiakes and Rosenstein 1980, p. 160, Taulbee 2004).

Table A-6 displays DCFs assigned to the additional organs listed in Table A-5 and also to several other organs. The DCFs were estimated as follows:

- Lungs. The overlay of the beam profile on an anatomical drawing indicated that approximately 10% of the lung volume is in the beam. Therefore, direct interaction with the primary beam was estimated to cause 10% of the energy deposition that occurs when the lungs are fully in a beam. An additional 10% energy deposition was estimated to be produced by scattering of photons to parts of the lung outside the primary beam. This estimate is based on the finding that scattered radiation produces a dose to the testes equal to 10% of the central beam dose when the testes are just outside a beam (Kereiakes and Rosenstein 1980, p. 205). Therefore, it is assumed that the lung DCF for a pelvis AP x-ray is 20% of the lung DCF for a chest AP x-ray (i.e., 20% of 381 mGy/Gy for an HVL of 2.0 mm Al per Table A5 of ICRP 34 (1982) where the male DCF rather than the lower female DCF is selected).

- Esophagus. The overlay of the beam profile on an anatomical drawing indicated that approximately 50% of the esophagus volume is exposed to the beam. Based on a 10% contribution from scattering, it is assumed that the esophagus DCF for a pelvis AP x-ray is 60% of the ovaries DCF (i.e., 60% of 174 mGy/Gy).

- Bone Surfaces. Based on the discussion in Section 3.1 of the main text, the bone surfaces DCF for a pelvis AP x-ray is taken as equal to the lung DCF for a chest AP x-ray as determined above (i.e., 20% of 381 mGy/Gy).

- Other Organs Identified in Table A-5. The other organs identified in Table A-5 were judged to be fully or nearly fully in the modified beam. They were assigned a pelvis AP x-ray DCF equal to the ICRP 34 (1982) ovaries DCF.

- Remainder Organs. Various listings of "remainder organs" are available. Most of the organs in a typical list (Eckerman and Ryman 1993, footnote 2 to Table II.1 on p. 7) would be wholly inside the modified beam. Therefore, the pelvis AP x-ray DCF for remainder organs is taken as equal to the ICRP 34 (1982) ovaries DCF.

- Breasts. The percentage of the breast volume in the primary beam is assumed to be the same as in the case of the lungs (10%) and the scattering effects are assumed to be the same as for the lungs. Therefore, it is assumed that the female breast DCF for a pelvis AP x-ray is 20% of the female breast DCF for a chest AP x-ray [i.e., 20% of 744 mGy/Gy for an HVL of 2.0 mm Al per Table A6 of ICRP 34 (1982)]. The same DCF is adopted for a male breast, which is claimant favorable.

A2.4.2.2 Organs Below the ICRP 34 (1982) Field Center

The only additionally impacted organs identified below the ICRP Publication 34 (1982) field center were the male testes. The distance between the testes center and the edge of the modified beam at the entrance surface was calculated. The testes center was found to be well within the beam (see Table A-7). Table 115 on p. 205 of Kereiakes and Rosenstein (1980) indicates that the testes DCF at the location found is nearly the same as the DCF of 810 mrad (tissue)/R (i.e., 933 mGy/Gy) that occurs when a 2 mm Al HVL beam is centered on the testes. Therefore, for claimant favorability 933 mGy/Gy is taken as the DCF for the testes.

A2.4.2.3 Active Bone Marrow

A larger beam would produce a larger dose to the active bone marrow. This was accounted for by using data in Table 116 (Active Bone Marrow Dose as a Function of Field Size) on p. 206 of Kereiakes and Rosenstein (1980). The ICRP 34 (1982) active bone marrow DCF for a pelvis AP x-ray was multiplied by 1.44 based on the upper limit of the correction factor 1.39 ± 0.05 given in Table 116 for a 14"x17" abdominal AP x-ray and a field area size ratio of 2.0. This yielded a DCF for active bone marrow of 33.1 mGy/Gy.

A2.5 DOSES

A2.5.1 Organs Other than Skin in the Beam

Except for skin, doses for organs wholly or partially in the beam were calculated using Equation A-1. For example, for lung dose the calculation was as follows:

Lung Dose = [0.0169 Gy(air)] [(0.20) (381 mGy(tissue)/Gy(air))]
[0.1 rad(tissue)/mGy(tissue)] [1 rem/rad(tissue)] = 0.129 rem

A2.5.2 Skin in the Beam

Entrance Dose
As stated earlier, skin dose is taken as 4700 mrad (tissue) or 4.70 rem. This dose would affect all skin surfaces in the beam on the entrance side of the body (see Figure A-1). To allow for anatomical variability and variation in the positioning of the patient, this dose is also assumed to apply to the skin of the front of the thighs and to all of the skin of the hands, forearms, and elbows.

Exit Dose
Skin dose in the beam on the exit side of the body was obtained by dividing the entrance dose by an absorption factor that accounts for attenuation in the body. Absorption factors are provided in Table B.7 of NCRP Report No. 102 (NCRP 1989). For the skin of the lower back and buttocks, an absorption factor of 26.6 was obtained by decreasing by 10% (0.9*29.5 = 26.6) the value tabulated for an HVL of 2.0 mm Al and a body thickness of 20 cm. The 10% decrease allows for differences between the tabulated values and actual values as specified in the footnote to Table B.7 (NCRP 102

1989). A body thickness of 20 cm was chosen to allow for a person whose body is thinner than that of the average worker (22-24 cm per Section 2.3 of the main text). This yielded an exit skin dose of

4.70 rem/26.6 = 0.177 rem

For the back of the thighs, an absorption factor of 5.39 was obtained by decreasing by 10% (0.9*5.99 = 5.39) the value in Table B.7 (NCRP 1989) for an HVL of 2.0 mm Al and a body thickness of 10 cm. This yielded an exit skin dose of

4.70 rem/5.39 = 0.872 rem

A2.5.3 Skin Outside but Near the Primary Beam

Entrance and exit doses to portions of the skin outside but near the beam are assumed to be 10% of the doses in the neighboring region inside the beam. This is based on the finding that the dose to the testes is 10% of the central beam dose when the testes are just outside the beam. Regions "outside but near" the beam are considered to be the following:

- Upper torso, from the beam edge (Figure A-1) to just below the neck;
- Knees;
- The upper arms, scattered dose (10%)

A2.5.4 Organs Outside but Near the Beam

The dose to an organ wholly outside but near the beam is taken as 10% of the dose to organs in the neighboring region inside the beam. The thymus falls in this category, so the dose to the thymus is taken as 10% of the dose to the ovaries.

A2.5.5 Body Parts Well Outside the Beam

Doses from scattering to skin and organs in a portion of the body well outside the beam (i.e., beyond the "outside but near" region) were estimated using the following parameters and assumptions:

- Entrance skin dose of 4.70 rem (choosing this rather than the alternative ESD of 2.40 rem is claimant favorable).

- Average depth dose value of 18.4% [based on Table B.8 of NCRP 102 (NCRP 1989), 2 mm Al HVL, 35 cm x 35 cm field size, a 10 cm depth (representing the midpoint of a 20 cm thick trunk), and multiplication by a factor 1.1 to allow for the 10% uncertainty of the tabulated values].

- 0.0005 ratio of scattered to incident exposure (based on exposure at 1 m due to 90 degree scattering of 70 kVp radiation per Table B-2 of NCRP Report No.49 1976).

- Scaling of scattered radiation with distance as $1/r^2$, where r represents the distance from the centerline of the modified beam to the closest part of the "well outside" body portion closest to the beam. The distance is based on the reference adult patient defined in Kereiakes and Rosenstein (1980) (Table 94 and Figures 2 and 3).

The base of the neck was determined to be 0.56 m from the center of the upward-displaced modified beam so the scatter dose for the neck and above was calculated as follows:

Scatter Dose (to the neck) = (4.70 rem) (0.184) (0.0005) (1 m/0.56 m)^2 = 1.38E-3 rem

Similarly, dose from scattered radiation to the knees was calculated by

Scatter Dose (to region below the knees)= (4.70 rem) (0.184) (0.0005) (1 m/0.48 m)^2 = 1.88E-3 rem

The lower edges of the knees were estimated to be 0.48 m from the center of the downward-displaced modified beam. This yielded a scattered radiation dose of 1.88E-3 rem below the lower edges of the knees. These two doses are assumed to apply to the entrance and exit surfaces of the skin and to internal organs in the respective regions. For example, the doses to the thyroid, eyes and brain are taken as 1.38E-3 rem.

A2.5.6 Organ Dose Tables

Resulting doses and their bases and uncertainties are provided in Tables A-2 through A-7 and summarized in Table A-8.

Table A-3. DCFs for a pelvic AP x-ray (HVL 2.0 mm Al) for organs listed in ICRP 34 (1982).

ICRP 34 table no.	Organ	Dose conversion factor (mGy/Gy)
A2	Thyroid	<0.01
A3	Ovaries	174
A4	Testes	69
A5	Lungs	1.0
A6	Female breast	— [a b]
A7	Uterus (embryo)	244
A8	Active bone marrow	33.1 [c]

a. Not computed in ICRP 34 (1982).
b. Used 20% of the 744 mGy/Gy DCF for AP chest with 2.0 mm Al HVL to determine dose in Table A-6.
c. ICRP 34 (1982) DCF was multiplied by 1.44 the upper limit of the correction factor 1.39 ± 0.05 from Table 116, p. 205 (Kereiakes and Rosenstein). 23* 1.44=33.1

Table A-4. DCFs for pelvic AP x-ray (HVL 2.0 mm Al) for analogue organs not listed in ICRP 34 (1982).

Organ	Assigned DCF [a] (mGy/Gy)
Bladder	174
Colon	174
Rectum	174
Urinary system (except kidneys)	174

a. Taken as equal to value for ovaries in Table A-3.

Table A-5. Impact of modified beam on organs outside ICRP 34 beam.

Organ	Estimated % of organ volume in modified beam[a]	Scattered dose (%) [b]
Adrenal gland	100	—[c]
Female Breast	10	10
Esophagus	50	10
Gall bladder	100	—[c]
Kidney	100	—[c]
Liver	100	—[c]
Lungs	10	10
Pancreas	100	—[c]
Spleen	100	—[c]
Stomach	100	—[c]

a. The field center of the modified beam was assumed to be located 3 cm above the field center of the ICRP 34 beam. The beam size was assumed to be that at the image receptor. The percentage was estimated as 100% if all or most of the organ was in the modified beam.
b. Dose contribution due to parts of the organ outside the beam due to scattered radiation; expressed as a percent of the dose that the organ would receive if it were fully in the beam.
c. Not applicable.

Table A-6. Assigned DCFs for organs above field center of ICRP 34 beam.

Organ	Reference dose factor (mGy/Gy)	Assigned dose conversion factor[a] (mGy/Gy)
Adrenal gland	174	1.74E+02
Bone surfaces	—	7.62E+01
Breast	744	1.49E+02
Esophagus	174	1.04E+02
Gall bladder	174	1.74E+02
Kidney	174	1.74E+02
Liver	174	1.74E+02
Lungs	381	7.62E+01
Pancreas	174	1.74E+02
Remainder	174	1.74E+02
Spleen	174	1.74E+02
Stomach	174	1.74E+02

a. Determined per Section A2.4.2.1 of the text.

Table A-7. Parameters related to dose to testes.

Location	Distance from phantom vertex (cm)[a]	Basis
Testes center	96.3	Kereiakes and Rosenstein (1980), p. 187
Rectangular ICRP 34 beam		
Center	80.0	Kereiakes and Rosenstein (1980), p. 188
Distance from center to lower edge, at image receptor	17.8	= 35.6/2, where 35.6 cm is height of beam
Distance from center to lower edge, at entrance surface	12.9	= 0.725 x 17.8, where 0.725 is the geometric reduction factor (from Table A-1)
Lower edge, at entrance surface	92.9	= 80.0 + 12.9
Location of lower edge at entrance surface relative to testes center [b]	3.4	= 96.3 – 92.9
Circular modified beam		
Center	83.0	Assumption
Circle radius at image receptor	31.3	$\sqrt{\frac{2x43.2x35.6}{\pi}}$ =, per criterion that area of circle is twice area of ICRP 34 beam
Circle radius at entrance surface	22.6	0.725 x 31.3, where 0.725 is the geometric reduction factor (from Table A-1)
Lower edge, at entrance surface	105.6	= 83.0 + 22.6
Location of lower edge at entrance surface relative to testes center [b]	-9.3	= 96.3 – 105.6

a. The vertex is assumed to be on the top of the phantom, on the entrance surface, centered [see Kereiakes and Rosenstein (1980), Figure 3].

b. A positive value means the lower edge of the beam is above the testes center; a negative value means the lower edge of the beam is below the testes center.

Table A-8. Organ doses from a pelvis AP x-ray.

Organ or region	Basis	Dose (rem)
Active bone marrow	A2.4.2.3, A2.5.1	5.59E-02
Adrenal gland	Table A-6, A2.5.1	2.94E-01
Bladder	Table A-4, A2.5.1	2.94E-01
Bone surfaces	Table A-6, A2.5.1	1.29E-01
Brain	A.2.5.5	1.38E-03
Breast	Table A-6, A2.5.1	2.50E-01
Colon	Table A-4, A2.5.1	2.94E-01
Esophagus	Table A-6, A2.5.1	1.78E-01
Eye	A.2.5.5	1.38E-03
Gall bladder	Table A-6, A2.5.1	2.94E-01
Kidney	Table A-6, A2.5.1	2.94E-01
Legs below knees and feet	A2.5.5	1.88E-03
Liver	Table A-6, A2.5.1	2.94E-01
Lungs	Table A-6, A2.5.1	1.29E-01
Neck and above	A.2.5.5	1.38E-03
Ovaries	Table A-3, A2.5.1	2.94E-01
Pancreas	Table A-6, A2.5.1	2.94E-01
Rectum	Table A-4, A2.5.1	2.94E-01
Remainder organs	Table A-6, A2.5.1	2.94E-01
Skin on entrance side of body:		
Front of body in beam (Fig. A-1)	A.2.5.2	4.70E+00
Front of thighs	A.2.5.2	4.70E+00
Front of torso from just above beam (Fig. A-1) to just below neck	A.2.5.3	4.70E-01
Front of knees	A.2.5.3	4.70E-01
Skin on exit side of body:		
Back of body in beam (Fig. A-1) except thighs	A.2.5.2	1.77E-01
Back of torso from just above beam (Fig. A-1) to just below neck	A.2.5.3	1.77E-02
Back of thighs	A2.5.2	8.72E-01
Back of knees	A.2.5.3	8.72E-02
Skin on all parts to the following:		
Hands, forearms, and elbows	A.2.5.2	4.70E+00
Upper arms	A.2.5.3	4.70E-01
Legs below knees and feet	A.2.5.5	1.88E-03
Neck and above	A.2.5.5	1.38E-03
Spleen	Table A-6, A2.5.1	2.94E-01
Stomach	Table A-6, A2.5.1	2.94E-01
Testes	A2.4.2.2, A2.5.1	1.58E+00
Thymus	A.2.5.4	2.94E-02
Thyroid	A.2.5.5	1.38E-03
Urinary system (except kidneys)	Table A-4, A2.5.1	2.94E-01
Uterus (embryo)	Table A-3, A2.5.1	4.12E-01

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